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MODERN METHODS FOR DETECTING RAILWAY TRACK DEFECTS

Annotation: *Railways remain an essential part of modern transportation, yet their safe functioning is often determined by the actual condition of the tracks. The study looks at various ways to detect faults in the rail infrastructure and splits them broadly into two categories: static and dynamic techniques. Different countries rely on different tools to monitor tracks, and this paper compares those tools based on practical factors like how precise they are, how much ground they cover, and how difficult or costly they are to operate. Rather than simply listing pros and cons, we try to show where each method works best. To make sense of the data, visuals like charts and summaries were added, making it easier to see where each approach fits. One part of the analysis pays special attention to how certain features of the railway - such as how wide the rails are or how much the outer rail is elevated – can influence the choice of inspection methods. Lately, there's been a shift toward smarter diagnostics. Technologies like AI, digital simulations of tracks (known as digital twins), and systems using many sensors at once are gaining ground. These tools are changing how track inspections are done and offer new opportunities for early problem detection. This paper doesn't just list methods – it gives a clear structure for understanding which approach fits what context. The outcomes can help transportation teams fine-tune how they take care of tracks and make the system more dependable in the long term.*

Key words: *railway inspection, static inspection methods, dynamic inspection methods, rail inspection train, rail monitoring, track diagnostics, smart diagnostics.*

Introduction. Railways have long stood as a practical choice for moving people and goods, combining efficiency with cost-effectiveness. In places like France, China, and Japan, the growing emphasis on high-speed travel has changed the way rail systems are built and operated, pushing the limits of technology and reshaping infrastructure policy. However, faster trains bring new kinds of stress to the tracks they run on. Rails, wooden or concrete ties, the ballast beneath, and even the electrical systems above – all of these face repeated strain day in and day out. The pounding weight of trains causes small shifts, gradual weakening, and damage that may not always be visible at first glance. Often, it's the tiny faults that prove most dangerous. A minor crack or misalignment, if ignored, can develop into something far worse. For routes where trains move frequently or at high speed, routine inspection becomes essential. It's not just a matter of keeping trains on time – it's about catching the warning signs before they turn into major problems [1]. People working in the railway industry have long relied on inspections to spot problems before they turn serious. These checks can be done in two main ways – either when trains are parked or while they're actually running. Not that long ago, such work was mostly done by hand. It took a lot of effort, and mistakes weren't uncommon. But things have shifted. Rail operators are now turning to machines and smart technology to take over some of those responsibilities.

This article explores how different countries go about checking the condition of their railway tracks. It compares methods that rely on stationary assessments with those carried out during motion, and it also looks at how new tools – especially those using artificial intelligence – might make these tasks faster and more dependable. Unlike many existing studies that either focus narrowly on describing a single method or report on the use of a specific system within a national rail network, this research takes a broader view. It offers a structured comparison of both static and dynamic inspection techniques, aiming to show how they relate to one another in practice. What sets this paper apart is its attempt to bring several aspects together: a clear technical classification of the approaches, a side-by-side evaluation of their measurement performance, visual illustrations that clarify the findings, and a forward-looking discussion of where railway diagnostics technology might be heading next.

Methods and materials. Track inspection methods carried out while the train is stationary have changed a lot over the years. Traditional manual checks, which once relied heavily on visual observation, are now being replaced by more advanced tools. Instead of just walking the track, specialists now use mechanical platforms, digital measurement systems, and even 3D diagnostic equipment with high accuracy.

These innovations make it possible to inspect rail conditions more efficiently and with far greater precision. The data collected using these systems helps detect subtle faults that older methods might miss, making the overall maintenance process more proactive and reliable. When people check tracks while no trains are running, they usually focus on a few basics: how far the rails are from each other, whether the track tilts on turns, and if everything stays lined up over a long stretch. Most rail systems go with 1435 mm – it's called standard gauge. This size has been around since 1937, when it got the official stamp from the International Union of Railways (UIC). Today, more than half the world's train lines use it [2]. Anything wider? That's broad gauge. Smaller? That's narrow. So, why does rail spacing matter? Because it affects how a train handles. Figure 1 shows a comparative diagram of railway track sizes, wider tracks – like 1520 mm in the former USSR or 1676 mm in India – help big, fast trains stay balanced. Narrow gauges, like 762 or 600 mm, are handy in tight spots – mountain areas, factory lines, things like that. When a train takes a turn, it's naturally pulled outward. That force can make it shift a bit off-center. To deal with that, the outer rail is raised higher than the inner one on curves. This setup is called superelevation. It really matters – without it, trains couldn't take turns safely at higher speeds.

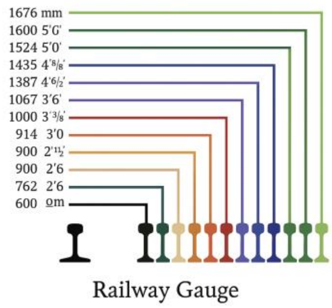

Figure 1 – Rail gauges around the world

This picture shows different rail sizes used in various countries. Each line represents the distance between the rails - shown in both millimeters and feet/inches. The biggest one is at the top, and they get smaller as you go down, so it's easy to compare. The widest is 1676 mm (5' 6"). You'll find that in India, then there's 1520 mm, common in places like Russia and other CIS countries. The most used is 1435 mm (4' 8½"), called the standard gauge. It's found in the US, Europe, and China. Smaller ones like 1067 mm, 1000 mm, 762 mm, and 600 mm are used on older or narrow tracks – for example, in mountains or factory areas. At the bottom of the diagram, you'll also see what the rails themselves look like. These shapes change depending on the size of the track.

To clarify the workflow underlying railway track monitoring methods, Figure 2 shows a general algorithm for monitoring methods. After making a decision to inspect a railway track, the approaches differ depending on whether static or dynamic diagnostics is selected. The diagram shows the key steps and tools used in each method.

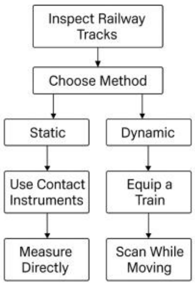

Figure 2 – General functioning of monitoring methods

1 Track geometry: measurement methods

Manual gauge and digital gauge

This is the classic tool still used on lower-speed tracks (up to 160 km/h). It's reliable in simple setups but needs a lot of effort and is affected by human error.

A more modern option, this tool can store, show, and send data. It adjusts for temperature changes automatically and gives both visual and audio alerts when something goes beyond the allowed range. One example is the CALIPRI module, which measures things like track width, rail tilt, and wheel-rail interaction [3].

2 Trolley-based and mobile measurement systems

GEDO CE (Germany)

This system includes a measuring trolley, an industrial computer, and a total station. It helps map the track's centerline, check elevation changes, and calculate superelevation with high accuracy [4]. It's used for both ballasted and ballastless tracks, especially during track laying and alignment of long rails.

Amberg GRP (Switzerland)

This setup works by taking relative measurements and verifying them with fixed references. It's highly accurate and works together with Leica total stations and GPS. It's ideal for switch installation, precise surveying, and inspecting high-speed lines [5]. Figure 3 shows the Amberg GRP System FX, designed for high-precision measurement of railway track geometry.

Figure 3 – Amberg GRP model

SOUTH FX (China)

This is a standard manual trolley equipped with modules to measure track gauge, rail tilt, and relative distances. It also comes with a radio modem to send data to a total station and a control unit.

Portable flaw detectors

These are handheld ultrasonic tools used to scan rails manually. They usually include a signal generator, several sensors, and a screen that shows either a B-scan or A-scan image. One downside is that they can miss defects, so the rail might need to be checked again.

Automatic testing trolleys

These are small machines that scan the rail automatically along its length. They're faster and more accurate than manual options.

Rail inspection trains

These are high-tech trains that inspect both rails while moving at high speeds. They're used on major lines and in metro systems. However, they are expensive and can be difficult to maintain [6].

Based on the information above, we carried out an analysis of different static inspection methods in table 1 used for railway tracks. The comparison looked at key factors such as accuracy, coverage, labor requirements, practicality, and cost.

Table 1 – Overview of static inspection methods

Method	Accuracy	The speed of the examination	Labor costs	Application	Advantages	Limitations
Manual calibre	High (up to 0.5 mm)	Very low (manual)	High	Sections up to 160 km/h	Simplicity, accessibility, no power required	Human factor, low speed
Digital calibre (for example, CALIPRI)	Very high (0.1-0.3 mm)	Low	Medium	All types of lines, especially high-speed ones	Automation, memory, alarms, versatility	Limited coverage, high device price
GEDO CE (Germany)	High	Average	Low	Ballast-free tracks, laying of long rails	High coordinate accuracy, digital processing	Requires training of personnel and measurement conditions
Amberg GRP (Switzerland)	Very high	Average	Average	Geodesy, laying of arrows	Integration with total stations, high accuracy	Expensive, sensitive to external conditions
SOUTH FX (China)	Average	Average	Average	Mass inspections in Asia	Leica hardware compatibility, portability	Limited in accuracy and software analytics
Portable flaw detectors	Average	Low	High	Search for cracks, welding defects	Ultrasound, visualization of A/B scans	Omissions, the need for repeated analysis
Automatic trolleys	High	Average	Low	Scheduled inspections	Automatic collection, stable quality	Limited format (rails only)
Flaw detection trains	Medium–high	High (up to 100 km/h)	Low	Highways and subways	Scale, high performance	Very high cost, difficult operation

Based on the analysis and data from various sources, Figure 4 shows how different types of static inspection equipment are used across several countries. The chart makes it easy to see which technologies are most common in specific regions and how local needs and specializations influence the development of measurement systems.

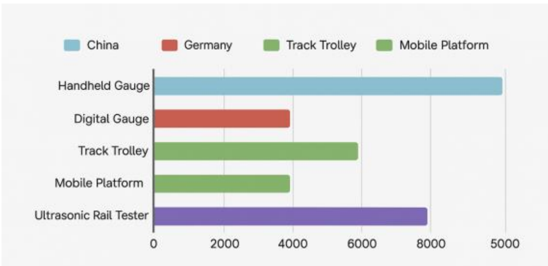

Figure 4 – Main equipment used for static railway track inspection

As shown in Figure 3, the use of static inspection tools varies by country, depending on the level of technology, infrastructure needs, and track gauge standards. For example, China leads in the number of manual gauges in use, while Germany focuses more on digital systems. Switzerland makes wide use of GRP trolleys, and South Korea is actively developing ultrasonic rail testing methods. This kind of visualization highlights how important it is to adapt inspection technologies to each country's specific rail network and technical regulations.

3 Dynamic railway track inspection

Dynamic inspection allows continuous monitoring of track conditions while a train is in motion. Its main advantage is the ability to collect data quickly over long distances. Modern inspection trains and telemetry systems can capture track geometry, overhead line data, signaling information, vibrations, and even detect internal rail flaws - all while moving.

IRIS 320 (France)

This is a modified high-speed TGV train built for inspection work at speeds of up to 320 km/h. It measures track geometry, overhead line conditions, and checks telecom and signaling systems [7]. It’s mainly used to carry out preventive maintenance across the high-speed rail networks in France and Belgium.

CIT-500 (China)

A diagnostic train based on the CRH-380A model, capable of operating at speeds up to 500 km/h. It performs full inspections of track systems, power supply, and onboard telematics. It includes space-time positioning, real-time monitoring, and advanced analysis modules.

East-i (Japan)

This multifunctional inspection train was developed from the Series 700 Shinkansen. It monitors pantograph-to-wire contact, uses laser tools for gauge measurement, tracks vibrations, and includes onboard video systems. It runs on both high-speed and conventional connected lines.

GeoRail-Xpress (Germany)

Developed with Deutsche Bahn, this special-purpose wagon is fitted with radar antennas to scan ballast and subgrade, laser systems for rail geometry, digital cameras, and GPS positioning. It can detect microcracks, breaks, and structural faults at speeds up to 100 km/h.

Archimede (Italy)

A platform created by the Italian rail company RFI. It combines video inspection, laser scanning, thermal imaging, and geometric measurement. The train includes a locomotive, four technical cars, and a control cabin.

Onboard dynamic monitoring systems

These systems are installed directly on locomotives and include sensors for acceleration, vibration, and position. They track how smooth the ride is and detect any unusual changes in track geometry. If a parameter goes beyond safe limits, the system sends a warning and suggests what action to take.

Portable vibration recorders

Small devices placed in the driver’s cabin. They measure vibration and acceleration while the train is running. These tools help quickly locate trouble spots without needing a full inspection crew.

Dynamic monitoring has made track inspections much faster and more efficient. Since it runs automatically and needs little human input, it’s especially useful on high-speed or long-distance routes – places where manual or static methods just don’t work well [8].

Results. To better illustrate the differences in diagnostic methods depending on the region, Figure 5 shows the classification of countries according to the main methods of railway inspection. The countries are grouped according to the prevailing use of static or dynamic diagnostic technologies. Static methods are more common in countries with advanced precision-oriented railway infrastructure, while dynamic methods are preferred in countries that prefer high-speed coverage and automation.

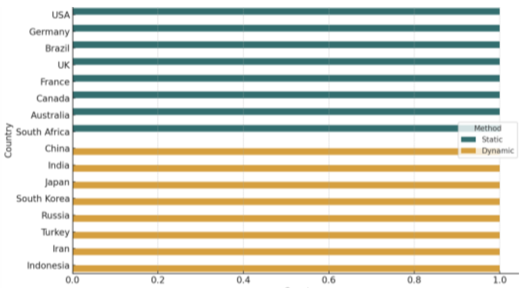

Figure 5 – Classification of countries by preferred diagnostic method

To fairly assess the effectiveness of different railway track monitoring techniques, we focus on three main criteria: inspection speed, measurement accuracy, and how much of the infrastructure can be covered. These factors are compared in Table 2 and also shown visually in the charts.

The figure 6 below shows a comparison of offsets in two different operating modes — static and dynamic. The graph shows that in static mode the displacement is about 0.5 mm, while in dynamic mode it increases to about 1.5 mm. These data clearly show the effect of the dynamic load on the displacement value.

Table 2 – Comparison of static and dynamic inspection methods

Criterion	Static inspection	Dynamic inspection
The speed of the examination	Up to 5 km/h	Up to 350 km/h
Measurement accuracy	High (error ~0.5mm)	Average (error ~1.5mm)
Coverage per shift	Up to 1 km	Up to 1000 km
Required personnel	High	Medium
Dependence on the conditions of the path	Minor	High

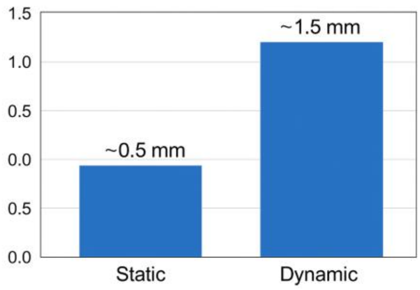

Figure 6 – Accuracy comparison of inspection methods

Static inspections tend to offer the highest accuracy. That's because they rely on direct contact tools like digital gauges and total stations. In dynamic setups, accuracy can drop a little due to train movement and vibrations.

One big advantage of dynamic inspection is how much ground it can cover. In a single work shift, an inspection train can scan up to 1000 kilometers. That makes this method ideal for keeping large railway networks under regular control. The diagrams figure 7 below clearly illustrate these differences. The first diagram shows the typical measurement accuracy for each approach, while the second diagram shows the difference in coverage range.

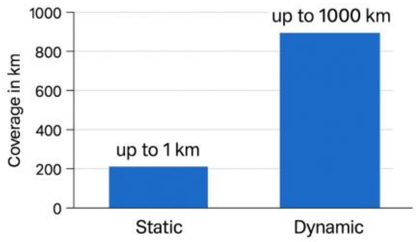

Figure 7 – Coverage comparison of inspection methods

This study organized and reviewed current methods for both static and dynamic railway track inspection. We compared them using three main criteria: measurement accuracy, inspection coverage, and labor requirements. We found that static tools-like manual and digital gauges, along with GEDO and Amberg GRP trolleys-are very accurate, especially for detailed checks on high-load track sections. On the other hand, dynamic systems such as inspection trains (IRIS 320, CIT-500, East-i) and advanced platforms can cover long distances quickly, sometimes up to 1000 km in a single shift. Charts were used to clearly show how these methods differ, helping to highlight the pros and cons of each approach. We also considered factors like track gauge and geometry, both of which influence which tools work best. Superelevation on curves was noted as especially important for accurate readings.

Discussion. A review of contemporary railway diagnostic procedures reveals that none of the procedures are universal. Static mode has the highest level of measurement accuracy and the possibility to monitor certain parts of the path in detail. They prove a valuable asset particularly in the technical inspection of complicated areas of infrastructure where fine track geometry is required e.g. at switchbacks or high-load sections. But these approaches have one thing in common, namely poor survey pace, intensive labor requirement, and are weather dependent, restricting their application on longer or inaccessible routes.

Dynamic methods, on the other hand, enable the real-time monitoring of infrastructure to delivers up to 1,000 km per shift. This would make them irreplaceable in the event of them being used in the case of preventive maintenance planning of high-speed traffic conditions or in running large backbone networks. Nevertheless, dynamic technologies are not as accurate as the static ones, and remain time consuming in terms of equipment and personnel. Under unstable train trajectories and vibration influences, measurement errors can occur, and such a scenario needs to be checked as well.

It is noteworthy that there is observed tendency to adopt intelligent technologies, such as artificial intelligence, digital twins and multisensory platforms. These options raise the level of automation of data analysis, minimize the human factor and make it possible to foresee the evolution of defects at the early stage. Such alteration of the system of diagnostics presupposes a shift to proactive management, as opposed to the reactive one in the technical state of the railway infrastructure.

The fact that a mixed approach is required can be also proven by a comparison of different ways offered in the article. The prospect of using dynamic monitoring as a primary tracking method to assess the state of the track and then the static method to clarify diagnostics allows enhancing the effectiveness and safety of the railway network maintenance end to end.

In general, the choice of diagnostic method should be determined by the characteristics of a particular section of the track, accuracy requirements, technical equipment and economic feasibility. To achieve maximum efficiency, it is important to develop flexible diagnostic systems adapted to national standards, track type and traffic intensity.

Conclusion. The reliability and safety of railway transport depend heavily on regular monitoring of track conditions. This review confirms that no single method is fully universal. Static inspection systems deliver high accuracy but are limited in coverage and require significant manual effort. In contrast, dynamic platforms are more suitable for large-scale assessments but come with high costs for equipment and infrastructure.

A balanced approach works best: dynamic scanning can be used to quickly detect potential problem areas, followed by focused static diagnostics to verify and analyze the findings. This combined strategy ensures both speed and reliability, which is especially important for high-speed rail networks.

Looking ahead, the field of railway infrastructure diagnostics is expected to benefit greatly from smart technologies. Among the most promising trends are machine learning and AI tools that help automate the processing of inspection data. These systems can identify patterns, detect early signs of wear, and even make recommendations for maintenance—faster and more reliably than manual analysis. Another key area is the development of digital twins: detailed virtual models of railway assets built using data from satellites and ground-based sensors. These models allow engineers to simulate and predict infrastructure behavior in real time.

In addition, researchers are working on multisensor platforms that combine laser scanning, ultrasonic testing, vibration monitoring, and thermal imaging [9, 10]. Making such tools work across different rail gauges and in harsh weather conditions is a priority. Cloud-based services are also gaining traction. These platforms can store massive amounts of inspection data and use predictive analytics to plan future repairs. This shift from reactive to proactive maintenance could lead to safer railways and lower costs in the long run.

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ТЕМІРЖОЛ ЖОЛДАРЫНЫҢ АҚАУЛАРЫН АНЫҚТАУДЫҢ ЗАМАНАУИ ӘДІСТЕРІ

Теміржолдар қазіргі заманғы тасымалдаудың ажырамас бөлігі болып қала береді, дегенмен олардың қауіпсіз жұмыс істеуі көбінесе жолдардың нақты жағдайымен анықталады. Зерттеу теміржол инфрақұрылымындағы ақауларды анықтаудың әртүрлі әдістерін қарастырады және оларды екі санатқа бөледі: статикалық және динамикалық әдістер. Әртүрлі елдер жолдарды бақылау үшін әртүрлі құралдарға сүйенеді және бұл мақалада бұл құралдар олардың қаншалықты дәл екендігі, қанша аумақты қамтитыны және оларды пайдалану қаншалықты қиын немесе қымбат екендігі сияқты практикалық факторларға байланысты салыстырылады. Артықшылықтары мен кемшіліктерін тізімдеудің орнына, біз әр әдістің қай жерде жақсы жұмыс істейтінін көрсетуге тырысамыз. Деректерді түсіну үшін диаграммалар мен қорытындылар сияқты көрнекіліктер қосылды, бұл әр тәсілдің қай жерде сәйкес келетінін көруді жеңілдетті. Талдаудың бір бөлігінде теміржолдың белгілі бір ерекшеліктері, мысалы, рельстердің қаншалықты кең екендігі немесе сыртқы рельстің қаншалықты көтерілгендігі – тексеру әдістерін таңдауға қалай әсер ететініне ерекше назар аударылады. Соңғы уақытта ақылды диагностикаға көшу жүріп жатыр. Жасанды интеллект, тректерді цифрлық модельдеу (цифрлық егіздер деп аталады) және бір уақытта көптеген сенсорларды қолданатын жүйелер сияқты технологиялар қарқын алуда. Бұл құралдар бақылау тексерулерін жүргізу тәртібін өзгертеді және ақауларды ерте анықтаудың жаңа мүмкіндіктерін ұсынады. Бұл мақалада әдістердің тізімі ғана емес, сонымен қатар қандай тәсілдің қандай контекстке сәйкес келетінін түсіну үшін нақты құрылым берілген. Нәтижелер көлік бригадаларына жолдарға қалай күтім жасау керектігін дәл реттеуге және жүйені ұзақ мерзімді перспективада сенімдірек етуге көмектеседі.

Түйін сөздер: *теміржол инспекциясы, статикалық тексеру әдістері, динамикалық тексеру әдістері, теміржол инспекциясы пойызы, теміржол мониторингі, жол диагностикасы, ақылды диагностика.*

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СОВРЕМЕННЫЕ МЕТОДЫ ОБНАРУЖЕНИЯ ДЕФЕКТОВ ЖЕЛЕЗНОДОРОЖНОГО ПОЛОТНА

Железные дороги остаются важной частью современного транспорта, однако их безопасное функционирование часто определяется фактическим состоянием путей. В исследовании рассматриваются различные способы обнаружения неисправностей в железнодорожной инфраструктуре и в целом они подразделяются на две категории: статические и динамические методы. Разные страны используют разные инструменты для мониторинга путей, и в этом документе сравниваются эти инструменты, основанные на практических факторах, таких как их точность, площадь охвата и сложность или дороговизна их использования. Вместо простого перечисления плюсов и минусов, мы стараемся показать, где каждый метод работает *лучше всего. Для придания смысла данным были добавлены визуальные элементы, такие как диаграммы и сводки, что упрощает понимание того, где подходит каждый подход. В одной из частей анализа особое внимание уделяется тому, как определенные характеристики железной дороги, такие как ширина рельсов или высота подъема внешнего рельса, могут влиять на выбор методов контроля. В последнее время наблюдается переход к более эффективной диагностике. Такие технологии, как искусственный интеллект, цифровое моделирование путей (известные как цифровые двойники) и системы, использующие множество датчиков одновременно, набирают обороты. Эти инструменты меняют методы проверки путей и открывают новые возможности для раннего обнаружения проблем. В этом документе не просто перечислены методы - он дает четкую структуру для понимания того, какой подход подходит для конкретного контекста. Результаты могут помочь транспортным командам усовершенствовать методы ухода за путями и повысить надежность системы в долгосрочной перспективе.*

Ключевые слова: *железнодорожная инспекция, методы статической инспекции, методы динамической инспекции, железнодорожный инспекционный поезд, мониторинг железных дорог, диагностика пути, интеллектуальная диагностика.*

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