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Quality and measurement approach of railway track geometry: a review

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Abstract

Purpose – This article aims to systematically review the state-of-the-art approaches for railway track geometry quality measurement and assessment. It identifies and compares available measurement platforms, classifies existing track quality indices (TQIs), and highlights current limitations and future research needs.

Design/methodology/approach – The review follows a structured literature search on Web of Science (2016–2026) using keywords related to track geometry, measurement and assessment. It categorizes measurement equipment into five types: trolleys, track recording vehicles, in-service railway vehicles, smartphones and drones. Quality assessment methods are classified into index-based (single and combined TQIs), vehicle response-based and smart (probabilistic and machine learning-based) approaches. Their formulations, advantages and limitations are analyzed.

Findings – Each measurement platform offers distinct trade-offs among cost, speed, accuracy and coverage. Most existing TQIs treat measurements deterministically, ignore wavelength-dependent effects and assume parameter independence. Vehicle response-based methods and smart TQIs (e.g. stochastic indices, machine learning) show promise in addressing these limitations. Key gaps include the lack of real-time onboard processing, probabilistic and wavelength-aware indices, drone-based quantitative measurement and harmonized measurement standards.

Originality/value – This review provides the first systematic comparison of measurement platforms and quality indices within a unified framework. It critically evaluates the limitations of conventional TQIs and identifies emerging alternatives. The findings serve as a structured reference for researchers and practitioners aiming to improve track geometry assessment and guide future developments in sensor technology, edge computing and standardization.

Keywords Railway track geometry, Track quality, Track quality index, Measurement

Paper type Literature review

1. Introduction

The reliable and durable performance of railway infrastructures is an essential component for the sustained economic growth and social development of modern society (Fan, Lin, Cai, & Liu, 2021). As a vital and effective means of mass transportation, railways play a key role in modern transportation and social development. Compared with other transportation modes, railway transportation has advantages of high capacity, high efficiency and low pollution (Soleimanmeigouni, Ahmadi, & Kumar, 2018; Liu, Feng, Guo, Zhang, & Fan, 2025). In recent years, there has been an increase in rail freight and passenger transportation in European countries. Portuguese will triple the existing high-speed rail network by 2030 for a dense railway network in all European member states (Vale & Lurdes, 2013). Sweden predicts that the average annual growth is estimated to be 3% for passenger traffic and 1% for freight traffic up to 2050 (Trafikverket, 2018). This will impose higher demands on the railway capacity and service quality.

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Railway infrastructure is a complex system consisting of track, signaling systems, electrical systems and telecommunications. Among these elements of this complex system, railway tracks are especially important, as they are designed and built with specific geometry and vary along a route due to topography constraints. The main function of the railway track is to guide the trains in a safe and economic manner with the desired ride comfort (Iwnicki, 2006). Generally, track condition can be defined as the three-dimensional geometry of the track (Esveld, 2001; Jovanovic, 2004). Once operational, the track can degrade due to several factors, causing deviations from the designed geometry that must be corrected to ensure passenger comfort and safety (Soleimanmeigouni *et al.*, 2018). When a geometry failure occurs, severe consequences including economic loss, operation interruption, damage to the railway assets and the environment, and a possible loss of human lives may happen. In addition, a degraded track geometry will affect subsequent loading and damage of the track (Karttunen, Kabo, & Ekberg, 2012).

In the past decade, track quality has attracted lots of attention both in academia and the industry domain. Degradation assessment, as a fundamental and critical process of track geometry quality evaluation, is used to ensure the safety, reliability and cost-efficiency of railroad operations (Beeck, 2017), and further provide support for planning track maintenance (Soleimanmeigouni *et al.*, 2018). Based on the technical route of degradation assessment and maintenance as the main line, this study presents a review of the state-of-the-art research on degradation and maintenance of track geometry (Fan *et al.*, 2023). The review focuses on developments from 2010 to the present time and aims to systematically review the measurement of track quality to maintain the reliability of railway track geometry.

The main contributions of this review to the current body of research are:

(1) The system compared five types of track geometry measurement platforms (trolleys, track recording vehicles (TRVs), in-service trains, smartphones and unmanned aerial vehicles (UAVs)), and analyzed their respective costs, speeds, accuracy and applicable scenarios.

(2) The existing TQI was classified and evaluated, differentiating between single and composite indices, and pointing out their common limitations such as ignoring the wave effect, parameter correlation and deterministic assumptions.

Section 2 defines the research questions, scope and literature selection. Section 3 covers track geometry measurement, including parameters, methods, sensors and equipment (trolleys, recording vehicles, in-service trains, smartphones, drones). Section 4 reviews index-based, vehicle-response and intelligent assessment methods, along with their limitations. Section 5 outlines future challenges: real-time onboard processing, probabilistic/wavelength-aware indices, drone-based quantification and standard harmonization. Section 6 summarizes the innovations and key findings. The abbreviations used throughout this article are summarized in Table 1.

2. Research methodology

A set of research questions guided the literature review and subsequently focused the selection of articles for detailed review.

2.1 Research questions

The following research questions focused the literature review on methods and considerations in railroad track quality:

(1) What parameters are used to characterize the track geometry?

(2) What equipment can be used to measure the track geometry, and what are the measurement approaches?

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Table 1. List of abbreviations

Abbreviation	Full name	Abbreviation	Full name
BSI	British Standards Institution	ORE	Office for Research and Experiments
BRR	Budapest Rack Rail	PSD	Power Spectral Density
BVLOS	Beyond visual line of sight	R2	Track Roughness Index
CNN	Convolutional neural network	RIM	Railway Inspection and Monitoring
CTRL	Channel tunnel rail link	SD	Standard Deviation
EASA	European Union Aviation Safety Agency	SNCF	Société Nationale des Chemins de fer Français
EC	Electrical conductivity	TGI	Track Geometry Index
EN	European Standard	TMD	Traction Maintenance Depot
FAA	Federal Aviation Administration	TQI	Track Quality Index
GEI	Generalized energy index	TRV	Track Recording Vehicle
GPS	Global positioning system	TSI	Track Structure Index
IEP	Intercity Express Programme	UAV	Unmanned Aerial Vehicle
IMI	Integral maintenance index	UGMS	Unattended Geometry Measurement System
ISO	International Organization for Standardization	UIC	International Union of Railways
KF	Kalman filter	UT	Ultrasonic Testing
LiDAR	Light detection and ranging	XGBoost	eXtreme Gradient Boosting
LSTM	Long short-term memory		

Source(s): Authors' own work

2.2 Scope and limitation

Based on the available resources and according to the purpose and objectives of this proposal, the scope and limitation of this study are as follows.

(1) This study mainly focuses on track geometry quality and the related measurement approach.

(2) This proposal is applicable to 1435mm and wider track gauges. The urban/light rail systems and tramways are excluded from the scope of this proposal.

2.3 Article selection

The authors systematically searched published peer-reviewed journal articles and papers found in the database of Web of Science from 2016 to 2026. The searched keyword string was "(track geometry OR quality) AND (measurement OR assessment)" for the title, abstract and keyword fields of their search engines. The initial total number of articles identified was 50,758. The author independently screened titles and abstracts against the following exclusion criteria: (i) non-English publications; (ii) conference abstracts, editorials or book chapters; (iii) studies not addressing railway track geometry measurement or quality assessment; (iv) studies focusing solely on tramways or light rail. This screening eliminated 40,254 records, leaving 10,504 full-text articles for eligibility assessment. Full-text exclusion criteria included: (v) no original measurement or assessment data; (vi) duplicate publication of the same dataset; (vii) full text unavailable. After full-text screening, 5,096 articles were excluded and 5,408 articles were included in the final review. All included articles are peer-reviewed journal papers from the Web of Science database. The screening process is summarized in the PRISMA-style flow diagram, shown in Figure 1.

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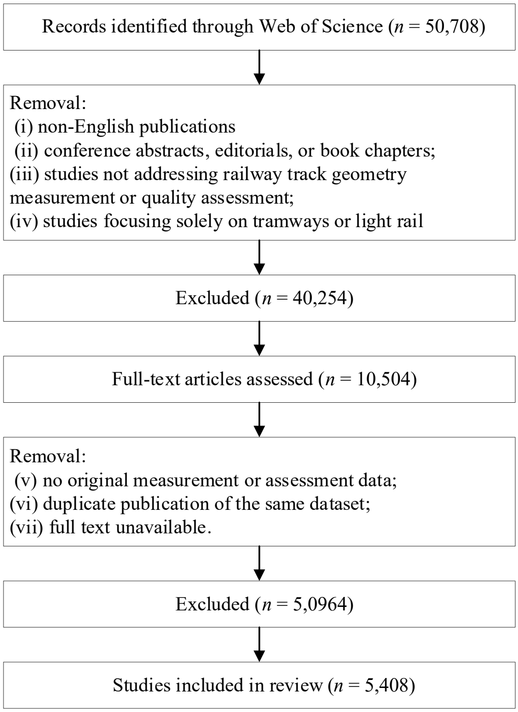

Figure 1. PRISMA-style flow diagram. Source: Authors' own work

3. Track quality measurement

Generally, the condition of railway track can be evaluated and represented in two different ways: track geometry quality or track structure condition, and the track geometry can be defined as three-dimensional geometry of track, which comprises the following five classes (Arasteh Khouy, 2013; Sadeghi, Fathali, & Bouloukian, 2009; Han, Liao, Wang, & Zhang, 2023) (as shown in Figure 2):

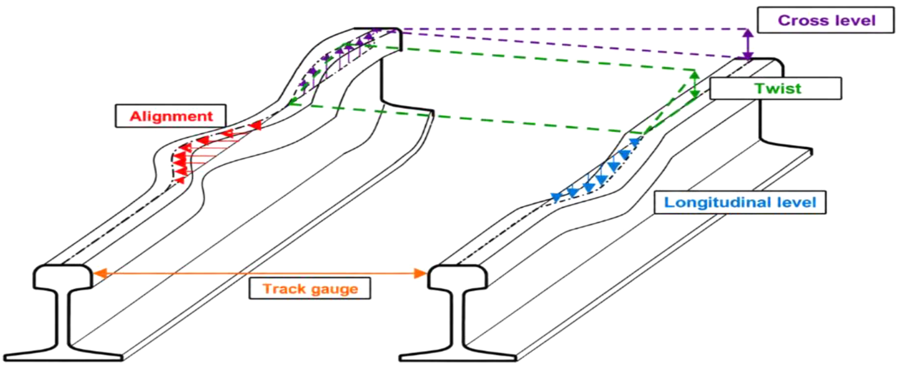

Figure 2. Schematic diagram of gauge calculation. Source: Figure courtesy of Han *et al.* (2023)

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(1) Longitudinal level: vertical profile, top or surface, is the track geometry of track centerline projected onto longitudinal vertical plane.

(2) Alignment: horizontal profile or line, is the track geometry of track centerline projected onto longitudinal horizontal plane.

(3) Gauge: is the distance between the gauge faces of two adjacent rails at a given location below the running surface.

(4) Cant: cross-level, is the difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane.

(5) Twist: is the algebraic difference between two cross-levels taken at a defined distance apart, usually expressed as a gradient between the two points of measurement.

And some secondary measures such as twist, cyclic top, corrugation and cant deficiency (Yeo, 2017) can be derived from the above measures.

The defects and irregularities in track geometry are mostly used to represent the quality of the track and to plan track maintenance. The track geometry degrades with age and usage and can negatively affect track performance and safety. When track geometry degrades to an unacceptable level, it can lead to derailment and the consequences can be significant (Soleimanmeigouni *et al.*, 2018).

To evaluate the defects and irregularities of track geometry, specific track inspection cars are developed, which run over track with a specific speed, monitor track geometry and record the mentioned track geometry measures for every assigned movement (usually 25 cm). Three indicators can be used to assess track geometry quality based on the recorded measurement data (measures proposed in section 3) by inspection trains, i.e. mean value, standard deviation over a specific length and extreme values of isolated defects. In the standard deviation indicator, which is mostly used for assessing track geometry quality, the geometry measures are recorded for every 25 cm over a track section (usually 200 m) and then the standard deviation of the obtained measurement data over the track section is calculated. Different track quality indices (TQIs) can be developed using the three indicators. Alignment and gauge are horizontal geometry measures, whilst longitudinal level, cant and twist are vertical measures. The track geometry irregularities can be classified into short-wavelength and long-wavelength irregularities.

Based on specific track inspection cars, track geometry irregularities index data can usually be measured and collected in two different ways: static and dynamic measurement (Barbosa, 2016).

(1) Static measurement: track inspection cars are usually developed as manual and hand-pushed trolleys, which can measure the quality of track without trains running.

(2) Dynamic measurement: mainly composed of TRVs, in-service railway vehicles, supplemented by onboard, portable loading and other detection equipment, which can not only measure the irregularities of track geometry, but also improve the efficiency and accuracy of measurement.

3.1 Trolleys

The manual mode is the current and typical approach employed to track geometry measurement using trolleys (e.g. Trimble GEDO CE (Moskal & Pastucha, 2016; Trimble, 2018) and Amberg GRP 1000 (Amberg Technologies, n.d.; Chen *et al.*, 2018)). Due to their compact design and small overall dimensions, trolleys are easy to place on or off the track to allow approaching trains to pass. Supported by matched software, the lateral and vertical deviations (of each track inspection point), which are collected and processed by trolleys

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(Li, Wang, Cen, & He, 2022; Sánchez Ríos, Sanjuán, & Bravo, 2020), can be displayed in real time. And modified by manual simulation adjustment, the measurement results can also be used as a guide for track maintenance. However, compared with other equipment, trolley has a great disadvantage in speed.

3.2 Track recording vehicles

Hence, a self-propelled and drivable rail vehicle without the need for an onboard crew is designed, named TRVs, to capture rail defects and track geometry irregularities (Li *et al.*, 2022). Equipped with sophisticated sensors, such as optical lasers, high-resolution cameras, UT and EC sensors, TRVs are more advanced and mature in dealing with image processing and data processing to identify the type and location of defects (Urda, Aceituno, Munoz, & Escalona, 2021; Wu, Azad, Cole, & Spiryagin, 2022). At an operating speed of 250 km/h, TRVs take advantage of cellular services and web tools to report measurement data and track defects to railway track administrators or maintenance crews. Although TRVs can be used for carrying out inspections throughout a railway line without limitations due to TRV capabilities, their high cost is a major limitation for not being widely used. Some common TRVs are Roger 1,000 (Gåsemyr, 2018), New Measurement Train (known as Flying Banana) (Network Rail, 2019).

3.3 In-service railway vehicles

In contrast with trolleys and TRVs which work separately from vehicles, some specific equipment is mounted on in-service railway vehicles, which have been widely used by railway companies all around the world, such as Acela (Marquis & Greif, 2015), DeltaRail (Scott, Chillingworth, & Dick, 2010), Deutsche Bahn ICE 2 (Erhard, Wolter, & Zacher, 2009), Japanese railway (Tsunashima, Naganuma, Matsumoto, Mizuma, & Mori, 2011), Raidarss (Mori, Tsunashima, Kojima, Matsumoto, & Mizuma, 2010), Iris 320 (UIC, 2012) and China railway high-speed trains (Wikipedia, n.d.). The condition monitoring systems in in-service railway vehicles can be categorized into compact onboard devices and car body devices. In compact onboard devices, all sensors and system components are housed and connected to each other in a compact body. In car body condition monitoring systems, sensors and especially accelerometers are installed on different parts of the car such as the car body, the axle box and bogies. For example, vertically and laterally sensing accelerometers have been added to in-service London Underground vehicles to monitor track geometry (Weston, Roberts, Yeo, & Stewart, 2015), while the speed of the vehicle is not taken into account in the processing, so that the accelerations will increase with vehicle speed. Besides, equipped with vertical acceleration on the bogie above the axlebox together with a vertically sensing displacement transducer to the axlebox, DeltaRail can provide accurate vertical rail profiles (King, 2004).

3.4 Smartphones

The performance and sensitivity of smartphone sensors have developed rapidly in recent years. Due to their accessibility and low costs compared to other industrial solutions, the use of smartphone sensors has become more and more common (Vinkó, Simonek, Ágh, Csikós, & Figura, 2023). Wang, Wang, Wang, Chen, and He (2020) developed a multi-source data (audio, acceleration and angle rate) collection framework via smartphone built-in sensors. Tested and proven in Hungary, the proposed XGBoost-based classifier runs fast while maintaining good accuracy. Simonyi, Fazekas, and Gáspár (2014) assessed passenger ride comfort in public transport modes in Budapest. In this research, a smartphone with built-in GPS and accelerometer was employed, and ISO 2631-5 (2004) was chosen to assess the effect of vibration on passenger comfort. The standard defines six different comfort levels based on acceleration measurement: not uncomfortable (0–0.315 m/s2), a little uncomfortable (0.315–

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0.5 m/s2), fairly uncomfortable (0.5–0.8 m/s2), uncomfortable (0.8–1.25 m/s2), very uncomfortable (1.25–2.0 m/s2) and extremely uncomfortable (above 2 m/s2). The experiment was conducted for a bus ride and the Budapest Rack Rail (BRR).

Despite their low cost and accessibility, smartphone-based measurement faces several practical challenges. First, built-in accelerometers and gyroscopes suffer from calibration drift and temperature sensitivity, requiring frequent recalibration to maintain accuracy. Second, sampling rates are often inconsistent and may vary with phone model or operating system load, introducing noise into geometry estimates. Third, the placement of the phone (e.g. on seat, floor or window) affects vibration coupling, and without rigorous mounting, the measured signals may not reliably represent track irregularities. These issues must be addressed before smartphones can be used for quantitative track geometry assessment rather than passenger comfort monitoring.

3.5 Drones

A drone or UAV is a small aircraft that can fly autonomously (or remotely controlled) and is able to capture rail defects such as deformed structure or missing parts (track and sleeper). Due to the low cost, high safety, mobility and flexibility, drones have recently become a potential tool for railway inspection and monitoring (RIM) worldwide. Considering a lack of information about the specific benefits and costs of RIM via drones, Askarzadeh, Bridgelall, and Tolliver (2023) proposed a review and contributed a cost analysis framework to identify the factors that affect drone performance in RIM. An important benefit of using drones lies in the reduced time necessary for inspectors to be in proximity to a railway line. Furthermore, in hazardous locations or areas where rail inspectors are at risk of moving trains, using drones is helpful. Depending on the capacity of the batteries and the distance from the operator, the speed of drones can reach 30 km/h. Different types of sensors can be employed by drones, such as thermographic cameras and high-definition digital video cameras. The distance between a drone and the operator (pilot) ranges between 1 and 10 km (Páli, Mathe, Tamas, & Buşoniu, 2014; Kovacevic, Gavin, Oslakovic, & Bacic, 2016; Singh, Swarup, Agarwal, & Singh, 2019). Recently, LiDAR technology has been exploited by drones to collect useful data during aerial surveys. There are some limitations that must be considered regarding the use of drones, such as the high cost in the case of crashes and the inability to conduct railway inspections in all weather conditions (Kaćunić, Librić, & Car, 2016).

Beyond weather limitations, drone deployment for track geometry measurement is constrained by battery endurance and regulatory restrictions. Typical commercial drones offer flight times of 20–30 min, which limits continuous inspection range and necessitates multiple battery swaps or ground support stations. Additionally, railway operations often require beyond-visual-line-of-sight (BVLOS) flights to cover long track sections, but BVLOS operations are subject to strict aviation authority approvals (e.g. FAA, EASA) and additional safety equipment. Many countries also prohibit drone flights over active railway lines without special permits due to collision and signal interference risks. These regulatory and endurance factors currently hinder the routine use of drones for quantitative track geometry measurement, confining them mainly to visual inspection and spot checks. Representative measurement equipment for the five platform categories discussed above is illustrated in Figure 3.

4. Measurement approach

4.1 Index-based measurement

Track geometry measurement data (e.g. longitudinal level, alignment, gauge, cant, twist) are typically recorded at intervals of 25 cm over a specified track section (e.g. 200 m or 1,000 m). Based on these raw data, three basic statistical indicators can be derived: the mean value, the standard deviation (SD) over the section and the extreme values of isolated defects. Among these, the SD is the most widely used for assessing track geometry quality. On this basis,

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Figure 3. Classic track geometry measurement equipment (a) German GEDO CE, (b) Norwegian Roger 1,000, (c) France Iris 320, (d) Parrot AR.Drone, (e) Smartphone. Source: Figure courtesy of Trimble (2018), Gåsemyr (2018), UIC (2012), Páli *et al.* (2014), Vinkó *et al.* (2023)

various TQIs have been developed by different railway administrations to quantify track conditions, support maintenance decision-making and compare quality across lines. These indices can be divided into two categories: single track quality indices (using one parameter or a simple ratio) and combined track quality indices (integrating multiple geometry parameters).

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4.1.1 Single track quality index. 4.1.1.1 Standard deviation (SD). Proposed by the Office for Research and Experiments (ORE) of the International Union of Railways in 1981 and later adopted by the European Standard EN 13848–5 (2008), the SD describes the dispersion of a geometry signal over a given track section. It is calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2}{N-1}}$$

where n is the number of samples, x_i the measured value and $\bar{x}$ the mean. The SD is simple, universal and easy to compare across sections. However, it does not capture the spatial distribution or the superposition effects of different irregularity wavelengths. Typical classification: very good ($\sigma < 1$), good ($1 < \sigma < 2$), average ($2 < \sigma < 4$), poor ($\sigma > 4$) (unit: mm).

4.1.1.2 K-value. The K-value is defined as the ratio of the total length of track with deviations below comfort limits to the total track length. It provides a macroscopic view of track condition over long distances but ignores the geographical location and specific irregularity types (e.g. longitudinal level vs alignment). It is expressed as:

$$K = \frac{\sum l}{L} \times 100\%$$

where l is the length of track with deviations below comfort limits, and L is the total track length. It provides a macroscopic view but does not identify specific irregularity types or locations.

4.1.1.3 Q index. The Q index considers the average standard deviation of longitudinal level, alignment and cant, together with allowable values for different track categories:

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H_{\lim}}} + 2\times\frac{\sigma_S}{\sigma_{S_{\lim}}}\right] \Big/ 3$$

where σ_H is the average of the standard deviation of left and right profile; σ_S is the average of the standard deviation of cross level, gauge and horizontal deviation; $\sigma_{H_{lim}}$ is the allowable value of σ_H based on track categories; and $\sigma_{S_{lim}}$ is the allowable value of σ_S based on track categories. Sweden Railway uses a chord length of 12 m to measure deviations. The minimum and maximum values for the Q index are 50 and 150, respectively, and the allowable values of the Q index lie between 70 and 90 (Sadeghi, 2010).

4.1.1.4 Length-based TQI. Derived from the ratio of the traced space curve length to the fixed track segment length:

$$TQI = \left(\frac{L_s}{L_0} - 1\right) \times 10^6$$

where TQI is the trac quality index for each individual track geometry parameter, L_s is the traced length of space curve and L_0 is the fixed length of track segment. The traced space curve length L_s is calculated by summing up the distances between any two points within the track segment.

$$L_s = \sum_{i=1}^{n} \sqrt{\Delta y_i^2 + \Delta x_i^2} = \sum_{i=1}^{n} \sqrt{\Delta y_i^2 + 1}$$

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where Δy is the difference between the two measurements, Δx is the sampling interval along the track (=1 ft) and i is the sequential number.

4.1.2 Combined track quality index. 4.1.2.1 W5. For each geometry parameter, defectiveness d is defined as the ratio of the length of subsections that have exceeded the acceptable deviation to the total length of the section:

$$w = \frac{\sum L_i}{L}$$

where L_i is the length of subsections that have exceeded the acceptable deviation and L is the total length of the track section. Assuming that the geometry parameters have negligible effects on each other, each geometry parameter is treated independently. Therefore, from probability theory, the five-parameter defectiveness is defined as:

$$w_5 = 1 - (1 - w_e)\left(1 - w_g\right)(1 - w_w)\left(1 - w_y\right)(1 - w_z)$$

where w_z and w_y are arithmetic averages for the vertical and horizontal irregularities, respectively, as determined from the defectiveness of the left and right rails, w_g is the defectiveness of cross level, w_w is the defectiveness of twist and w_e is the defectiveness of the track gauge. The amounts of deviations are calculated over a chord length of 18.9 m.

4.1.2.2 MDZ. Another quality index called MDZ represents the track quality condition from a different point of view (Lyngby, 2009). The MDZ comprises both horizontal and vertical deviations in track together with speed and lack of super elevation. This measurement is developed to capture the changes in acceleration over a certain distance from a passenger point of view by direct mathematical analysis of the real track geometry data, recorded by the measuring wagon.

$$MDZ = c \times \frac{1}{L} \times v^{0.65} \times \sum_{i=1}^{L/\Delta x} \sqrt{(\Delta vert.level)^2 + (\Delta horiz.level + \Delta cant)^2}$$

where $\Delta vert.level$ and $\Delta horiz.level$ are the differences in track deviation from one measurement point to the next. Here, $\Delta cant$ is the difference in cant level from one measurement point to the next.

4.1.2.3 R2. In the United States, the track roughness index was developed by Amtrak. The Amtrak database can import and present measured data and calculated roughness data from the Amtrak geometry recording car (Sadeghi, 2010). This index is calculated by dividing the summation of the squares of deviations by the number of measured points as expressed in the following equation:

$$R^2 = \sum_{i=1}^{n} \frac{d_i^2}{n}$$

where n is the number of measurements and d_i is the amount of deviation measured over the 20 m mid-chord offsets. This index is used for profile, alignment, cross level and gauge.

Table 2 indicates the condition of a track based on the roughness index for data obtained from a track field (Sadeghi, 2010).

4.1.2.4 Chinese TQI. TQI can be used as the decisive indicator for maintenance planners. This quality index can either be the track geometry index (TGI) or the track structure index (TSI), but these two indices are not independent variables. The TGI is the track quality from the perspective of the user and is obtained from track geometry data recorded by track geometry recording cars. It indicates only the geometry conditions of the track, such as profile, twist, gauge and alignment, which have a direct influence on track riding comfort. The TSI

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Table 2. Track condition based on roughness index

Track condition	R^2 value
Very good	$R^2 < 1$
Good	$1 < R^2 < 4$
Average	$4 < R^2 < 16$
Poor	$16 < R^2$

Source(s): Authors' own work

represents the structural conditions of the track, including the condition of the rail, sleeper, fastening systems, subgrade and drainage systems. This index refers directly to the actual condition of the track and can indicate the track's potential for degradation (Sadeghi & Askarinejad, 2010; Liu, Xu, Sun, Zou, & Sun, 2015).

$$TQI = \prod_{i=1}^{5} \sigma_i$$

$$\sigma_i = \sqrt{\frac{1}{N} \sum_{j=1}^{N} \left(X_{ij} - \overline{x}_i \right)^2}$$

where N is the number of sampling points within 200 m, $\overline{x_i}$ is the arithmetic mean of each indicator and σ_i is the standard deviation of each indicator.

4.1.2.5 J index. In Poland, J index is used for the determination of track geometry quality. This coefficient is calculated using the following formula (Sadeghi, 2010):

$$J = \frac{S_z + S_y + S_w + 0.5S_e}{3.5}$$

where S_e is the standard deviation of vertical irregularities, S_y is the standard deviation of horizontal irregularities, S_w is the standard deviation of track twist and S_z is the standard deviation of track gauge.

The allowable values of the J index for different speeds are presented in Table 3 (Sadeghi, 2010).

4.1.2.6 Power spectral density. Power spectrum density (PSD) gives the energy of the signal in relation to frequency for a given track geometry parameter measured over a given track section. Chen, Yang, Wu, and Chai (2006) gave PSD models for vertical and alignment irregularity for railways in China. For vertical irregularity PSD, the model is

$$S_v(f) = \frac{A \cdot B^2}{f^2 \left(f^2 + B^2 \right)}$$

Table 3. Allowable amounts of J index for different speeds

Speed (km/hr)	30	40	90	120	160	200
J index	12.0	11.0	6.2	4.0	2.0	1.4

Source(s): Authors' own work

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And the model for alignment irregularity

$$S_y(f) = \frac{A \cdot B^2}{\left(f^2 + B^2\right)\left(f^2 + C^2\right)}$$

where $S(f)$ is track irregularity PSD, f is spatial frequency A, B and C are fitting parameters.

4.1.2.7 TQI combined standard deviations. Assessment of the overall track geometry quality of a track section (200 m, 1000 m, ...) can be made by a combination of standard deviations (SDs) of the individual geometric parameters. An example of such a TQI is given below (BSI Group, 2010; Tzanakakis, 2013).

$$TQI = \sqrt{w_{Al} \cdot \sigma_{Al}^2 + w_G \cdot \sigma_G^2 + w_{Cl} \cdot \sigma_{Cl}^2 + w_{Tp} \cdot \sigma_{Tp}^2}$$

where Al is the mean of alignment of both rails, G is the track gauge, Cl is the cross level, Tp is the mean of longitudinal level of both rails, w is the weighting factor of the geometry parameters and σ is the standard deviation of the individual geometry parameters.

4.1.2.8 Integral maintenance index. Li and Xu (2009) proposed an integral maintenance index (IMI) that considers the distribution of track geometry parameters to evaluate track condition, and they developed an integral maintenance plan based on this index. The IMI combines the track geometry parameters, maintenance history, as well as lateral and vertical acceleration.

$$IMI = \sum_{i=1}^{7} W_i \cdot C_i^{N_i} \cdot B_i$$

where W_i are weight factors of the track geometry such as profile, alignment and lateral acceleration, vertical acceleration, history maintenance works, etc. C_i are punishment factors of the track geometry such as profile, alignment and lateral acceleration, vertical acceleration, history maintenance works, etc. N_i are incremental factors for punishment of the track geometry such as profile, alignment and lateral acceleration, vertical acceleration, history maintenance works, etc. B_i is the equivalent value of the track geometry such as profile, alignment and lateral acceleration, vertical acceleration, history maintenance works, etc.

4.1.2.9 Generalized energy index. The other integrated index is the generalized energy index (GEI) proposed by Li and Xiao (2014). They developed a grey model to predict the GEI sequence over time. The GEI can capture various effects of different wavelength components of track irregularity on the vehicle dynamic response. Because the GEI can consider different track irregularity wavelength and speed, they argued that it is a better index than the TQI to evaluate dynamic performance.

$$GEI = \sum_{i=1}^{7} \alpha_i \sqrt{\frac{1}{n-1} \sum_{j=0}^{n-1} w(f_i) E_i(f_i)}$$

where α_i stands for a prescribed single weight coefficient in advance, $E_i(f_i)$ stands for the energy of wavelength f_j corresponding to individual irregularity j, $w(f_i)$ stands for the energy weight coefficient corresponding to the wavelength f_j and n is the number of sampling points.

The timeline and the development of various track quality index are shown in Figure 4.

4.2 Vehicle response-based assessment

4.2.1 Vehicle-body acceleration. Odashima, Azami, Naganuma, Mori, and Tsunashima (2017) propose a track condition monitoring technique using car-body acceleration that can be easily

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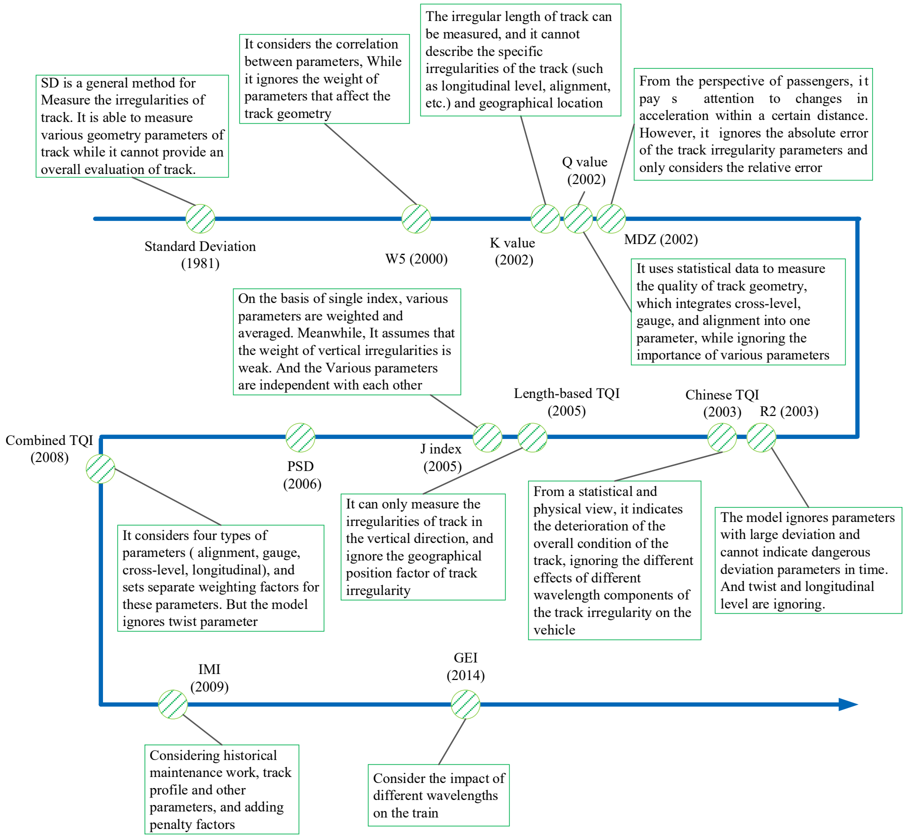

Figure 4. Timeline of various track quality index. Source: Authors' own work

measured by an in-service vehicle for the sake of an increase in safety of railway transportation. This article demonstrates the possibility of estimating track irregularities of conventional railway tracks using car-body acceleration only. The methodology proposed uses inverse dynamics to estimate track irregularity from car-body acceleration, applying a Kalman filter (KF) to solve this problem. This technique estimates the track irregularity in the longitudinal plane (track geometry and 10 m-chord versine). The KF can be applied to inverse analysis by expressing track geometry as a random walk model and incorporating the model in an equation of state. The estimation technique can support a change of the vehicle velocity by selecting an appropriate impulse response in the measurement equation for the vehicle velocity. Estimation results in simulation and full-scale tests revealed that the proposed estimation technique is effective for track condition monitoring with acceptable accuracy for conventional railways.

Li, Berggren, Berg, and Persson (2008) present a study of assessing track geometry quality (longitudinal level and alignment) by the use of dynamic track-vehicle simulations and wavelength spectra analysis. Two simulation models are developed: one is based on the software package GENSYS, which provides realistic simulations of the nonlinear dynamic behavior of a vehicle running on a real track, and the other one is based on a newly developed linear track-vehicle model, which is suitable for effectively calculating wheel-rail forces for very long track sections. The linear model, to assess vertical track geometry quality

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(longitudinal level), is extended in the present article to simulate lateral track-vehicle dynamic interaction and, thus, to assess lateral track geometry quality (alignment) as well. Numerical results are presented to compare the simulation results with online measurement and to demonstrate the possibilities of enhancing track quality assessment and maintenance by simulations of track-vehicle interaction.

Naganuma, Kobayashi, and Tsunashima (2013) describe a track condition monitoring technique using car-body motions. In an inverse problem to estimate track geometry in longitudinal level from vertical car-body acceleration and pitching rate measured by in-service vehicle, dynamic programming filter and KF were applied. Study results confirmed that proposed solutions can be used to estimate track geometry in level with desired precision.

4.2.2 Vehicle-body vibration. Ma, Gao, Liu, and Lin (2019) give a method to predict vehicle-body vibration based on deep learning, which represents one of the newest areas in artificial intelligence. By integrating convolutional neural network (CNN) and long short-term memory (LSTM), a CNN-LSTM model is proposed to make accurate and point-wise prediction. To achieve optimal performance and explore the internal mechanism of the model, structural configurations and inner states are extensively studied. CNN-LSTM can take advantage of the powerful feature extraction capacity of CNN and LSTM, and outperforms the fully-connected neural network and the plain LSTM on the experimental data of a high-speed railway.

Tsunashima, Naganuma, and Kobayashi (2014) demonstrate the possibility of estimating the track geometry of Shinkansen tracks using car-body motions only. In an inverse problem to estimate track irregularity from car-body motions, a KF was applied to solve the problem. Estimation results showed that track irregularity estimation in the vertical direction is possible with acceptable accuracy for real use.

4.2.3 Hybrid vehicle response. The use of vehicle responses in the track geometry assessment process allows identifying critical defects and improving the maintenance operations. Kraft, Causse, and Coudert (2018) present a vehicle response-based assessment method using multi-body simulation. The choice of the relevant operation conditions and the estimation of the simulation uncertainty are outlined. The defects are identified from exceedances of track geometry and vehicle response parameters. They are then classified using clustering methods and the correlation with vehicle response is analyzed. The use of vehicle responses allows the detection of critical defects which are not identified from geometry parameters.

Luber, Haigermoser, and Grabner (2010) proposed a method for track geometry assessment that considers the vehicle/track interaction. “Representative” transfer functions are used for the prediction of the vehicle reaction. Therefore, the results show a significant enhancement of the correlation between the track assessment quantities and the VR forces.

Prediction of the vehicle dynamic response to existing track geometry can be used to locate potentially unsafe locations in track, based on a range of vehicle configurations and operating speeds. While this is currently done in an offline mode, it would be advantageous to achieve this on a track geometry car in real-time. A limited real-time dynamic simulation system was developed for just this purpose. The model was initially based on the track analyzer method developed by the Volpe National Transportation Systems Center but was significantly enhanced to provide accurate predictions over a wider variety of vehicle behavior and in response to a wider variety of track geometry quality. Responses predicted by the model, including the vehicle bounce, roll and pitch, as well as vertical wheel/rail forces, are compared with established limitations on vehicle response to identify unsafe locations in track. Inputs to the model include the relevant physical parameters of the vehicle, the range of vehicle traveling speeds to be analyzed and the dynamic response safety thresholds with which exceptions are located. Finally, the system was validated (by comparison with NUCARS predictions) and tested for its real-time capabilities (Bonaventura, Palese, & Zarembki, 2000).

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4.3 Smart track quality index

Many Track Quality Index calculation methods are listed in sections 4.1.1 and 4.1.2. These methods have been applied in many countries and organizations. However, these methods contain a common issue, that is, these assessment methods have great subjectivity and bias in the measurement of track geometry quality (Fan, Wang, Liu, & Ren, 2016). As shown in Figure 5, if the SD assessment method is used, the quality of track geometry is always in a state of maintenance, but if the J index assessment method is used, the track does not need to be maintained (Movaghar & Mohammadzadeh, 2020).

Movaghar and Mohammadzadeh (2020) propose a stochastic track quality index that considers the uncertainty regarding the quality classification that remains even after the data have been observed. To achieve this, the problem is set into a probability context by selecting a Bayesian framework to characterize the unknown parameters of probabilistic models for track geometry parameters. To demonstrate the efficiency of the approach, the proposed quality index is applied to the data recorded from field observation. To verify the validity of the presented approach, the obtained results are compared to those of deterministic results and reasonable accuracy can be reported. Subsequently, this index enables the infrastructure manager to efficiently prioritize maintenance actions.

Sadeghi and Askarinejad (2012) used the neural network technique to correlate track geometry irregularities to track structural defects. The main aim was to predict structural defects without performing expensive and time-consuming visual inspections. Track geometry data were considered as inputs of the neural network model, and the structural defects in the rail, sleeper, fasteners and ballast were quantified and considered model outputs. The researchers concluded that their model is sensitive to track quality condition, and the model accuracy is not adequate for new tracks with high-quality condition.

Lasisi and Attoh-Okine (2018) developed a principal component analysis. To validate the use of principal components as TQI, they employed a two-phase approach. The first phase was to identify a classic machine learning technique that works well with track geometry data. The second step was to train the identified machine learning technique on the sample mile-track data using combined TQIs and principal components as defect predictors. The performance of the predictors was compared using true and false positive rates. The results show that three principal components were better at predicting defects and revealing salient characteristics in track geometry data than combined TQIs even though there were some correlations that are potentially useful for track maintenance.

In the study by Li, Liu, Li, and Wang (2019), the recovery rates of track geometry quality and track geometry degradation rates between two adjacent tamping operations corresponding to each track geometry irregularity index were used as recovery measure indexes to establish models for the recovery measure of tamping on different track geometry irregularity indexes. Box plots were used for comparative analyses of the recovery effects of tamping on different track geometry irregularity indexes. The test showed that the recovery measure models proposed in this study can be used to effectively guide tamping operations. The tamping strategy based on these models helped significantly improve the tamping of the Shenmu–Shuozhou railway in terms of the tamping length of track and tamping cost. This was verified by comparing with the traditional tamping strategy and the tamping strategy based on the longitudinal level.

In the present work, a machine learning-based fault classifier for the condition monitoring of track irregularities in the lateral direction is proposed by Galván-Núñez and Attoh-Okine (2018). The classifiers are trained with a dataset composed of numerical simulation results and validated with a dataset of measurements acquired by a diagnostic vehicle on the straight track sections of a high-speed line (300 km/h). Classifiers based on decision tree, linear and Gaussian support vector machine algorithms are developed and Figure 1 compared in terms of performance: good results are achieved with the three algorithms, especially with the Gaussian support vector machine. Even though classifiers are data-driven, they retain the essence of lateral dynamics. To facilitate comparison, the representative track geometry measurement

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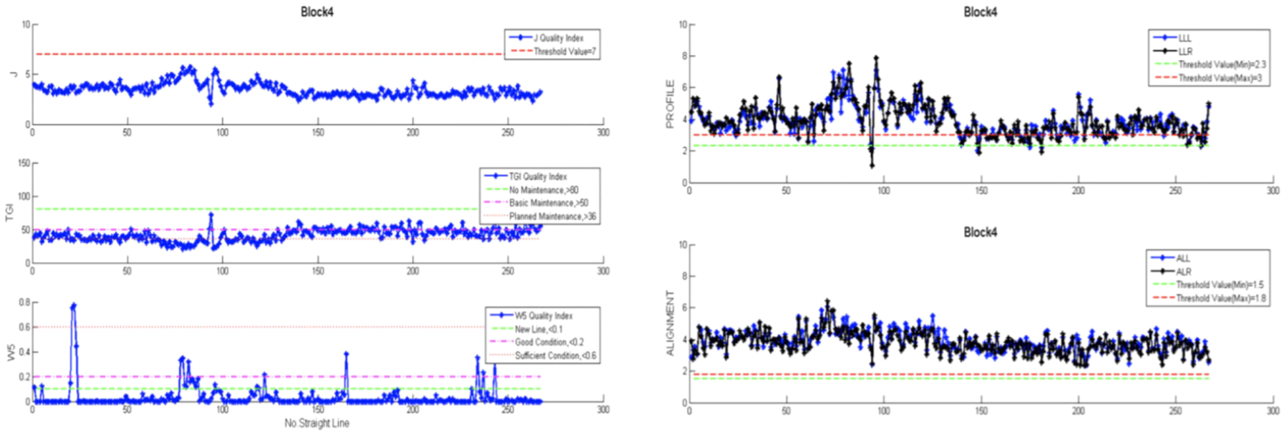

Figure 5. Left: J, TGI and W5 quality indices, right: EN quality index. Source: Figure courtesy of Movaghar and Mohammadzadeh (2020)

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equipment is summarized in Table 4. The reviewed track quality evaluation indicators are summarized in Table 5. Furthermore, the technical characteristics of representative track geometry measurement platforms are compared in Table 6.

5. Future work

Despite significant advances in the measurement and quality assessment of railway track geometry, several challenges remain open. Based on the critical review conducted in this article, future research directions are identified from three perspectives: measurement equipment and platforms, TQIs and data processing methodologies.

5.1 Real-time onboard processing for instant alerts

Most systems rely on offline post-processing, causing delays between defect occurrence and detection. Future research should focus on real-time onboard processing using edge computing platforms to compute geometry parameters and quality indices instantly, enabling immediate alerts for critical defects (Liu, Feng, Hai, Ren, & Fan, 2022). Key challenges include lightweight algorithms, robust multi-sensor fusion and reliable wireless communication.

5.2 Probabilistic and wavelength-aware quality indices

Existing TQIs (e.g. SD, J, W5) treat measurements as deterministic and aggregate all wavelengths into a single value, ignoring uncertainty and wavelength-dependent effects on vehicle dynamics. Future indices should be probabilistic (providing confidence intervals) and wavelength-separated (using band-pass filtering or wavelet decomposition) to better reflect safety and comfort (Wei, Qian, Li, Ren, & Fan, 2025).

5.3 Drone-based quantitative measurement

Drones are already used for visual inspection, but their application for quantitative track geometry measurement (e.g. longitudinal level, alignment) remains immature. Future work should develop high-precision drone-based systems with LiDAR or stereo vision, robust motion compensation and GPS-denied localization, particularly for inaccessible or hazardous track sections.

6. Conclusion

This article presents a comprehensive review of the quality and measurement approaches for railway track geometry, covering developments from 2010 to the present. Five categories of measurement platforms are identified and compared: trolleys, TRVs, in-service railway vehicles, smartphones and drones. Each platform offers distinct trade-offs among cost, speed, accuracy and coverage. TRVs provide the highest accuracy and speed but are expensive, while smartphones and drones offer low-cost alternatives with current limitations in quantitative precision. In-service vehicles equipped with inertial sensors enable continuous monitoring without disrupting traffic, representing a significant step toward cost-effective condition assessment.

For quality assessment, a wide range of TQIs are classified into single indices (standard deviation, K-value, Q index, length-based TQI) and combined indices (W5, MDZ, R^2, Chinese TQI, J index, power spectral density, IMI, GEI). While combined indices provide a more holistic view, most existing TQIs suffer from common limitations: they treat measurements as deterministic, ignore wavelength-dependent effects and assume independence among geometry parameters. Vehicle response-based assessment and smart TQIs (stochastic indices, machine learning-based methods) have emerged as promising alternatives to address these limitations.

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Table 4. Comparisons of measurement equipment

No	Name	Developer	Data collection	Measured parameters	Application	Note
Trolleys						
1	GEDO CE	German	Directed track geometry measured data	Longitudinal level; Alignment; Gauge; Cant; Twist	TSTJV Taiwan Shinkansen Trackwork Joint Venture, Danish Rail, Network Rail (UK), SNCF (France) etc	Track recording vehicles (Hand push)
2	GRP1000	Switzerland	Directed track geometry measured data + GPS	Gauge; Cant	Demanding projects have been successfully realized in, e.g. Germany, Austria, Belgium, Denmark, France, Italy, UK, Korea, USA, PR China etc	Track recording vehicles (Hand push)
Track recording vehicles						
3	Roger 1,000	Norwegian	Laster + GPS	Longitudinal level; Alignment; Gauge; Cant; Twist	Italy, Switzerland, Germany and Norway	Track recording vehicles (160km/h)
4	New Measurement Train	United Kingdom	Lasers, vertical and horizontal actuators, gyros, accelerometers, video/image system	Gauge; Alignment; Twist; Cant; Wear	It is allocated to Heaton TMD in Newcastle-upon-Tyne, returning there for scheduled maintenance every week	Track recording vehicles (200km/h)
In-service railway vehicles						
5	UGMS	United Kingdom	Directed track geometry measured data + GPS	Longitudinal level; Alignment; Gauge; Cant; Twist	New intercity express programme (IEP) vehicles	Condition monitoring from in-service railway vehicles
6	Acela train	USA	Car body vertical acceleration, lateral acceleration, bogie lateral acceleration + GPS	–	American high-speed trains (Acela train)	Condition monitoring from in-service railway vehicles (240km/h)
7	DeltaRail Track line system	Europe	Vertical acceleration on the bogie above the axle box, vertically sensing displacement transducer to the axle box	Vertical rail profiles	CTRL between London and Paris/ Brussels	Condition monitoring from in-service railway vehicles (300km/h)

(*continued*)

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Table 4. Continued

No	Name	Developer	Data collection	Measured parameters	Application	Note
8	Deutsche Bahn ICE 2 train	Germany	Accelerometers	–	S-Bahn Hamburg, S-Bahn Berlin	Condition monitoring from in-service railway vehicles
9	Japanese railway	Japanese	Vertical and lateral acceleration of the car body, rate gyroscope, cabin noise + GPS	Rail irregularities	Japanese conventional railway	Condition monitoring from in-service railway vehicles
10	RAIDARSS	Japanese	axle-box-mounted, vertically sensing accelerometers + GPS	Rail irregularities	Japanese high speed train	Condition monitoring from in-service railway vehicles
11	Iris 320	France	Accelerometers + GPS	–	Eurotunnel, High Speed 1, high-speed line in Belgium for Infrabel	Condition monitoring from in-service railway vehicles (200km/h)
12	China Railway comprehensive inspection trains	China	Accelerometers on axle box, frame and car body, wheel-rail force + GPS	–	Chinese "He Xian" trains	Condition monitoring from in-service railway vehicles (350km/h)
Smartphones						
13	Smartphones	–	GPS, accelerometer, vibrations		Budapest Rack Rail (BRR), trains in Montreal, Santo Domingo and London	Mainly taking passenger comfort or discomfort as a criteria
Drone						
14	Drone	–	Image	Gauge	–	Condition monitoring by drone

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Table 5. Summary of evaluation indicators

No	Geometry index	Developer	Parameters	Advantage	Disadvantage	Year
Objective (single) track quality indices						
1	Standard deviation (BSI Group, 2010)	Europe standard (EN 13848–5)		General method covering various geometry parameters	Cannot measure superposition effect of irregularities	1981
2	K value (Khouy, Larsson-Kråik, Nissen, Juntti, & Schunnesson, 2014)	Sweden National Railway	Total length of the track with deviations below comfort limits	The irregular length of track can be measured	(1) Does not identify specific irregularities (e.g. longitudinal level, alignment) (2) Ignores location, no maintenance guidance	2002
3	Q (Sadeghi, 2010)	Sweden National Railway	Combination of alignment, gauge and cant	Covers cant, gauge, alignment irregularities	(1) Ignores weights of cant, gauge, alignment (2) Omits twist & longitudinal level (vertical irregularities common; twist linked to derailment)	2002
4	Length-based TQI (El-Sibaie & Zhang, 2004)	US railway	Traced length of space curve	Measures irregular longitudinal length	(1) Cannot measure lateral irregularities (derailment risk) (2) Lacks location information for maintenance	2005
Objective (combined) track quality indices						
5	W5 (Sadeghi, 2010)	Austrian Railway	☑ Longitudinal level ☑ Alignment ☑ Gauge ☑ Cant ☑ Twist	Considers correlation among five geometry parameters	Ignores parameter weights	2000
6	MDZ (Lyngby, 2009)	–	☑ Longitudinal level ☑ Alignment ☒ Gauge ☑ Cant ☒ Twist	Passenger-centric; focuses on acceleration change over distance	(1) Considers relative error but ignores absolute error (2) Omits gauge & twist; cannot assess derailment risk	2002

(*continued*)

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Table 5. Continued

No	Geometry index	Developer	Parameters	Advantage	Disadvantage	Year
7	R^2 (Sadeghi, 2010)	American	☒ Longitudinal level ☑ Alignment ☑ Gauge ☑ Cant ☒ Twist	Comprehensively considers alignment, gauge, cant	(1) Ignores large deviations; no timely alert for dangerous parameters (2) Omits twist and longitudinal level – vertical irregularities common; twist linked to derailment	2003
8	TQI (Sadeghi and Askarinejad, 2010)	Chinese National Railroad	☑ Longitudinal level ☑ Alignment ☑ Gauge ☑ Cant ☑ Twist	Describes deterioration from statistical & physical perspectives	Ignores wavelength-dependent effects on vehicle (comfort, derailment)	2003
9	J (Sadeghi, 2010)	Polish Railway	☑ Longitudinal level ☑ Alignment ☑ Gauge ☒ Cant ☑ Twist	Weighted average with lower weight for vertical irregularities	(1) Assumes parameters are independent (2) Omits cant; cannot assess train turbulence	2005
10	PSD	–	☑ Longitudinal level ☑ Alignment ☒ Gauge ☒ Cant ☒ Twist	(1) Reflects wavelength effects on track quality (2) Enables comparison of track spectra across countries	Depends on data quality & sample representativeness	2006
11	TQI combined SD (BSI Group, 2010; Tzanakakis, 2013)	Europe standard (EN 13848–5)	☑ Longitudinal level ☑ Alignment ☑ Gauge ☑ Cant ☒ Twist	Considers four parameters with individual weights	Omits twist – cannot assess derailment risk	2008
12	IMI (Li & Xu, 2009)	–	Profile, alignment and lateral acceleration, vertical acceleration, history maintenance works	Considers maintenance history, profile, other parameters and penalty factor	Omits gauge & twist – no derailment assessment	2009
13	GEI (Li & Xiao, 2014)	–	Wavelength corresponding to individual irregularity	Considers wavelength effects on train	(1) Ignores parameter weights and correlations (2) Ignores large deviations; no timely alert for dangerous parameters	2014

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Table 6. Technical comparison of representative track geometry measurement platforms

	Trolley	Track recording vehicle	In-service vehicle	Smartphone	Drone
Measurement principle	Inertial + optical encoder	Inertial + laser profiling	Inertial (car-body/bogie accel.)	MEMS accelerometer + GPS	LiDAR + stereo vision
Main sensor type	IMU, laser ranger, encoder	IMU, gyro, laser cameras, GPS	Accelerometers, rate gyro, GPS	3-axis accel., gyro, GPS	LiDAR, RGB camera, IMU, GPS
Sampling resolution	0.25 m	0.25 m	0.5–1 m (dependent on speed)	10–100 Hz (time-based)	0.05–0.1 m
Operating speed	Manual push (≤5 km/h)	Up to 160 km/h	Revenue speed (≤240 km/h)	Any (passenger ride)	≤30 km/h (hover/slow)
Measurable parameters	Long. level, alignment, gauge, cant, twist	Long. level, alignment, gauge, cant, twist	Vertical/lateral accel., derived geometry	Vibration level, qualitative comfort	Gauge, alignment (2D), defects (visual)
Accuracy	±1 mm, calibration before each use	±0.5 mm, periodic calibration	Low (qualitative trend), no absolute calibration	High drift, needs frequent recalibration	±10–30 mm (absolute), needs ground control
Spatial wavelength range	3–50 m (short to medium)	3–120 m (medium to long)	10–100 m (medium, speed-dependent)	Limited (aliasing, noise)	1–20 m (short)
Data processing pipeline	Real-time display, offline post-processing	Onboard processing + web reporting	Edge processing (limited real-time)	Cloud post-processing	Offline point cloud processing

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This review provides the first systematic comparison of measurement platforms and quality indices within a unified framework, identifying critical gaps including the lack of real-time onboard processing, probabilistic and wavelength-aware indices, drone-based quantitative measurement and standardized measurement protocols. The findings serve as a structured reference for researchers and practitioners seeking to improve track geometry assessment.

Future developments in sensor technology, edge computing and artificial intelligence should be directed toward real-time onboard processing that enables instant alerts for critical geometry defects (Liu *et al.*, 2022). Further research is also needed to develop probabilistic TQIs that provide confidence intervals, wavelength-separated indices that better reflect safety and comfort, and harmonized measurement standards across different railways. Addressing these challenges will advance railway track geometry assessment toward greater accuracy, intelligence and international interoperability.

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