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A Review on the Development of a Track Irregularity Measurement Tool

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Abstract: Railway transportation is one of the most vital transportation modes for people and goods. Ensuring railway transportation safety and efficiency is very important. The condition of the track is one of the most vital factors in ensuring railway safety, as irregularities in the track can lead to severe accidents. Thus, it is essential to have proper gauges and methods to measure track irregularities. This paper will discuss different methods to measure track irregularities and their advantages and limitations. Several track irregularity measurement tools will be divided into groups based on different aspects, such as the contact types and their location. Contact methods can measure more detailed irregularities, but have limitations such as injury and equipment damage. Non-contact methods are less invasive and can measure larger rail sections, but are less accurate. The inspection method will be chosen based on the track configuration that must be carefully studied to ensure the most efficient and effective inspection methods for a rail type. Regardless of the method, it is important to keep developing and improving existing track irregularity measurement tools to increase efficiency and reduce measurement errors.

Keywords: *Railway, Track Irregularities, Measurements, Sensors*

INTRODUCTION

Railway transportation is a vital mode of transport for people and goods. However, ensuring its safety and efficiency is of utmost importance[1]. The condition of the rail is a crucial factor in ensuring railway safety, as track irregularities, such as irregularities of gauge, alignment, longitudinal level, cross-level, and twist, can lead to severe accidents[2]. Thus, it is essential to have proper gauges and methods to track irregularities for maintenance and repair planning. Understanding the significance of rail conditions and implementing appropriate measures is vital to ensure safe and efficient railway transportation[3].

Various types of track irregularity measurement tools are available, including contact and non-contact methods. Contact methods use equipment that directly interacts with the rail to measure irregularities. These tools measure several irregularities such as gauge, alignment, longitudinal level (profile), cross-level, and twist. Non-contact methods, on the other hand, use equipment to measure rail geometry without touching it. These tools include track inspection systems, which use lasers or cameras to measure rail profiles and other irregularities such as gauge, cant, and curvature[4]. Measuring and tracking track irregularities is essential for the safe and efficient operation of narrow-gauge railways.

Both contact and non-contact methods have their own advantages and limitations. The main advantage of the contact method is that it provides more accurate data and can be used in various environmental conditions. Contact methods can measure more detailed irregularities, but contact methods have some limitations, such as the risk of injury and equipment damage, and are limited to certain rail types[5]. On the other hand, non-contact methods have the advantage of being less invasive, so they are less likely to cause damage to the rail and reduce the risk of injury to personnel. Non-contact methods can also measure larger rail sections and can be used across different rail types. However, non-contact methods are generally less

[1] Tomas Lidén, "Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research," *Transportation Research Procedia* 10 (2015): 574–83, https://doi.org/10.1016/j.trpro.2015.09.011.

[2] Hitoshi Tsunashima, "Condition Monitoring of Railway Tracks from Car-Body Vibration Using a Machine Learning Technique," *Applied Sciences (Switzerland)* 9, no. 13 (2019), https://doi.org/10.3390/APP9132734.

[3] [3,4]

[4] [5-7]

[5] Q. Feng et al., "Research on a High-Speed Railway Track Irregularity Detection and Analysis System," 2018.

accurate than contact methods[6], especially when measuring more minor deviations. Ultimately, the choice of method depends on the specific needs of the railway track and the resources available. Therefore, it is crucial to analyze the advantages and limitations of each method before deciding which method to use for measuring track irregularities[7].

Developing new measurement tools and improving existing methods have enabled more accurate and efficient tracking of irregularity measurements. As a result, research in this area has become increasingly important to ensure the safety and efficiency of railway systems[8]. This review will provide an overview of the current state of track irregularity measurement and highlight opportunities for further development in this area.

REGIONAL GEOLOGY

Design and Development of Measuring Tools

The development of a railroad irregularity measuring instrument is carried out to find the best solution for the times and the needs that are always different. There are phases in product development, namely planning, concept development, system design, detailed design, testing, and improvement.

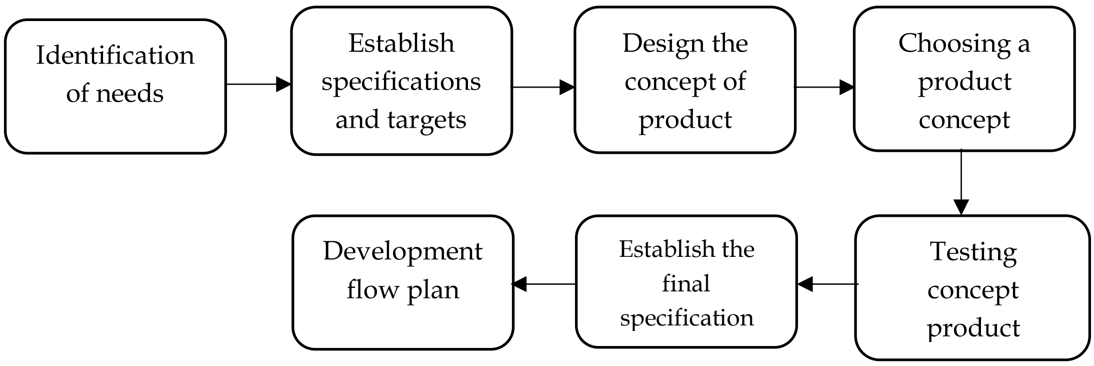

Figure 1 Steps of Product Design [9]

[6] Chen et al., "Railway Track Irregularity Measuring by GNSS/INS Integration."

[7] Y. Li et al., "A Review of Railway Track Irregularity Detection Methods," *Measurement*, 2019.

[8] [10,11]

[9] C T Ulrich and S D Eppinger, "Product Design and Develop. Yang Delin, Transl. Dalian" (Dongbei University of Finance & Economics Press, Liaoning, China, 2001).

The development of a railroad irregularity measuring instrument commences with the identification of specific needs within the railway industry. Subsequently, precise specifications and performance targets are established to address these requirements. The conceptualization phase entails the design of the product, followed by a meticulous selection of the most suitable product concept. The concept product undergoes rigorous testing to ensure its functionality and reliability. Based on the test results, final specifications are determined. A comprehensive development flow plan is then crafted to guide the subsequent stages of the instrument's development process.

Quality Function Deployment (QFD)

The basic concept of Quality Function Deployment (QFD) was first introduced by Yoki Akao, Professor of Management Engineering from Tagawa University, who developed the practices and experiences of industries in Japan, in 1992 by Mitsubishi company and developed in various ways by Toyota and other companies[10].

QFD is a structured methodology used in the product planning and development process to establish specifications for consumer needs and wants, and systematically evaluate the strengths and weaknesses of a product or service's capability to meet consumer needs and wants[11]. The QFD process starts from hearing the voice of the customer and then continues through 4 main activities, namely[12]: 1) Product planning; 2) Product design; 3 Prosses planning; 4) Process planning control. The main benefits when companies use QFD are to reduce costs, increase revenue, and reduce production time.

RESEARCH METHODS

House of Quality (HoQ)

House of Quality is a method that supports the process of product identification into a design specification. The HoQ concept is essentially based on a quality table and has been successfully used by manufacturing

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[10] Lou Cohen, "Quality Function Deployment: How to Make QFD Work for You," *(No Title)*, 1995.

[11] Hamzah Abdul-Rahman, C L Kwan, and Peter C Woods, "Quality Function Deployment in Construction Design: Application in Low-cost Housing Design," *International Journal of Quality & Reliability Management* 16, no. 6 (1999): 591–605.

[12] Lai-Kow Chan and Ming-Lu Wu, "Quality Function Deployment: A Literature Review," *European Journal of Operational Research* 143, no. 3 (2002): 463–97.

industries[13]. The HoQ shows a structure for design and shaping cycles and resembles a house. The key inputs to the matrix are customer needs and wants. Product strategy information and product quality characteristics[14]. Other information contained in HoQ is the target value of HoQ which contains several parts, each part can and must be adjusted to function properly. The HoQ matrix can be seen in Figure 2.

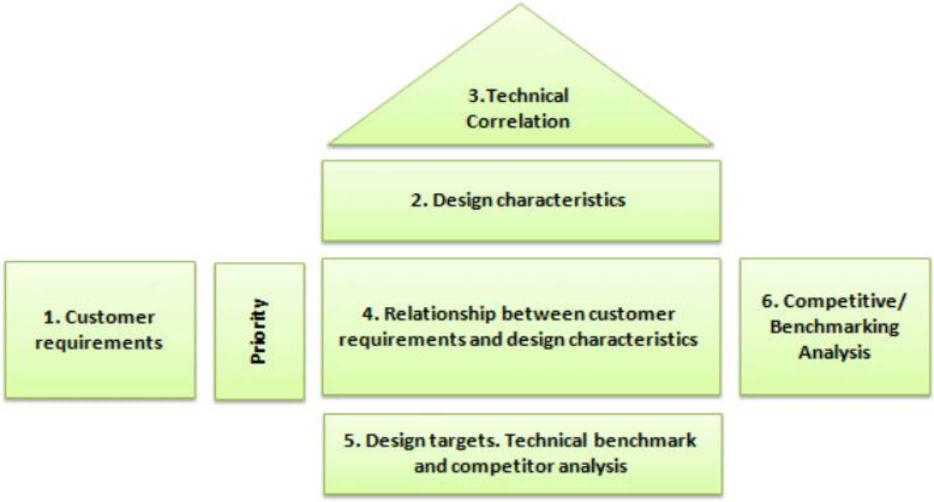


Figure 2 House of Quality (HoQ)

In product development, the initial step involves identifying customer requirements as the primary foundation. Subsequently, a House of Quality (HoQ) matrix is constructed to link these customer requirements to the design characteristics of the product. Additionally, technical correlation analysis plays a pivotal role in understanding how design characteristics interrelate. Furthermore, an evaluation of the relationship between customer requirements and design characteristics is facilitated through this HoQ matrix. Following this, design targets can be established, and technical benchmarking and competitor analysis are performed to ensure the product excels in the market. To comprehend competition and enhance the product, it is also essential to conduct competitive analysis and benchmarking.

Four primary phases of QFD – Product development steps

[13] John R Hauser and Don Clausing, "The House of Quality," 1988.
[14] Christian N Madu, *The House of Quality in a Minute: A Guide to Quality Function Deployment* (IAP, 2019).

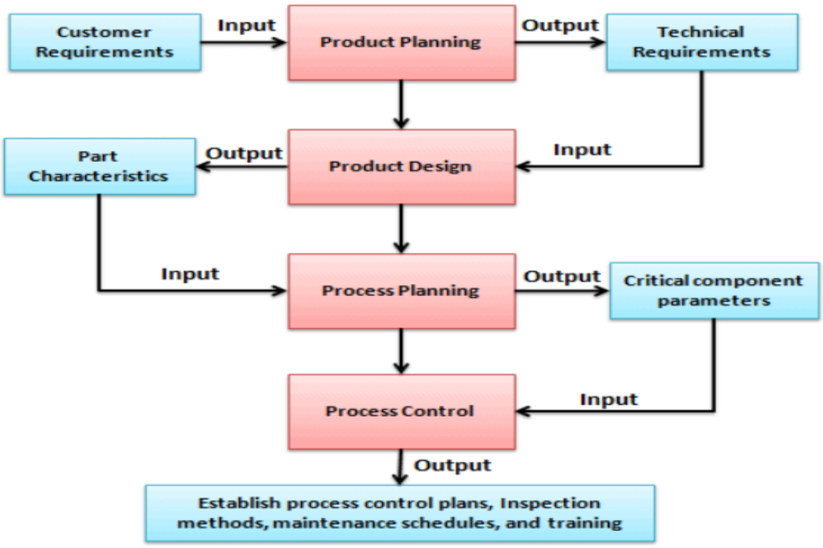


Figure 3 Product development steps

The four primary phases of Quality Function Deployment (QFD) in product development involve a structured progression from customer requirements to process control plans[15]. It starts with identifying customer requirements and translating them into product planning inputs, which then leads to defining technical requirements in the product design phase. Subsequently, the product design outputs inform part characteristics, which in turn drive the process planning inputs. The process planning phase results in the establishment of critical component parameters, serving as inputs for process control. Finally, in the process control phase, the outputs include the development of process control plans, inspection methods, maintenance schedules, and training programs, ensuring the product meets quality standards consistently across its lifecycle.

RESEARCH RESULT

Data Acquisition Methods

Railways are a critical mode of transportation, and ensuring the safety and reliability of railway tracks is of utmost importance[16]. Two main methods are used to measure track irregularities in railways: onboard and offboard (portable) inspection methods. Both of these methods play a

[15] Christian N. Madu, "*The House Of Quality In a Minute - A Guide To Quality Fuction Deployment*" 2019.

[16] Lidén, "Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research."

crucial role in detecting defects early and accurately to maintain the safety and efficiency of railway operations[17]. The onboard inspection method is a crucial technique used by railway operators to track irregularities in their networks. This method involves using a specially designed vehicle equipped with sensors and measuring devices that are driven slowly and steadily along the track while recording various measurements such as vertical and lateral accelerations, gauge width, and alignment. One of the major advantages of this method is that data is measured in real-time when trains run across the rail lines, eliminating the need for an operator to collect readings, and thus reducing inspection time. However, the accuracy of the data obtained depends on the excellent condition of the devices used, which must constantly be maintained. Furthermore, this method relies on train movements, and the necessary infrastructure and installation must be provided in the railway to facilitate the inspection process. Despite its limitations, the onboard inspection method is still considered a crucial tool for maintaining the safety and reliability of railway tracks. It helps prevent derailments, reduce maintenance costs, and improve the overall performance of the railway system[18]. Additionally, the onboard systems can simulate the effects of train weight on the track geometry, as the weight of the train deforms the track.

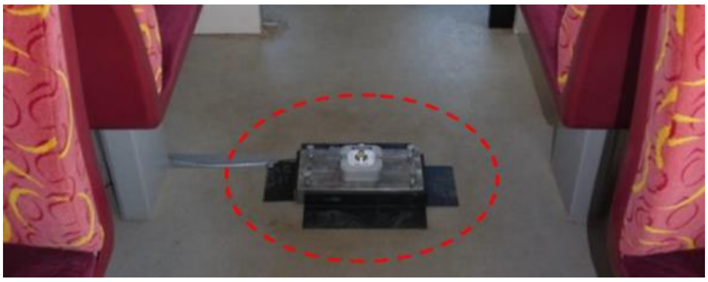


Figure 1 Onboard inspection measurement system[19].

The offboard inspection method is another technique used by railway operators to measure track irregularities in their networks. This method

[17] Chudzikiewicz et al., "Condition Monitoring of Railway Track Systems by Using Acceleration Signals on Wheelset Axle-Boxes."

[18] Cyprien Hoelzl et al., "On-Board Monitoring for Smart Assessment of Railway Infrastructure: A Systematic Review," *The Rise of Smart Cities: Advanced Structural Sensing and Monitoring Systems*, 2022, 223–59, https://doi.org/10.1016/B978-0-12-817784-6.00015-1.

[19] Deutzer Technische Kohle GmbH, "DTK Measurement System (UIC 513)," 2019.

involves using a portable measuring instrument, such as a track recording car or a trolley, that is equipped with sensors and measuring devices and is either pushed along the track manually or towed by a locomotive. One of the main advantages of this method is that the devices used are portable and stand-alone, which makes their construction more compact. However, this method requires an operator to manually push the instrument along the track, and the inspection of railway tracks can only be carried out when the train is not passing, which can limit its effectiveness. Additionally, there may be range constraints due to the operator's physical limitations. Despite this limitation, the offboard inspection method is still an essential tool for railway operators to maintain the safety and reliability of their tracks. It helps identify defects that may not be visible to the naked eye and supplements data collected by the onboard inspection method. By detecting track irregularities early and accurately, this method helps prevent derailments, reduce maintenance costs, and improve the overall performance of the railway system[20].

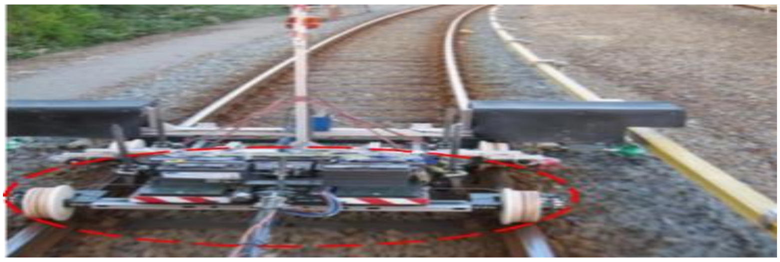


Figure 2 Trolley as an example of an offboard (portable) inspection method[21]

Track Irregularity Parameters

Monitoring the condition of track geometry plays a vital role in ensuring the safety and performance of railways during operation. Track irregularities are deviations of the actual track geometry from the designed nominal track geometry[22]. The irregularities are defined by five specific measurements. First, the gauge is the closest distance between the left and right rails, which is measured from a point 14 mm below the top surface of the rail head. Then, alignment refers to the deviation of the rail head in the

[20] Yasukuni Naganuma, Taro Yada, and Takayuki Uematsu, "Development of an Inertial Track Geometry Measuring Trolley and Utilization of Its High-Precision Data," *International Journal of Transport Development and Integration* 3, no. 3 (2019): 271–85, https://doi.org/10.2495/TDI-V3-N3-271-285.

[21] Deutzer Technische Kohle GmbH, "DTK Measurement System (UIC 513)."

[22] Kalle Karttunen, *Mechanical Track Deterioration Due to Lateral Geometry Irregularities* (Chalmers Tekniska Hogskola (Sweden), 2012).

lateral direction, which is measured at the gauge measurement reference. The longitudinal level is another type of irregularity, referring to the deviation of the running surface of the rail measured against the reference line. The next type is cross-level, which is the difference in height from the right rail to the left rail at a given location. Lastly, the twist is a type of cross-level that measures the difference in height between the right and left rails over shorter distances per 3 meters[23]. The illustration of each type of track irregularitie is shown in Figure 3.

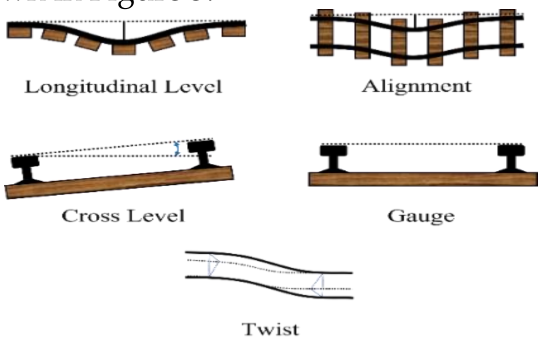


Figure 3 Illustration of different types of track irregularities[24].

Sensors for Detecting Track Irregularities

Different types of sensors are used to monitor and track irregularities. Some examples of track irregularity sensors are cameras, laser scanning technology, accelerometers, and complementary sensors[25]. Different sensors have different capabilities of measuring specific track irregularity parameters, which is summarised in Table 1.

Tabel 1 Sensor capabilities of measuring different track irregularities parameters

Sensor Type	Track Irregularity Parameter				
	Longitudinal Level	Alignment	Cross Level	Gauge	Twist
Laser scanning sensor	v	v	v		v

[23] Hitoshi Tsunashima and Ryota Hirose, "Condition Monitoring of Railway Track from Car-Body Vibration Using Time–Frequency Analysis," *Vehicle System Dynamics* 60, no. 4 (2022): 1170–87, https://doi.org/10.1080/00423114.2020.1850808.

[24] Tsunashima and Hirose.

[25] Amir Falamarzi, Sara Moridpour, and Majidreza Nazem, "A Review on Existing Sensors and Devices for Inspecting Railway Infrastructure," *Jurnal Kejuruteraan* 31, no. 1 (2019): 1–10, https://doi.org/10.17576/jkukm-2019-31(1)-01.

Camera		v			v
Accelerometer	v		v		
LVDT				v	
Measurement trolley	v	v	v	v	v
Instrumented wheelset	v	v	v	v	v

In general, sensors that are used to measure track irregularities can be categorized into two groups: contact and non-contact methods. A non-contact method for measuring track irregularities is a measurement technique that does not require direct contact with the track's surface. This method uses various types of sensors and technologies, such as laser scanning technologies, cameras, accelerometers, and other remote sensing technologies, to accurately measure track irregularities. The non-contact technique allows for fast and efficient measurement of track irregularities without requiring traffic stoppages or direct interaction with the track surface. Data collected by non-contact sensors can be processed automatically using specialized software to generate detailed and accurate profiles of track irregularities. This method is typically used in measuring track irregularities on highways, railways, airport runways, and other transportation systems. In addition, the technique can help monitor track conditions and identify areas that require further repair or maintenance. Included in the non-contact category are laser scanning sensors, cameras, accelerometers, and other complementary sensors, such as gyroscopes and global positioning systems (GPS).

The utilization of non-contact laser scanning technologies for measurement purposes has proven to be a valuable tool in capturing a diverse range of track geometry parameters. In order to determine distances and track geometric parameters, the sensor emits a focused beam of light towards the intended object and subsequently gauges the duration it takes for the pulse to rebound back to the device following its reflection off the target. The Light Detection and Ranging (LiDAR) technique is a laser-based scanning technology employed in railway inspection to identify surface rail anomalies. This technique has the capability to produce detailed three-dimensional representations of objects through the emission of ultraviolet and near-infrared radiation. The aforementioned sensor has the potential to serve as a roadside detector, capable of detecting vehicle rotation, tracking errors, and inter-axle misalignment. The foremost benefit of this sensor is its ability to generate measurements at a comparatively high frequency[26].

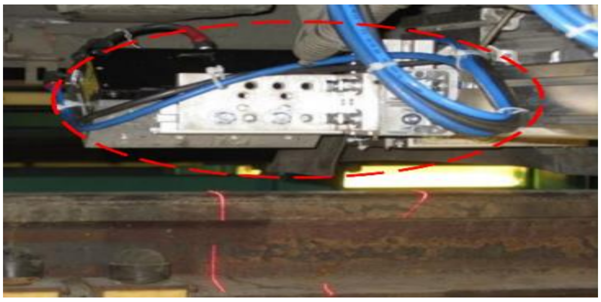


Figure 4 Laser scanning sensor

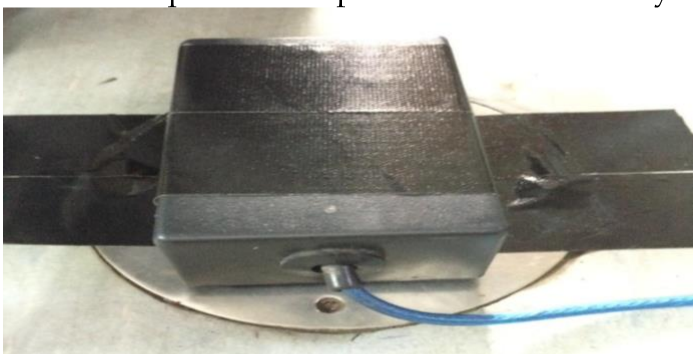
The modern practice of utilizing high-resolution and thermographic cameras as instruments for railway inspections is widespread. Automated visual inspection systems rely on camera-captured data as their primary input. The aforementioned systems utilize image processing methodologies to identify various anomalies in railway infrastructure, such as broken rail profiles, corrugations, track gauges, and missing bolts. The essential elements of image processing consist of the acquisition of data, assessment of images, and recognition of patterns. Machine learning and deep learning algorithms are used to accurately process images and videos within pattern recognition. Thermographic cameras, commonly referred to as thermal imaging cameras, utilize infrared radiation to produce thermal images. The thermal imaging camera can detect residual heat patterns that could indicate irregular structural soundness and other operational issues related to railway components[27].

[26] Zhiguo Li and Qing He, "Predicting Failure Times of Railcar Wheels and Trucks by Using Wayside Detector Signals," *2014 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2014*, 2014, 1113–18, https://doi.org/10.1109/ICMA.2014.6885854.

[27] Niloofar Minbashi et al., "Turnout Degradation Modelling Using New Inspection Technologies: A Literature Review," *Lecture Notes in Mechanical Engineering*, 2016, 49–63, https://doi.org/10.1007/978-3-319-23597-4_5.

Figure 5 Camera mounted on measurement trolley [28]

Accelerometers are electromechanical sensors designed to measure acceleration signals. Vibrations in tracks can be caused by faulty wheels, rail deterioration, faulty switches, or an irregular track geometry. Using acceleration data and a series of mathematical calculations, rail defects, and track irregularities can be found[29]. Accelerometers have been incorporated into a variety of railway inspection devices, including trolleys and instrumented wheelset measurement systems, as well as smartphones. Accelerometer sensors can provide more inspection points per unit of track length than other sensors. Additionally, accelerometers have been used to measure ride comfort in public transportation fleets recently[30].



[28] Ali Akbar Shah et al., "Real Time Identification of Railway Track Surface Faults Using Canny Edge Detector and 2D Discrete Wavelet Transform," *Annals of Emerging Technologies in Computing (AETiC)* 4, no. 2 (2020).

[29] Abdollah Malekjafarian et al., "Railway Track Monitoring Using Train Measurements: An Experimental Case Study," *Applied Sciences (Switzerland)* 9, no. 22 (2019), https://doi.org/10.3390/app9224859.

[30] Qingyong Li et al., "A Cyber-Enabled Visual Inspection System for Rail Corrugation," *Future Generation Computer Systems* 79 (2018): 374–82, https://doi.org/10.1016/j.future.2017.04.032.

Figure 6 Accelerometer sensor

The global positioning system (GPS) and gyroscopes are two essential sensors that have been utilized in railway data collection procedures. A GPS sensor is equipment that communicates with a dedicated satellite system and provides end-users with real-time geographical location and time data. Currently, GPS sensors are used in a variety of railway inspection applications, including trollies and instrumented wheelset measurement systems. Gyroscope sensors built into inspection devices are used to determine the three-dimensional rotation of vehicles[31]. The type of gyroscopes used in the inspection devices are rate gyroscopes, which are engineered to display the rate of change of an angle over a period of time as opposed to solely indicating the movement direction[32].

Figure 7 GPS (left) and gyroscopes (right) as complementary sensors

A contact method for measuring track irregularities is a measurement technique that involves direct contact with the surface of the track. This method uses various types of measuring devices, such as instrumented wheelsets, linear variable differential transformers (LVDT), and trolleys, to measure track irregularities with a high level of accuracy. The contact technique requires direct interaction with the track surface, which may require traffic stoppage and longer measurement time[33]. However, this method can provide highly detailed and accurate measurement results, including information on track irregularities' amplitude, wavelength, and frequency. This method is typically used in measuring track irregularities

[31] Mahda Alfian Fajrun Najah, Santi Tri Wijaya, and Dadang Sanjaya Atmaja, "Alat Inspeksi Jalan Rel Pada Lori Inspeksi Akademi Perkeretaapian Indonesia," in *Prosiding Forum Studi Transportasi Antar Perguruan Tinggi*, 2019.

[32] I. Durazo-Cardenas et al., "Precise Vehicle Location as a Fundamental Parameter for Intelligent Selfaware Rail-Track Maintenance Systems," *Procedia CIRP* 22, no. 1 (2014): 219–24, https://doi.org/10.1016/j.procir.2014.07.002.

[33] D. Barke and K. W. Chiu, "Structural Health Monitoring in the Railway Industry: A Review," *Structural Health Monitoring* 4, no. 1 (2005): 81–94, https://doi.org/10.1177/1475921705049764.

on highways, railways, airport runways, and other transportation systems. The technique can help monitor track conditions and identify areas that require further repair or maintenance and can also be used to validate non-contact measurements. Although it requires direct interaction with the track surface, contact measurement techniques remain one of the primary methods for measuring track irregularities with high accuracy.

An instrumented wheelset is a system used to measure the interaction between the wheel and rail of a railway vehicle. It consists of transducers, such as electrical resistance strain gauges, that are fitted onto the wheel or axle body to sense the elastic strain of these bodies. This allows for the reconstruction of forces mutually exchanged at the wheel-rail contact. Using an instrumented wheelset provides continuous measurement of track irregularities during the railway vehicle operation without requiring significant modifications to the vehicle itself. The collected data can be used to improve understanding of track conditions and to develop more accurate maintenance schedules. For example, analyzing data from an instrumented wheelset makes it possible to identify defects in the rail surface or areas where track geometry is out of tolerance. This information can then be used to prioritize maintenance activities and allocate resources more effectively. In addition, an instrumented wheelset can be used to monitor changes in track conditions over time. By comparing data from multiple runs over a given section of track, it is possible to detect changes in track geometry or surface conditions that may indicate developing problems. This early warning system can help prevent derailments and other safety incidents. Overall, an instrumented wheelset is valuable for monitoring and maintaining railway infrastructure. It provides continuous measurement of track irregularities during railway vehicle operation, allowing for more accurate maintenance scheduling and improved safety[34].

[34] Andrea Bracciali, F Cavaliere, and Mattia Macherelli, "Review of Instrumented Wheelset Technology and Applications," in *Proc. 2nd Int. Conf. Railway Technol., Res., Develop. Maintenance*, 2014, 1–16.

Figure 8 Instrumented wheelset under a carriage

LVDTs are linear variable differential transformers that are used by many engineering disciplines because of their high-precision characteristics. LVDTs are electromechanical devices that convert linear motion or position into an electrical signal. They consist of a primary coil, a secondary coil, and a movable core that is connected to the object being measured. As the core moves, it induces a voltage in the secondary coil that is proportional to its position. As a result, LVDTs have high accuracy, repeatability, and resolution, making them ideal for measuring small changes in position or displacement[35].

Figure 9 LVDT sensors mounted on a trolley

Trolleys are low-cost, manually operated devices used for inspecting rail and railway infrastructure. Due to their lightweight construction and tiny overall dimensions, it is simple to position them on or off the track to make way for oncoming trains. Trolleys can be outfitted with sensors such as ultrasonic transducers, mechanical sensors, and laser measurement systems in order to inspect tracks for rail fatigue, rail profile defects, and track geometry irregularities. In addition, carriages can be outfitted with a

[35] Burak Akpinar and Engin Gülal, "Multisensor Railway Track Geometry Surveying System," *IEEE Transactions on Instrumentation and Measurement* 61, no. 1 (2012): 190–97, https://doi.org/10.1109/TIM.2011.2159417.

PC and GPS to store collected data and pinpoint the precise location of measured data. The pace of trolleys, which cannot be compared to instrumented wheelset measurements, is the primary distinction between them and other inspection applications. Recently, trolleys outfitted with advanced laser scanning technologies and measurement equipment have effectively measured track geometry. Due to the abilities of this form of inspection, it is suited for limited portions of a railway network[36].

Figure 10 Measurement trolley

Comparison Of Sensors and Inspection Devices

Track irregularity measuring devices are essential tools used to measure the unevenness or irregularity of railway tracks. These devices provide critical data that helps maintenance teams identify and address issues before they become more significant problems. However, like any technology, these devices have advantages and disadvantages that must be considered.

Laser scanning technologies have many benefits, such as high precision and accuracy, fast data collection, and the ability to scan things from all angles[37]. However, the technology has some drawbacks, such as high price, small range, and restrictions on where it can be used[38]. Therefore, these pros and cons must be carefully weighed when considering how to use laser scanning technologies in different situations.

[36] [28,29]

[37] Mario Soilán et al., "Review of Laser Scanning Technologies and Their Applications for Road and Railway Infrastructure Monitoring," *Infrastructures* 4, no. 4 (2019), https://doi.org/10.3390/infrastructures4040058.

[38] Han-Mei Chen, Cristian Ulianov, and Ramy Shaltout, "3D Laser Scanning Technique for the Inspection and Monitoring of Railway Tunnels," *Transport Problems* 10, no. spec. (2015): 73–84.

Cameras are popular for monitoring and measuring track irregularities due to their accuracy, low cost, and ease of use[39]. However, weather, lighting, and their limited range, which is based on the distance between the sensor and the train, can all reduce their usefulness. Despite these drawbacks, cameras are still often utilized and are simple to incorporate into current surveillance systems[40].

Accelerometers are commonly used for measuring track irregularities due to their small size, sensitivity, and ability to provide real-time information about changes in speed and acceleration. In addition, they are sensitive in detecting minor vibrations on the train and can be mounted in various locations that are challenging for other sensors to reach[41]. However, they are unable to convey information regarding the exact location of the object being measured, are susceptible to noise or other disturbances that may impair measurement accuracy, and are unable to convey information regarding the contour or topography of the track surface being traversed[42].

Linear Variable Differential Transformers (LVDTs) are another commonly used tool for measuring track irregularities due to their high accuracy, durability, and flexibility. They do not require direct touch with the object being measured, have very high precision, react to position changes quickly, and all of these characteristics. They can, however, be rather pricey and have a complex installation process. In addition, they might not be appropriate for assessing track imperfections over extended distances due to their restricted range. Despite these drawbacks, LVDTs are still widely used tools because of their efficiency and dependability[43].

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[39] Yunus Santur, Mehmet Karaköse, and Erhan Akın, "Learning Based Experimental Approach For Condition Monitoring Using Laser Cameras In Railway Tracks," *International Journal of Applied Mathematics, Electronics and Computers* 4, no. Special Issue-1 (2016): 1–1, https://doi.org/10.18100/ijamec.270656.

[40] Yunus Santur, Mehmet Karaköse, and Erhan Akin, "A New Rail Inspection Method Based on Deep Learning Using Laser Cameras," *IDAP 2017 - International Artificial Intelligence and Data Processing Symposium*, 2017, https://doi.org/10.1109/IDAP.2017.8090245.

[41] Wenzhu Huang et al., "Detection of Rail Corrugation Based on Fiber Laser Accelerometers," *Measurement Science and Technology* 24, no. 9 (2013), https://doi.org/10.1088/0957-0233/24/9/094014.

[42] M. Bocciolone et al., "A Measurement System for Quick Rail Inspection and Effective Track Maintenance Strategy," *Mechanical Systems and Signal Processing* 21, no. 3 (2007): 1242–54, https://doi.org/10.1016/j.ymssp.2006.02.007.

[43] Alessandro Sabato and Christopher Niezrecki, "Feasibility of Digital Image Correlation for Railroad Tie Inspection and Ballast Support Assessment," *Measurement:*

Measurement trolleys or track inspection trolleys are effective tools for measuring track irregularities due to their accuracy, speed, and versatility. They can accurately measure track irregularities, travel on rails at high speeds, and measure track irregularities on hard-to-reach rails[44]. However, they can be expensive to make and maintain, and the data they collect requires considerable time and labor to process. Despite these limitations, measurement trolleys remain a popular tool for maintaining railway tracks[45].

The instrumented wheelset is a valuable tool for measuring track irregularities because it can precisely and thoroughly identify the causes of such irregularities, such as rail deformation, wheel wear, and modifications in rail geometry[46]. The technology can also assist in resolving track anomalies and enhancing overall track operation[47]. The instrumented wheelset, however, is expensive to buy and run and needs a lot of time and labor to function correctly[48]. Nevertheless, despite these disadvantages, many rail companies still consider the instrumented wheelset to be a worthwhile investment for upholding the safety and effectiveness of their railways[49].

Based on previous comparisons, it can be inferred that laser scanning sensors are one of the best sensors that can detect and measure various types of track irregularities, such as twist, cross-level, longitudinal level,

Journal of the International Measurement Confederation 103 (2017): 93–105, https://doi.org/10.1016/j.measurement.2017.02.024.

[44] Chao Chang et al., "Dynamics Performance of New Type of Fully Automatic Track Inspection Vehicle," *Jiaotong Yunshu Gongcheng Xuebao/Journal of Traffic and Transportation Engineering* 21, no. 6 (2021): 194–208, https://doi.org/10.19818/j.cnki.1671-1637.2021.06.015.

[45] Alonso Sánchez Ríos, Eva López Sanjuán, and José Luis Bravo, "Experimental Validation of Track Inspection Trolley Using a Rigorous Self-Checking Procedure," *Journal of Surveying Engineering* 146, no. 3 (2020), https://doi.org/10.1061/(asce)su.1943-5428.0000315.

[46] Yu Ren and Jianzheng Chen, "A New Method for Wheel–Rail Contact Force Continuous Measurement Using Instrumented Wheelset," *Vehicle System Dynamics* 57, no. 2 (2019): 269–85, https://doi.org/10.1080/00423114.2018.1460853.

[47] Ren and Chen.

[48] P. Gullers et al., "Track Condition Analyser: Identification of Rail Rolling Surface Defects, Likely to Generate Fatigue Damage in Wheels, Using Instrumented Wheelset Measurements," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 225, no. 1 (2011): 1–13, https://doi.org/10.1243/09544097JRRT398.

[49] Bracciali, Cavaliere, and Macherelli, "Review of Instrumented Wheelset Technology and Applications."

and alignment, with high accuracy. Laser scanning can provide high-quality, three-dimensional data on the rail surface.

However, it is essential to note that selecting the best sensor also depends on the requirements and the specific environment in which the measurements will be carried out. For example, a camera can be a good choice if accurate visual measurements are required. On the other hand, if the measurement needs to focus more on rail acceleration or deformation, then accelerometers or linear variable differential transformers (LVDT) may be more suitable

Measurement Data from Inspections

The data obtained from inspections to measure track irregularities are crucial in implementing preventive maintenance activities and developing a railway track degradation prediction model. By collecting and analyzing data from track inspections, maintenance teams can identify potential issues and take corrective action before they escalate into major problems. The data collected from track inspections include track geometry, track gauge, and track alignment measurements. These measurements are used to identify deviations from the ideal track condition and assess the severity of any irregularities. This data is then analyzed to determine the appropriate course of action, such as adjusting the track, replacing worn components, or scheduling more frequent inspections.

In addition to facilitating preventive maintenance activities, the data obtained from track inspections are also used to develop predictive models that can forecast the rate of track degradation over time. By analyzing historical data on track irregularities and maintenance activities, these models can identify patterns and predict when and where issues will likely occur. This information enables maintenance teams to proactively plan maintenance activities and reduce the risk of unexpected downtime or safety incidents. The data obtained from inspections to measure track irregularities is essential for maintaining safe and efficient railway operations. It enables maintenance teams to implement preventive maintenance activities and develop predictive models to forecast, track degradation, and plan future maintenance activities.

Track Gauge Consideration

Gauge refers to the distance between the two rails on a railway track, measured from the inside edges of the rails. Narrow gauges and standard gauges are two of the most common types of railway track gauges. The standard gauge of 1.435 m set by the International Union of Railways in

1937 is referred to as a standard-gauge railway. The standard gauge is used on 60% of the world's railways. Due to their bigger size and higher carrying capacity, standard gauge railways are typically more effective than narrow gauge railways for various tasks, including transporting people and goods[50].

Narrow gauge tracks typically have a track width distance of less than 1.435 meters, which is the standard gauge used by most railways in the world[51]. Narrow gauge railways are generally found in locations where it is impractical to create a broader gauge track because of the terrain or other limitations and are frequently utilized for specific purposes, such as mining activities.

The contact method requires direct contact with the rail to measure irregularities. However, the narrow rail width makes placing the measuring instrument on the rail difficult. Meanwhile, the non-contact method requires sufficient distance between the gauge and the rail. The narrow rail width may allow the non-contact gauge to get closer to the rail, but due to the narrow track width, the non-contact gauge can capture less irregular data compared to the standard rail width. Therefore, proper measuring instruments can help in accurate measurements, regardless of the track width used. While standard rail width may be easier to measure track irregularities, proper measuring instruments can help in accurate measurements, regardless of the track width used. Therefore, during track irregularities measurements, it is necessary to consider the track width used, the method used, and the measuring instrument to ensure accurate measurements.

There are several challenges during the operation of track irregularity measurement tools in different track gauges. Track irregularities measurement tools are designed to measure the track geometry of a specific track gauge. For example, a tool designed for standard gauge tracks will not be suitable for narrow gauge tracks. This is because the tool may not be able to fit between the rails of the narrow-gauge track, or it may not be able to measure the track geometry accurately. To overcome this challenge, track irregularities measurement tools can be designed to be adjustable to different track gauges, allowing the tool to be used on various track gauges

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[50] Ian Taylor, "Kenya's New Lunatic Express: The Standard Gauge Railway," *African Studies Quarterly* 19, no. 3–4 (2020): 29–52.

[51] Taylor.

without the need for a new tool to be purchased. However, adjustable tools can be more expensive than tools designed for a specific track gauge[52].

Another challenge arises from the need for repeated recalibration of the measurement tools when used on different track gauges. Recalibration becomes a crucial step to maintain measurement accuracies, as the tools need to account for each gauge's specific characteristics and dimensions. However, this repetitive recalibration process can be time-consuming and resource-intensive, reducing efficiency in tracking irregularity measurements. The effort and costs associated with frequent recalibration add to the operational challenges faced when using these tools across various track gauges[53]. Furthermore, the need for recalibration impacts the measurement accuracy and adds an additional burden on the operational process. To reduce the impact of calibration on efficiency, it is important to plan the calibration process carefully. The calibration process should be scheduled during periods of low train traffic. Additionally, the tool should be calibrated by a qualified technician. Valuable time and resources are allocated to calibrating the devices, which could otherwise be utilized for other essential maintenance and inspection tasks. This reduction in efficiency can hinder the overall productivity of track maintenance operations and further contribute to increased operational costs[54].

Future Development of Track Irregularity Measurements

The future development of track irregularity measurement tools faces several challenges that must be addressed to enhance efficiency and effectiveness. One significant challenge involves exploring remote measurement and monitoring systems as a viable development path. Implementing such systems would offer increased efficiency and reduced operational costs by enabling remote data collection and analysis, eliminating the need for manual on-site measurements and recalibration[55].

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[52] Shubin Zheng et al., “Railway Track Gauge Inspection Method Based on Computer Vision,” *2012 IEEE International Conference on Mechatronics and Automation, ICMA 2012*, 2012, 1292–96, https://doi.org/10.1109/ICMA.2012.6284322.

[53] Ying Li et al., “Rail Component Detection, Optimization, and Assessment for Automatic Rail Track Inspection,” *IEEE Transactions on Intelligent Transportation Systems* 15, no. 2 (2014): 760–70, https://doi.org/10.1109/TITS.2013.2287155.

[54] Zheng et al., “Railway Track Gauge Inspection Method Based on Computer Vision.”

[55] Harbhajan S. Hayre, “Automatic Railroad Track Inspection,” *IEEE Transactions on Industry Applications* IA-10, no. 3 (1974): 380–84, https://doi.org/10.1109/TIA.1974.349164.

Another challenge lies in developing integrated software capable of processing data from multiple measurement tools. Creating a unified software solution that can seamlessly analyze data from various measurement tools would enable more accurate analysis of track irregularities. In addition, this integrated approach would provide a comprehensive understanding of the track condition and recommend appropriate courses of action for maintenance and repairs[56].

Furthermore, ensuring the durability of measurement tools under extreme working conditions is another critical challenge for future development. Track irregularity measurement tools must withstand harsh environmental factors, including extreme weather conditions, vibrations, and humidity. Enhancing the durability and robustness of these tools will enable them to consistently perform accurate measurements in challenging operational environments, reducing maintenance needs and improving their overall reliability[57].

Addressing these challenges in future developments of track irregularity measurement tools will contribute to increased efficiency, improved data analysis, and enhanced durability. By embracing remote measurement systems, developing integrated software solutions, and enhancing the tools' durability, the track maintenance industry can benefit from more efficient operations, better-informed decision-making processes, and reduced manual intervention, ultimately leading to safer and more reliable railway networks.

CONCLUSION

This journal review concludes that railway track unevenness measurement devices have advantages and disadvantages. Laser scanning technologies have many benefits but have drawbacks such as high price, small range, and restrictions on where they can be used. LVDTs, measurement trolleys, instrumented wheelsets, and laser scanning sensors are all popular tools for measuring track irregularities due to their high accuracy, durability, and flexibility. Despite these drawbacks, LVDTs are still widely used due to their efficiency and dependability. While using track irregularity measurement tools can help improve safety, efficiency, and maintenance operations, their accuracy and reliability can vary

[56] Li et al., "Rail Component Detection, Optimization, and Assessment for Automatic Rail Track Inspection."

[57] Fan Peng, *Scheduling of Track Inspection and Maintenance Activities in Railroad Networks* (University of Illinois at Urbana-Champaign, 2011).

depending on the type of device used. In addition, the costs associated with their use can be significant. Further research and development are needed to improve these devices and identify new opportunities for their use in maintaining safe and reliable railway operations. Remote measurement systems, integrated software solutions, and enhancing the tools' durability will lead to increased efficiency, improved data analysis, and improved reliability, leading to safer and more reliable railway networks.

BIBLIOGRAPHY

Abdul-Rahman, Hamzah, C L Kwan, and Peter C Woods. “Quality Function Deployment in Construction Design: Application in Low-cost Housing Design.” *International Journal of Quality & Reliability Management* 16, no. 6 (1999): 591–605.

Ahac, Maja, and Stjepan Lakusic. “Tram Track Maintenance-Planning by Gauge Degradation Modelling.” *Transport* 30, no. 4 (2015): 430–36. https://doi.org/10.3846/16484142.2015.1116464.

Akpinar, Burak, and Engin Gülal. “Multisensor Railway Track Geometry Surveying System.” *IEEE Transactions on Instrumentation and Measurement* 61, no. 1 (2012): 190–97. https://doi.org/10.1109/TIM.2011.2159417.

Bar-Am, Michael, and Zichron Yaakov. On-train rail track monitoring system. US 8,942,426 B2. United States, issued 2015.

Barke, D., and K. W. Chiu. “Structural Health Monitoring in the Railway Industry: A Review.” *Structural Health Monitoring* 4, no. 1 (2005): 81–94. https://doi.org/10.1177/1475921705049764.

Bocciolone, M., A. Caprioli, A. Cigada, and A. Collina. “A Measurement System for Quick Rail Inspection and Effective Track Maintenance Strategy.” *Mechanical Systems and Signal Processing* 21, no. 3 (2007): 1242–54. https://doi.org/10.1016/j.ymssp.2006.02.007.

Bracciali, Andrea, F Cavaliere, and Mattia Macherelli. “Review of Instrumented Wheelset Technology and Applications.” In *Proc. 2nd Int. Conf. Railway Technol., Res., Develop. Maintenance*, 1–16, 2014.

Chan, Lai-Kow, and Ming-Lu Wu. “Quality Function Deployment: A Literature Review.” *European Journal of Operational Research* 143, no. 3 (2002): 463–97.

Chang, Chao, Liang Ling, Yu Sun, Wan Ming Zhai, Kai Yun Wang, and Gui

Dong Wang. "Dynamics Performance of New Type of Fully Automatic Track Inspection Vehicle." *Jiaotong Yunshu Gongcheng Xuebao/Journal of Traffic and Transportation Engineering* 21, no. 6 (2021): 194–208. https://doi.org/10.19818/j.cnki.1671-1637.2021.06.015.

Chen, Han-Mei, Cristian Ulianov, and Ramy Shaltout. "3D Laser Scanning Technique for the Inspection and Monitoring of Railway Tunnels." *Transport Problems* 10, no. spec. (2015): 73–84.

Chen, Qijin, Xiaoji Niu, Quan Zhang, and Yahao Cheng. "Railway Track Irregularity Measuring by GNSS/INS Integration." *Navigation, Journal of the Institute of Navigation* 62, no. 1 (2015): 83–93. https://doi.org/10.1002/navi.78.

Chudzikiewicz, Andrzej, Roman Bogacz, Mariusz Kostrzewski, and Robert Konowrocki. "Condition Monitoring of Railway Track Systems by Using Acceleration Signals on Wheelset Axle-Boxes." *Transport* 33, no. 2 (2018): 555–66. https://doi.org/10.3846/16484142.2017.1342101.

Cohen, Lou. "Quality Function Deployment: How to Make QFD Work for You." *(No Title)*, 1995.

Deutzer Technische Kohle GmbH. "DTK Measurement System (UIC 513)," 2019.

Durazo-Cardenas, I., A. Starr, A. Tsourdos, M. Bevilacqua, and J. Morineau. "Precise Vehicle Location as a Fundamental Parameter for Intelligent Selfaware Rail-Track Maintenance Systems." *Procedia CIRP* 22, no. 1 (2014): 219–24. https://doi.org/10.1016/j.procir.2014.07.002.

Engstrand, Andreas. "Railway Surveying Case Study of the GRP 5000." KTH Royal Institute of Technology, 2011.

Evans, Mark, Andrew Lucas, and Ian Ingram. "The Inspection of Level Crossing Rails Using Guided Waves." *Construction and Building Materials* 179 (2018): 614–18.

Falamarzi, Amir, Sara Moridpour, and Majidreza Nazem. "A Review on Existing Sensors and Devices for Inspecting Railway Infrastructure." *Jurnal Kejuruteraan* 31, no. 1 (2019): 1–10. https://doi.org/10.17576/jkukm-2019-31(1)-01.

Fallah Nafari, Saeideh, Mustafa Gül, Alireza Roghani, Michael T. Hendry, and JJ Roger Cheng. "Evaluating the Potential of a Rolling Deflection Measurement System to Estimate Track Modulus." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 232, no. 1 (2018): 14–24. https://doi.org/10.1177/0954409716646404.

Feng, Q., G. Wang, X. Li, H. Zhou, and J. He. "Research on a High-Speed Railway Track Irregularity Detection and Analysis System," 2018.

Gullers, P., P. Dreik, J. C.O. Nielsen, A. Ekberg, and L. Andersson. "Track Condition Analyser: Identification of Rail Rolling Surface Defects, Likely to Generate Fatigue Damage in Wheels, Using Instrumented Wheelset Measurements." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 225, no. 1 (2011): 1–13. https://doi.org/10.1243/09544097JRRT398.

Hauser, John R, and Don Clausing. "The House of Quality," 1988.

Hayre, Harbhajan S. "Automatic Railroad Track Inspection." *IEEE Transactions on Industry Applications* IA-10, no. 3 (1974): 380–84. https://doi.org/10.1109/TIA.1974.349164.

Hoelzl, Cyprien, Vasilis Dertimanis, Matthias Landgraf, Lucian Ancu, Marcel Zurkirchen, and Eleni Chatzi. "On-Board Monitoring for Smart Assessment of Railway Infrastructure: A Systematic Review." *The Rise of Smart Cities: Advanced Structural Sensing and Monitoring Systems*, 2022, 223–59. https://doi.org/10.1016/B978-0-12-817784-6.00015-1.

Huang, Wenzhu, Wentao Zhang, Yanliang Du, Baochen Sun, Huaixiang Ma, and Fang Li. "Detection of Rail Corrugation Based on Fiber Laser Accelerometers." *Measurement Science and Technology* 24, no. 9 (2013). https://doi.org/10.1088/0957-0233/24/9/094014.

Karttunen, Kalle. *Mechanical Track Deterioration Due to Lateral Geometry Irregularities*. Chalmers Tekniska Hogskola (Sweden), 2012.

Li, Qingyong, Zhiping Shi, Huayan Zhang, Yunqiang Tan, Shengwei Ren, Peng Dai, and Weiyi Li. "A Cyber-Enabled Visual Inspection System for Rail Corrugation." *Future Generation Computer Systems* 79 (2018): 374–82. https://doi.org/10.1016/j.future.2017.04.032.

Li, Y., L. Li, W. Li, H. Feng, and Y. Li. "A Review of Railway Track Irregularity Detection Methods." *Measurement*, 2019.

Li, Ying, Hoang Trinh, Norman Haas, Charles Otto, and Sharath Pankanti. "Rail Component Detection, Optimization, and Assessment for Automatic Rail Track Inspection." *IEEE Transactions on Intelligent Transportation Systems* 15, no. 2 (2014): 760–70. https://doi.org/10.1109/TITS.2013.2287155.

Li, Zhiguo, and Qing He. "Predicting Failure Times of Railcar Wheels and Trucks by Using Wayside Detector Signals." *2014 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2014*, 2014, 1113–18. https://doi.org/10.1109/ICMA.2014.6885854.

Lidén, Tomas. "Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research." *Transportation Research Procedia* 10 (2015): 574–83. https://doi.org/10.1016/j.trpro.2015.09.011.

Madu, Christian N. *The House of Quality in a Minute: A Guide to Quality Function Deployment*. IAP, 2019.

Malekjafarian, Abdollah, Eugene OBrien, Paraic Quirke, and Cathal Bowe. "Railway Track Monitoring Using Train Measurements: An Experimental Case Study." *Applied Sciences (Switzerland)* 9, no. 22 (2019). https://doi.org/10.3390/app9224859.

Minbashi, Niloofar, Morteza Bagheri, Amir Golroo, Iman Arasteh Khouy, and Alireza Ahmadi. "Turnout Degradation Modelling Using New Inspection Technologies: A Literature Review." *Lecture Notes in Mechanical Engineering*, 2016, 49–63. https://doi.org/10.1007/978-3-319-23597-4_5.

Naganuma, Yasukuni, Taro Yada, and Takayuki Uematsu. "Development of an Inertial Track Geometry Measuring Trolley and Utilization of Its High-Precision Data." *International Journal of Transport Development and Integration* 3, no. 3 (2019): 271–85. https://doi.org/10.2495/TDI-V3-N3-271-285.

Najah, Mahda Alfian Fajrun, Santi Tri Wijaya, and Dadang Sanjaya Atmaja. "Alat Inspeksi Jalan Rel Pada Lori Inspeksi Akademi Perkeretaapian Indonesia." In *Prosiding Forum Studi Transportasi Antar Perguruan Tinggi*, 2019.

Pau, Massimiliano, Francesco Aymerich, and Francesco Ginesu. "Distribution of Contact Pressure in Wheel-Rail Contact Area." *Wear* 253, no. 1–2 (2002): 265–74. https://doi.org/10.1016/S0043-1648(02)00112-6.

Peng, Fan. *Scheduling of Track Inspection and Maintenance Activities in Railroad Networks*. University of Illinois at Urbana-Champaign, 2011.

Ren, Yu, and Jianzheng Chen. "A New Method for Wheel–Rail Contact Force Continuous Measurement Using Instrumented Wheelset." *Vehicle System Dynamics* 57, no. 2 (2019): 269–85. https://doi.org/10.1080/00423114.2018.1460853.

Sabato, Alessandro, and Christopher Niezrecki. "Feasibility of Digital Image Correlation for Railroad Tie Inspection and Ballast Support Assessment." *Measurement: Journal of the International Measurement Confederation* 103 (2017): 93–105. https://doi.org/10.1016/j.measurement.2017.02.024.

Sánchez Ríos, Alonso, Eva López Sanjuán, and José Luis Bravo. "Experimental Validation of Track Inspection Trolley Using a Rigorous Self-Checking Procedure." *Journal of Surveying Engineering* 146, no. 3 (2020). https://doi.org/10.1061/(asce)su.1943-5428.0000315.

Santur, Yunus, Mehmet Karaköse, and Erhan Akin. "A New Rail Inspection Method Based on Deep Learning Using Laser Cameras." *IDAP 2017 - International Artificial Intelligence and Data Processing Symposium*, 2017. https://doi.org/10.1109/IDAP.2017.8090245.

Santur, Yunus, Mehmet Karaköse, and Erhan Akın. "Learning-Based Experimental Approach For Condition Monitoring Using Laser Cameras In Railway Tracks." *International Journal of Applied Mathematics, Electronics and Computers* 4, no. Special Issue-1 (2016): 1–1. https://doi.org/10.18100/ijamec.270656.

Shah, Ali Akbar, Bhawani S Chowdhry, Tayab D Memon, Imtiaz H Kalwar, and Andrew Ware. "Real Time Identification of Railway Track Surface Faults Using Canny Edge Detector and 2D Discrete Wavelet Transform." *Annals of Emerging Technologies in Computing (AETiC)* 4, no. 2 (2020).

Soilán, Mario, Ana Sánchez-Rodríguez, Pablo Del Río-Barral, Carlos Perez-Collazo, Pedro Arias, and Belén Riveiro. "Review of Laser Scanning Technologies and Their Applications for Road and Railway Infrastructure Monitoring." *Infrastructures* 4, no. 4 (2019). https://doi.org/10.3390/infrastructures4040058.

Taylor, Ian. "Kenya's New Lunatic Express: The Standard Gauge Railway." *African Studies Quarterly* 19, no. 3–4 (2020): 29–52.

Tsunashima, Hitoshi. "Condition Monitoring of Railway Tracks from Car-Body Vibration Using a Machine Learning Technique." *Applied Sciences (Switzerland)* 9, no. 13 (2019). https://doi.org/10.3390/APP9132734.

Tsunashima, Hitoshi, and Ryota Hirose. "Condition Monitoring of Railway Track from Car-Body Vibration Using Time–Frequency Analysis." *Vehicle System Dynamics* 60, no. 4 (2022): 1170–87. https://doi.org/10.1080/00423114.2020.1850808.

Vaishnav, Swati, and Arti Hadap. "Railway Track Monitoring System." *Smart Innovation, Systems and Technologies* 290 (2023): 475–83. https://doi.org/10.1007/978-981-19-0108-9_49.

Zheng, Shubin, Xiaodong Chai, Xiaoxue An, and Liming Li. "Railway Track Gauge Inspection Method Based on Computer Vision." *2012 IEEE International Conference on Mechatronics and Automation, ICMA 2012*, 2012, 1292–96. https://doi.org/10.1109/ICMA.2012.6284322.