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Boots Off Ballast: Transforming Railway Inspection, Maintenance, and Operations

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Abstract

Track maintenance practices in the UK have changed little over the past two centuries and continue to rely heavily on manual inspection and intervention. However, traditional approaches are increasingly challenged by rising costs, limitations in effectiveness and efficiency, growing demands for infrastructure availability and reliability, and a greater frequency of extreme weather events. These pressures raise a fundamental question: how can we continue to keep our staff safe?

Carrying out physical inspections in 40 °C heat or during prolonged periods of heavy rainfall presents both safety risks and productivity constraints. Moreover, the physically demanding nature of trackside work, combined with the limited use of modern technology, is increasingly viewed as an unattractive career proposition by younger generations, contributing to ongoing skills and resource shortages.

This paper presents a technical overview of Network Rail Eastern Region's Boots Off Ballast programme, an operational transformation aimed at reducing unnecessary trackside exposure through remote inspection technologies. The programme integrates artificial intelligence, advanced video analytics, and unattended track geometry monitoring to enable condition- and risk-based maintenance. Case studies demonstrate how these tools improve defect detection, enhance decision-making, and deliver measurable safety, performance, and productivity benefits. Collectively, Boots Off Ballast represents a strategic shift toward a safer, smarter, and more sustainable model for maintaining the UK rail network.

Keywords: remote railway inspection, boots off ballast, artificial intelligence, unattended track geometry monitoring, risk-based maintenance, automatic detection.

1 Introduction

The UK's rail network is one of the most complex and asset intensive transport systems in the world. Increasing operational demands, safety expectations, and extreme weather conditions have created the need for new approaches to infrastructure inspection and maintenance. The Boots Off Ballast initiative on the Eastern Region seeks to minimise physical trackside exposure by replacing manual inspections with technology enabled alternatives wherever feasible.

The initiative is not simply a technology deployment but a strategic transformation in how engineering, operations, and maintenance activities are carried out.

2 Background and Problem Statement Methods

As with many asset-intensive industries, Network Rail manages a large, geographically dispersed asset base, much of which has very long operational lives. This includes approximately 20,000 miles of track, 820 signal boxes, 2,500 stations, and millions of natural and lineside features, as illustrated in Figure 1. All of these assets require regular inspection and maintenance. The sheer scale and diversity of this portfolio present significant challenges for safety, operational performance, and inspection coverage, particularly in the context of a constrained funding envelope over the next five years.

- 20,375 miles of track
  - 42,000,000 sleepers, 40,000 miles or 67,244km of rail
- 35,000 bridges and tunnels
- 820 signal boxes
- 2,500 stations
- 8,200 commercial properties
- 7,000 level crossings
- 40,000 + employees

- One of the largest landowner in UK
- Largest or second largest purchaser of electricity in UK
- Third largest Telecoms network in the UK
- 14,000 miles of fencing
- 9,000 miles of drainage
- 2,500,000 trees on our land and a further 5,000,000 adjacent to our land

Figure 1: Asset base in Network Rail

Several converging challenges reinforce the need to reduce trackside working. These include

- Rising injury trends post pandemic (Figure 2)
- Change in staff risk profile following recent business changes (night-time working when trains are not running, access constraints, rapid use of technology etc.)

- Increasing demand for higher infrastructure availability and reliability
- Increasing number of severe weather events and climate driven disruptions

Traditional inspection methods are increasingly unsustainable, both from a safety, effectiveness and efficiency perspective. Improved inspection and monitoring technology allows us to identify and respond rapidly to immediate issues, and also to determine where to implement longer-term interventions more effectively.

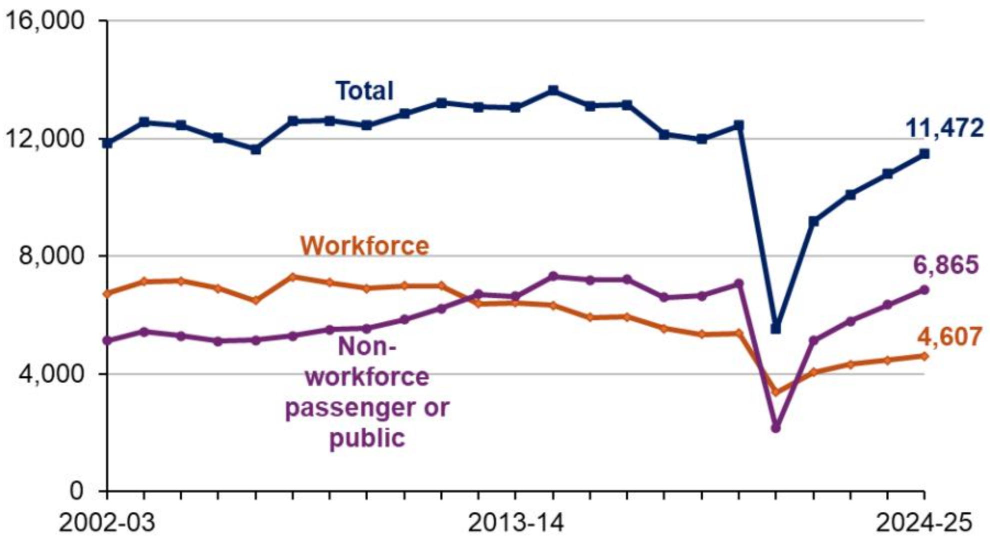

Figure 2: ORR report shows rising number of injuries to both workforce and non-workforce since the pandemic.

3 Programme Vision and Objectives

The vision is to embed remote inspection as the norm, modernising the industry by moving away from a physically intensive, traditional model towards a safer, smarter, and more attractive career for the next generation.

The Boots Off Ballast programme aims to:

- Reduce unnecessary physical presence on track
- Shift to technology enabled inspections
- Improve network intelligence and therefore great network availability
- Enhance data driven decision making and therefore the effectiveness of work interventions
- Support modernising national standards
- Deliver productivity and performance improvements

4 Technology Enablers

Mobile communications technology has advanced rapidly in recent years, enabling faster data transmission and driving the widespread adoption of smart connected devices. The Internet of Things is now embedded across everyday and industrial environments, placing the railway firmly within an increasingly data-rich landscape.

These developments, combined with significant improvements in battery capacity, have fundamentally changed how railway assets can be monitored. Real-time condition data is now readily available, providing insight into parameters such as sleeper movement, rail temperatures, on-track lubrication levels, and ground displacement at known subsidence sites. At the same time, an increasing proportion of in-service fleets are equipped with condition monitoring systems capable of reporting threshold exceedances in near real time, enabling proactive maintenance intervention before asset failure occurs.

Over the past five years, Network Rail has developed and trialled a range of these technologies in collaboration with suppliers, consultants, and academic partners. Deployment has been deliberately phased and evidence-led, ensuring that each solution delivers tangible operational benefits and can be sustained at scale. A few key examples are shown below.

4.1 Automatic Intelligent Visual Review (AIVR)

AIVR is a universal video intelligence platform that hosts geo-referenced video from multiple sources, including drones, body-worn cameras, and train-borne systems. The platform is accessible across Network Rail, contractors, and suppliers, and currently supports over 12,000 active users. Figure 3 shows an example of the AIVR dashboard.

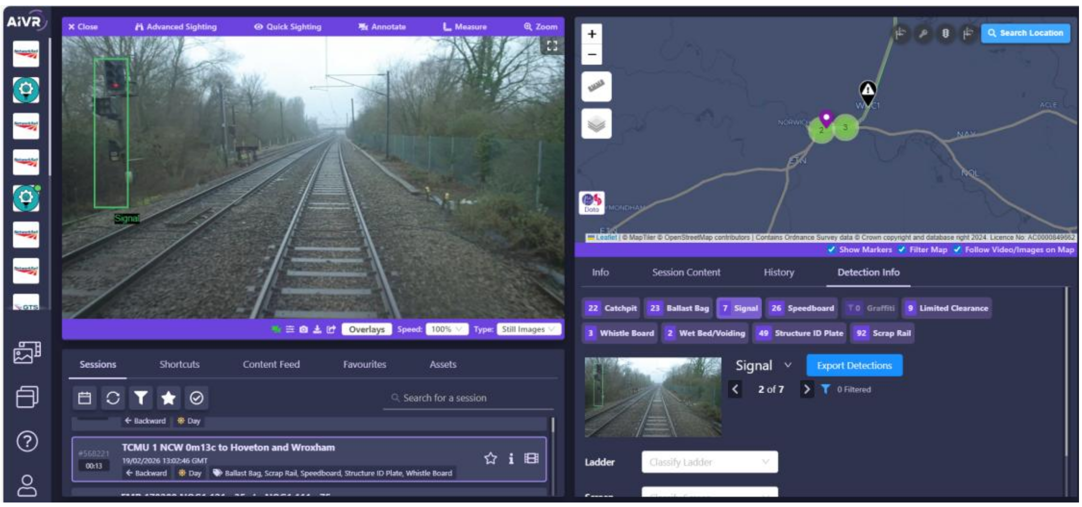

Figure 3: AIVR Dashboard showing the detection of a signal head.

AIVR provides daily visual coverage of the network, including:

- Forward-facing, downward-facing, and lineside video captured from both infrastructure monitoring trains and in-service fleets.
- High-resolution imagery available within hours of capture, enabling virtual site inspections and remote asset assessments.
- AI-enabled detection of rail and lineside assets and, where applicable, asset condition. Current use cases include signal sighting assessment, vegetation monitoring, wet bed identification, ballast condition analysis, and rail defect detection.

4.2 Track Geometry Monitoring (UGMS)

Unattended Geometry Measurement Systems (UGMS) are not new; they have been commercially available since the early 2000s and are capable of capturing daily track geometry and acceleration (force) data, where available, using a complex array of sensors installed on in-service fleets. Historically, however, the lack of accessible visualisation tools meant that the data collected was difficult to interpret and therefore under-utilised.

Over the past decade, the emergence of mature commercial big-data dashboards has transformed the usability of UGMS outputs. Raw data can now be converted into meaningful information and actionable insight, readily accessible to engineers and operational teams across the business. Key benefits include:

- Continuous monitoring, for example daily track geometry data capture on the East Coast Main Line.
- Rapid detection of geometry shifts, with automated alerts issued directly to depots to enable proactive intervention.
- Early warning of high-risk track conditions, such as severe voiding, broken rails, track buckles, and other emerging defects.
- Integration with corporate systems, enabling the automated generation of work orders and streamlined maintenance workflows.

4.3 Risk-Based Maintenance (RBM) Framework supported by Readily Available Asset Data

We are also transitioning towards Risk-Based Maintenance (RBM), also referred to as Reliability-Centred Maintenance. The core principle of RBM is delivering the required asset performance by undertaking the right maintenance at the right time.

This approach aligns inspection intervals and maintenance interventions with asset condition, risk profiles, and real-time data. As a result, the programme moves away from traditional, time-based inspection regimes and places greater emphasis on targeted corrective activity rather than non-value-adding inspections. With the increasing availability of high-quality data, maintenance decisions can be informed by observed deterioration rates and emerging risk, enabling more effective and efficient intervention planning.

4.4 Digital Platforms and Integration

Some consider the ideal state to be a single platform hosting all data sources; however, this approach is increasingly unnecessary and can be inefficient, particularly as most modern applications are web-based and therefore already easily accessible. Digital platforms are typically designed and optimised for specific functions – accordingly, a video platform is unlikely to be well suited to plotting linear data, just as a data analytics dashboard is not optimised for high-volume video review.

That said, targeted integration between platforms can deliver clear operational benefits where the use case is well defined. For example, our UGMS data dashboard can identify a localised 'high-force' site and provide a direct link to AIVR via a camera icon. Selecting this link takes the user straight to the relevant imagery, enabling rapid visual assessment of asset condition without duplicating functionality across systems.

Appropriate linkage between platforms enables:

- Improved decision support, with complementary datasets presented for the same location
- Cross-disciplinary analysis, for example between earthworks and track teams when investigating rapid track geometry deterioration – an issue becoming more frequent as landslide events increase due to extreme weather
- Targeted maintenance, where detailed defect analysis in advance of site visits ensures the right tools and resources are available for a right-first-time repair to minimise repeat failures and improve asset availability

Enhanced possession planning, with improved scoping producing more robust rectification plans and reducing the need for excessive contingency

5 Case Studies and Performance Improvements – Video Based Inspection Capability

5.1 Forward-Facing Video (FFV)

All in-service trains are mandated to be equipped with forward-facing video (FFV) systems. Historically, access to this footage has been limited, with short clips typically shared by train operators with Network Rail only for the investigation of specific incidents, such as road vehicle incursions or train collisions at level crossings. Since the pandemic, however, some train operators have shown a growing willingness to share FFV footage more routinely to support infrastructure maintenance activities.

With FFV now available to Network Rail covering approximately 95% of the network, this capability provides near-continuous visual coverage, including daily footage on high-traffic routes. To extract timely and actionable insight from this extensive data source, Network Rail has been working with specialist suppliers to develop machine-learning models that automatically analyse video footage. These tools enable the detection of critical assets, assessment of asset condition, and evaluation of compliance with engineering standards, significantly reducing the need for manual inspection.

Some applications have already become ‘business as usual’. An example is provided below.

Low Ballast Detection

As part of routine hot weather preparation, ballast levels have traditionally been assessed through targeted track walks or cab rides to confirm compliance with standards and reduce the risk of track buckling. Forward-facing video imagery provides a comparable viewpoint to a cab-ride inspection and, where image quality is sufficient, enables machine-vision techniques to distinguish between compliant (‘good’) and non-compliant (‘bad’) ballast conditions.

Following several iterative trials, a supervised classification machine-learning approach was adopted to assess ballast levels. While this method does not deliver a fully quantitative measurement, it provides a rapid visual indication of ballast shortage using a severity index linked to the length of deficient ballast sections.

This capability has been operational for the past three years and has contributed to strong hot-weather performance across the Eastern Region. Despite experiencing four heatwave events during this period, the region outperformed all others except Scotland, which was not subject to extreme temperatures.

Figure 4: Using a ‘letterbox’ approach to hone in on relevant track for the low ballast classifier model

5.2 Downward-Facing Video Systems

Network Rail was an early adopter of machine-vision technology through the introduction of the Downward-Facing Video Plain Line Pattern Recognition (PLPR) system in 2013. This train-borne, semi-automated inspection capability has progressively replaced approximately 70% of manual inspections on modern track formed of continuously welded rail. Nevertheless, nearly 10,000 km of the network remains constructed with legacy components that continue to require significant levels of manual inspection.

Within the PLPR process, high-speed video imagery captured from moving trains is analysed using pattern-recognition algorithms in combination with track geometry data. The system automatically identifies ‘candidate defects’, including missing, damaged, or incorrect components, as well as locations exhibiting abnormal track geometry. These are triaged by a dedicated team of track inspectors in Derby, who undertake detailed desktop reviews. Defects that are confirmed, together with those classified as ‘uncertain’, are then reported to local maintenance teams to support targeted planning and rectification.

Building on this capability, the Eastern Region is progressing towards full video-based inspection of the track using advanced linescan camera technology capable of capturing very high-definition imagery. These systems are deployed across the Visual Inspection Units (VIUs – converted Class 153 single-car DMUs), Ultrasonic Test Units (UTUs), and selected in-service trains. The VIUs in particular offer world-leading performance, operating at speeds of up to 75 mph, with inspection data available on desktop or laptop devices within one hour and achieving locational accuracy of approximately 30 mm. An example application is presented below.

<u>Poor Condition Insulated Rail Joint.</u>

Track circuit failures due to damaged IRJs are common and the failure can be expensive. One recent incident caused more than 2800 mins of train service delay, costing over £1.4m in compensation. Hot weather preparation typically involves checking the condition of the insulated end posts, or ‘T-pieces’, and checking for any rail end lipping. During warm weather rail expansion compresses the end post, and on worn or dipped IRJs this can cause the insulation to fail, allowing the rail ends to touch, bridging the track circuit (Figure 5).

We have trained computer models to detect IRJs, and classify them by joint type, such as six-hole factory made (glued) or four-hole encapsulated (dry, site-made). This makes it possible to jump quickly between joints on the video footage, reviewing their condition as part of hot weather preparation and ongoing assurance over the summer months. Figure 6 shows the screenshot of this functionality.

Incorporating additional detail such as track geometry information means that work can be prioritised and targeted. By further classifying the joints it is possible to build up comprehensive condition information, identifying assets that meet certain criteria so that clear priorities can be determined. This information can then be used to develop the algorithms further to automatically detect sub-standard conditions and proactively report any detections to the maintenance engineers.

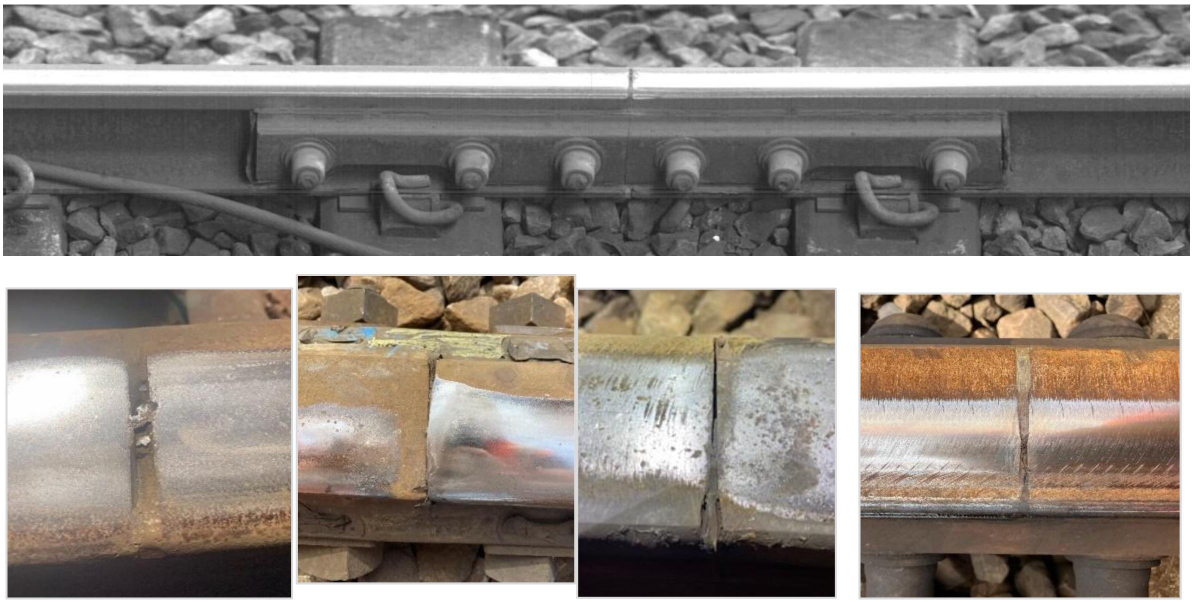

Figure 5: Examples of damaged or broken IRJ end posts, leading to rail lipping or burring resulting in track circuit failures.

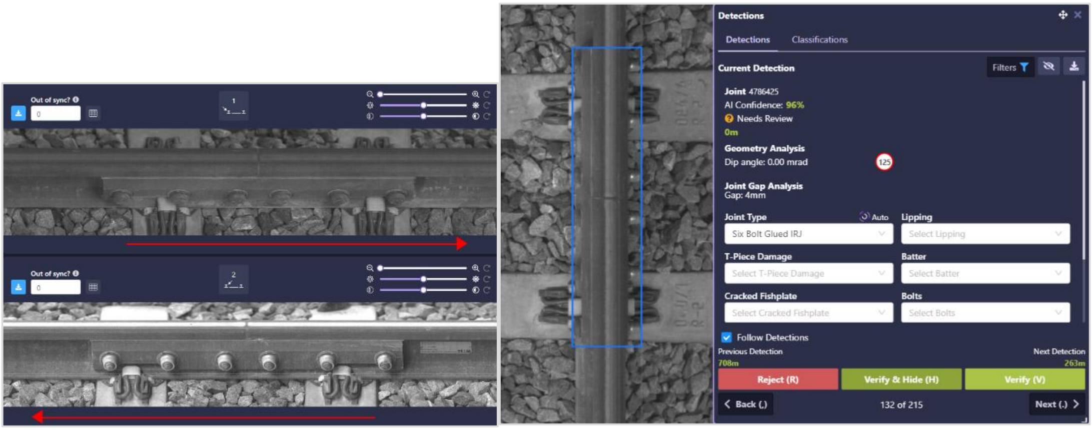

Figure 6: Automatic asset detection makes it possible to review and record condition information quickly. This can then be used to further develop algorithms to detect and report sub-standard conditions automatically.

5.3 AI-Enhanced Analysis

Machine learning is generally considered to be a subset of AI, using mathematical models to help a computer learn without direct instruction. This enables the system to continue to improve on its own, based on vast quantity of ingested data.

As seen in the previous sections, we now have AI functionality that automatically detects visible track defects and checks the condition of critical assets, such as the insulated rail joints and low ballast sites examples above, adjustment switches, switches and crossings or drainage catchpits. Detectable rail defects including squats, wheel burns, cracks, broken rails, broken fishplates, and deterioration trends (dip angle), see Figure 7.

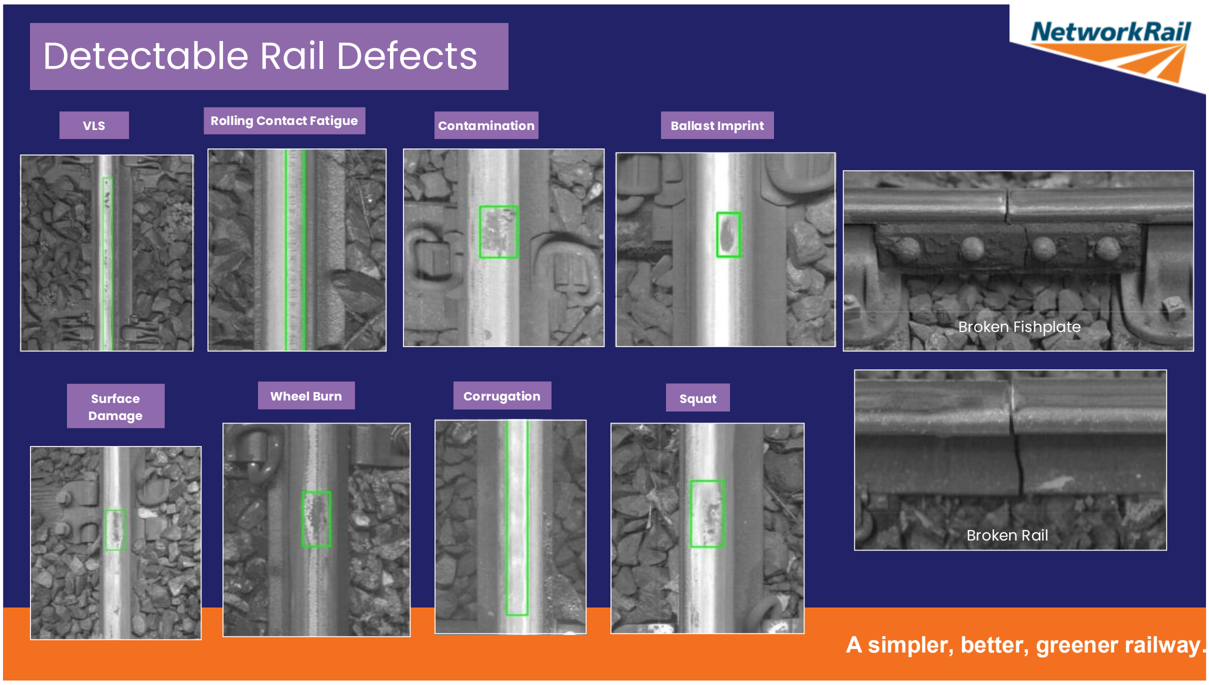

Figure 7: Detectable rail defects

For other asset types, the available AI functions are:

- Vegetation assessment
- Catchpit condition monitoring
- Overhead Line Equipment bonding and arcing detection
- Telecoms troughing condition assessment
- Signal sighting and obscuration analysis

This capability set continues to expand and is now embedded within routine maintenance activities. All Eastern Region maintenance depots are actively using these technologies to support day-to-day decision-making. The next phase of development will focus on introducing AI functions capable of analysing sudden changes in track geometry data.

5.4 High-Force (Acceleration) Monitoring

A year ago, we initiated a trial using bogie-mounted acceleration data readily available from Unattended Geometry Measurement Systems (UGMS). Currently, six trains operate along the East Coast Main Line, generating multiple datasets each day. By correlating acceleration outputs with site observations, we have refined intervention threshold values for the specific rolling-stock type operating on this route.

As acceleration measurements are captured at the bogie, they are intrinsically influenced by the vehicle's primary suspension characteristics. Consequently, threshold values are dependent on train type and line speed, and are not directly transferrable between routes or fleets.

By using bogie acceleration as a proxy measure for forces acting on the rail, this approach enables proactive management of rapid track deterioration, either preventing failure altogether or significantly reducing disruption duration. Practical applications include:

- Identification of voiding or poor-ride sites (for example, acceleration peaks of approximately 2.5 g at wet bed locations)
- Early detection of localised defects, such as broken rails or fractured fishplates
- Identification of persistent defects that remain after previous track repairs

Figure 8 shows the dashboard for continuous daily monitoring of high force sites on East Coast main line. Each blue dot represents the maximum bogie acceleration recorded by a train passing the asset.

Figure 8: Acceleration (Force) sensors on passenger trains monitoring our asset condition

Recent incidents as shown in Figure 9 comparing technology-detected and manually reported defects show:

- Technology-triggered detections result in fewer delay minutes
- Early intervention reduces damage and disruption

Incident	Site Name	Detection method	Delay minutes	Comment	Condition of Site
Broken Rail	Tuxford	Reported by Driver	6409	Site was severely damaged and required more than one shift to repair.	
Broken Rail	Cadwell North	Technology detected high force site	1000+	High force triggered an inspection and the broken rail found. No damage to sleeper. Speed imposed. Rail replaced on the night with minimal disruption.	
Broken plates	Yaxley	Reported by Driver	10,273	Severe disruption due to initial inspection leading to line closure and a delay to rectify fault from late running last train.	
Broken plate	Barnby Moor	Technology detected high force site	0	High force triggered an inspection and broken plate found; rail was rectified on the night.	

Figure 9: Technology's Impact on Reliability: Highlights from Recent Case Studies

6 Programme Roadmap and Challenges

The Boots Off Ballast transformation journey is being delivered through a phased roadmap to ensure that new technologies and ways of working are introduced in a controlled and sustainable manner. The foundation phase focuses on the development and trial of enabling technologies, early operational rollouts, and the delivery of targeted training to build capability and confidence within the workforce.

This is followed by an expansion phase, during which successful solutions are aligned nationally, supported by updates to standards and the development of Common Safety Method Risk Assessment workstreams to enable wider adoption. We are currently in this phase.

The programme ultimately aims to reach full adoption, where risk-based maintenance is embedded as business as usual and the majority of inspections are undertaken remotely rather than through routine trackside activity.

Delivering this transformation requires significant organisational change, infrastructure upgrade (faster broadband) alongside the deployment of technology. Workforce training and upskilling are essential to ensure that engineers and operational teams can interpret data effectively and make informed, evidence-based decisions. New engineering workflows are being developed in the form of regional instructions to integrate digital inspection outputs into maintenance planning, while reporting practices are being updated to reflect condition- and risk-based approaches rather than traditional time-based regimes. Improving digital literacy across the organisation is a key enabler, supported by closer partnerships between engineering, safety, standards, and fleet teams to ensure end-to-end alignment.

The programme also faces a number of challenges that must be actively managed. These include achieving trade union buy-in, maintaining the reliability of fleet-mounted and trackside technologies, and addressing data quality issues and gaps that can limit confidence in digital outputs. Existing standards can constrain the pace of change, requiring careful engagement and assurance processes. However, the most significant challenge is cultural change, as the programme requires a shift in mindset away from long-established inspection practices towards greater trust in remotely captured data and technology-enabled decision making.

7 Conclusions

Boots Off Ballast represents the future of UK railway maintenance by shifting the industry towards remote inspection and data driven engineering. Through this approach, the programme significantly reduces workforce exposure to trackside risk, improves productivity and asset reliability, enables earlier and higher quality defect detection, and delivers clear environmental and cost benefits.

Importantly, it also strengthens network resilience in the face of increasingly extreme weather. To accelerate this transformation, Network Rail is seeking active collaboration with suppliers, consultants, and academic partners to drive innovation and develop new tools that support safer, smarter railway operations.

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