Rail Buckling Detection Method: A Comparative Analysis of Technologies for Early Detection

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ABSTRACT

The climate issue has emerged as a significant global challenge. One of the impacts of climate change on railroads is rail buckling. The lateral movement of the rail could potentially result in derailment. This project aims to evaluate the most appropriate method for detecting rail buckling in order to be applied in the UK railway network. The methodology adopted is a comprehensive literature review. All the literature utilised is derived from prior studies on the advancement of sensing technology. The UKCP18 forecasting is adapted for projecting the climate change for decades. Additionally, the Bartlett method is used to estimate buckling. The other analyses adapted is used to select the most suitable technology applied in the UK railroad. The analyses being referred to are SWOT and multi-criteria analysis. The UKCP18 projection indicates a uniform growth throughout all regions with significant escalation occured in the southern regions of the UK. The buckle phenomena may occur between the years 2061 and 2080 for several locations. Several technologies are designed for detecting buckling phenomenon. Upon completing the SWOT and multi-criteria decision analysis, it has been determined that the integration of WSN and FBG is the optimal technology for detecting rail buckling.

Kata kunci: Rail Buckling; Buckling Detection Technology; Sensor.

1 INTRODUCTION

1.1 Background

Railways are an essential component of the societal and economic infrastructure. They have a crucial function in facilitating the transportation of goods and individuals around the United Kingdom. It is imperative to effectively oversee the railway tracks considering the potential consequences of climate change. It is probable that summer temperatures will attain elevated maximums and the yearly temperature range will expand (2022). Dobney et. al. (2009) stated the Alterations Database records 137 occurrences of railway buckling, which is a direct result of the severe weather conditions. This exceeds the long-term average of 30-40 instances of buckling per year.

According to Bruzek et. al. (2013), excessive rail temperature leading to track buckling is a major cause of derailments, which can have severe effects and poses a significant risk to railway safety, and it is crucial to address this issue as soon as possible. To this end, researchers have explored various sensing technologies and methods, including fibre-bragg gratings (FBG), wireless network sensor (WSN), and digital image correlation (DIC). In addition, predictive models such as the rail temperature predictor and rail buckling predictor have been developed to anticipate the occurrence of rail buckling. This research will evaluate the models in detecting rail buckling and effectiveness of these sensors.

This research aims to examine the potential effects of climate change and predicted heatwaves on the UK railway system, particularly regarding the probability of rail buckling. The project will concentrate on the creation and deployment of an optional sensor for detecting rail buckling. The objective is to determine the best suitable sensor type for detecting rail buckling through analyses from multiple sensor types.

2 METHODOLOGY

2.1 Data Scope

The inquiry utilizes data from the UK railway system. Data obtained by methods devoid of scientific publication and public reporting indicate the susceptibility of the compromised rail network and pinpoint the most trafficked line in the whole UK rail system. The timeframe is split into two separate intervals: 2021-2040 and 2061-2080. The chosen time period is derived from the data supplied by UKCP18.

2.2 Maximum Air Temperature in The UK Rail Network

The maximum temperature may indicate the weather conditions in the UK from the summer of 2030 to 2070. The temperature variation can be illustrated by contrasting the temporal changes. This projection utilises UKCP18. The analysis employs the product named "Probabilistic projections of climate extremes (25km) over the UK, 1961-2100". To ascertain the correlation between maximum ambient temperature and rail buckling, it is essential to acquire the anticipated maximum air temperature in a specific place that acts as a sample for forecasting rail buckling. In addition, the utilised UKCP18 product is the "Variables from local projections (2.2km) regridded to 5km over the UK for daily data."

2.3 Rail Buckling Prediction

The suggested model for application is the Track Buckling Predictor (Bartlett Model), developed by ARTC. By employing defined criteria including rail type, rail and trackbed properties, rolling stock characteristics, and rail traffic volume.

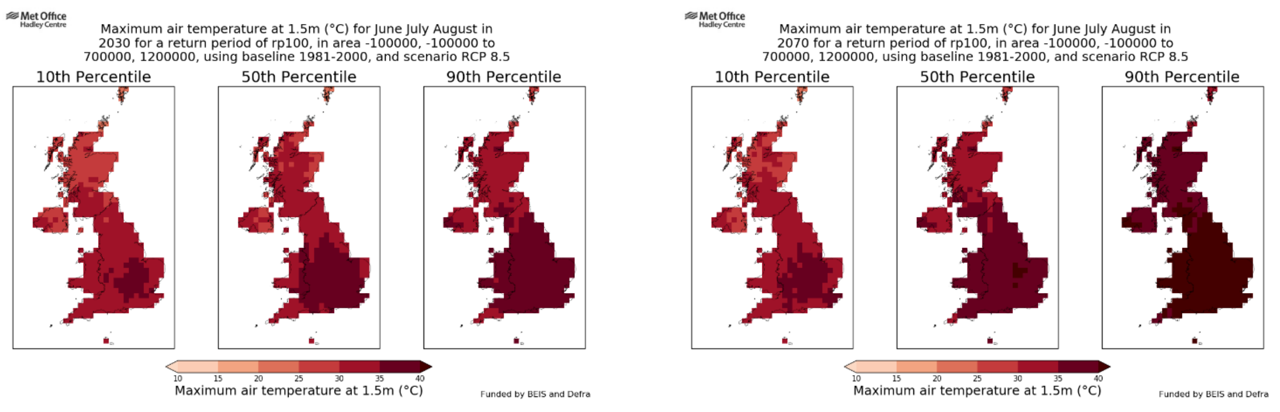
2.4 Selecting The Most Suitable Technology

The first stage of the analytical process entails the most proper technology of rail bucking detection. This study focuses on the comparative statistics concerning technology and sensor kinds. The selected strategy will incorporate the application of the SWOT method and multi-criteria decision analysis.

3 RESULT AND DISCUSSION

3.1 Climate Change Entire UK and It's Impact on Railway Infrastructure

This study employs the methodology of "Probabilistic projections of climate extremes (25km) over the UK, 1961-2100." The particular years were chosen based on an extensive forecast across multiple locations. Consequently, the years 2030 and 2070 were designated as the specific intervals for assessing the comprehensive effects of climate change across the UK. The UKCP18 projections indicate that the maximum air temperature in the UK is anticipated to rise from 2030 to 2070. In the 10th percentile data, there is no significant variation in temperature. Nonetheless, the distinction is apparent in the 50th and 90th percentiles, when the southern UK region records temperatures exceeding 35 °C.

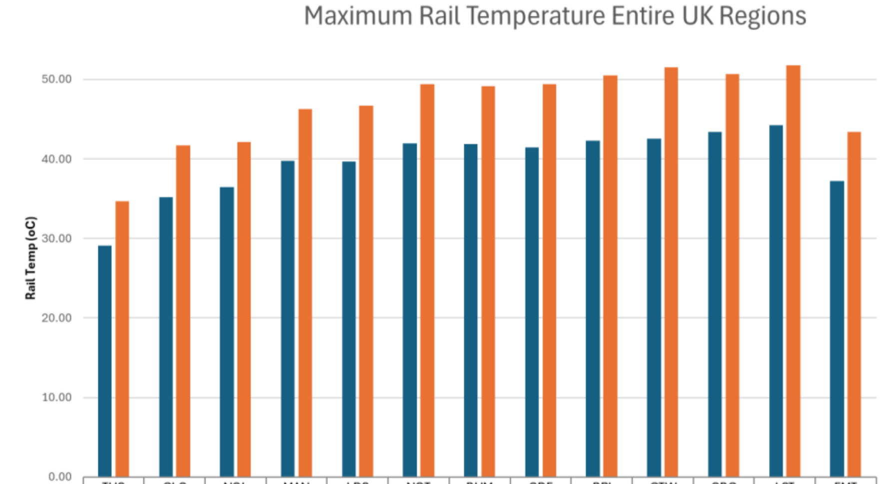


(a) (b)

Figure 1. UKCP18 Maximum Air Temperature Projections for the heat of the summer season in (a) 2030 and (b) 2070 (Met Office, 2024).

The rise in air temperature might harm numerous sectors, including trains. The principal effect on railway infrastructure is the rail expansion induced by ambient temperature. To assess the effect of elevated temperatures on railroad infrastructure, it is essential to get data on the present ambient air temperature. The UKCP18 Projection can yield the maximum potential air temperature. This study employed coverage data from the decades 2021-2040 and 2061-2080 to analyze the prevalence of climatic changes in the United Kingdom. The designated area is the most congested station vicinity (within a 2.2 km radius) throughout all areas in the UK, as reported by the Office of Rail and Road (ORR, 2023). Moreover, it is the most remote station in the UK, extending from the northern to the southern regions.

Dobney et al. (2009) elucidated that a widely utilized guideline in the industry is applied to convert temperatures between air and become 1.5 temperature rail. The graph below illustrates the maximum rail temperature for the entire UK region during two time intervals.



	THS	GLC	NCL	MAN	LDS	NOT	BHM	CDF	BRI	GTW	CBG	LST	FMT
2021-2040	29.12	35.22	36.48	39.74	39.65	41.97	41.90	41.43	42.31	42.51	43.38	44.20	37.18
2061-2080	34.71	41.73	42.11	46.30	46.70	49.40	49.18	49.40	50.49	51.51	50.63	51.79	43.35

Code	Station
THS	Thurso
GLC	Glasgow Central
NCL	Newcastle
MAN	Manchester Piccadilly
LDS	Leeds
NOT	Nottingham
BHM	Birmingham New Street
CDF	Cardiff Centra;
BRI	Bristol Temple Meads
GTW	Gatwick Airport
CBG	Cambridge
LST	London Liverpool Street
FMT	Falmouth

Figure 2. The peak rail temperature for sectors in the United Kingdom.

3.2 Bartlett Model for Predicting Rail Buckling

In this calculation, all samples are presumed to conform to the Network Rail standard. Several parameters, including those derived from assumptions on the misalignment, were collected based on the prevalent misalignment seen in the UK. Subsequent to computations utilizing the buckle predictor that provided by the ARTC. The graph indicates that the lowest temperature occurs at wavelengths of 6m and 7m, measuring 48°C. The buckle potential of the regions can be determined by integrating the buckle temperature with the maximum air temperature as shown in figures below.

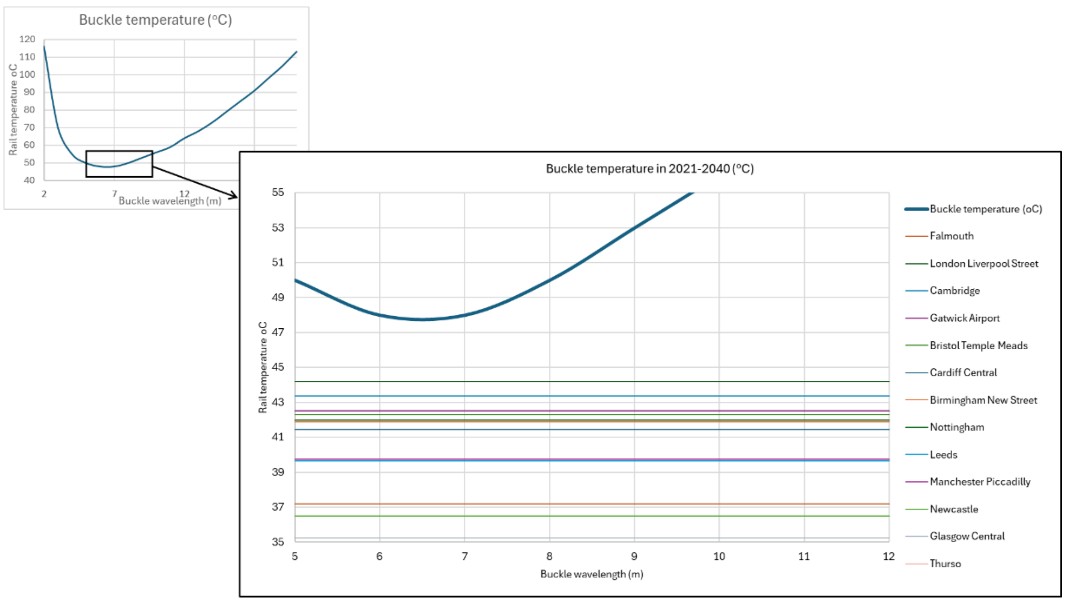


Figure 3. Comparison of maximum air temperature and buckle temperature from 2021 to 2040.

Figure 3 indicates that no samples exceeding the threshold temperature resulted in buckling. The graphic distinctly depicts the overall trend of maximum temperatures necessary to avert buckling and the maximum temperatures attainable by samples throughout the UK from 2021 to 2040. According to the highest temperatures at several sites around the UK, over half of the samples surpassed 40°C. However, there are no samples that exceed the buckle temperature of 48°C, which is the lowest documented buckle temperature.

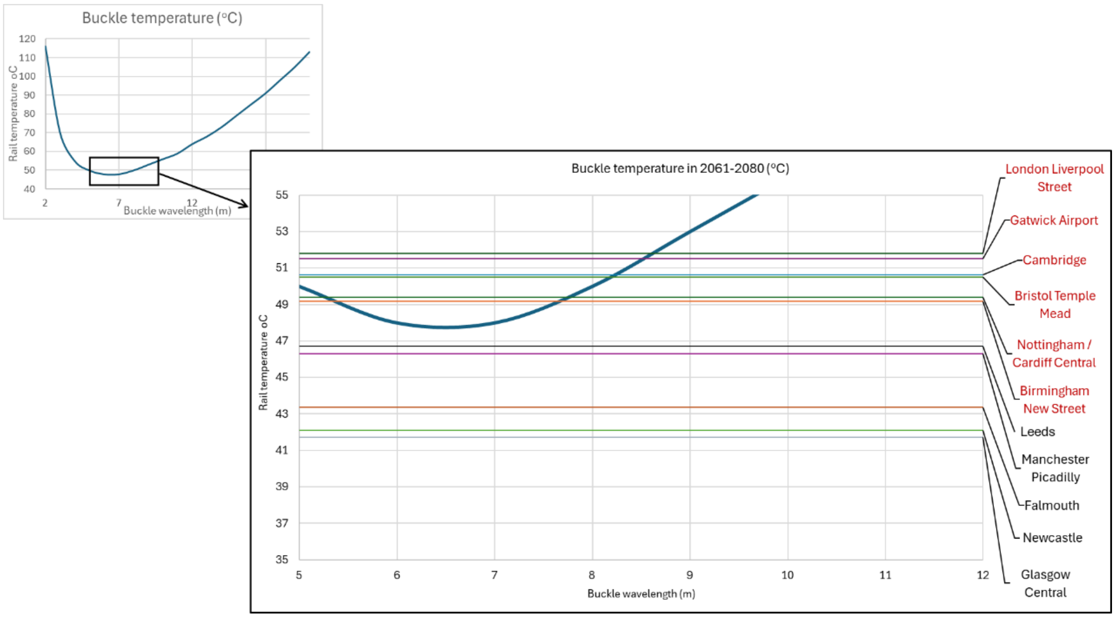


Figure 4. The maximum air temperature surpasses the buckling threshold limit according to numerous samples in 2061-2080.

Figure 4 shows that several rails may have undergone the buckling phenomena. Figure 5.5 illustrates the significant rise in buckling recorded in seven regions, occurring within the temperature range of 49°C to 52°C. The figures exceed the maximum buckling temperature limit, established at below 48°C.

3.3 SWOT Analysis of Potential Rail Buckling Detection Technologies

Numerous technologies enabled by technical breakthroughs can be utilized to detect the rail buckling phenomenon. The most potential technologies that could be adapted are FBG, DIC, and WSN. SWOT Analysis is adapted for measuring the advantages and disadvantages of every technology. According to several studies, the SWOT analysis can be shown in the figure 5 below.

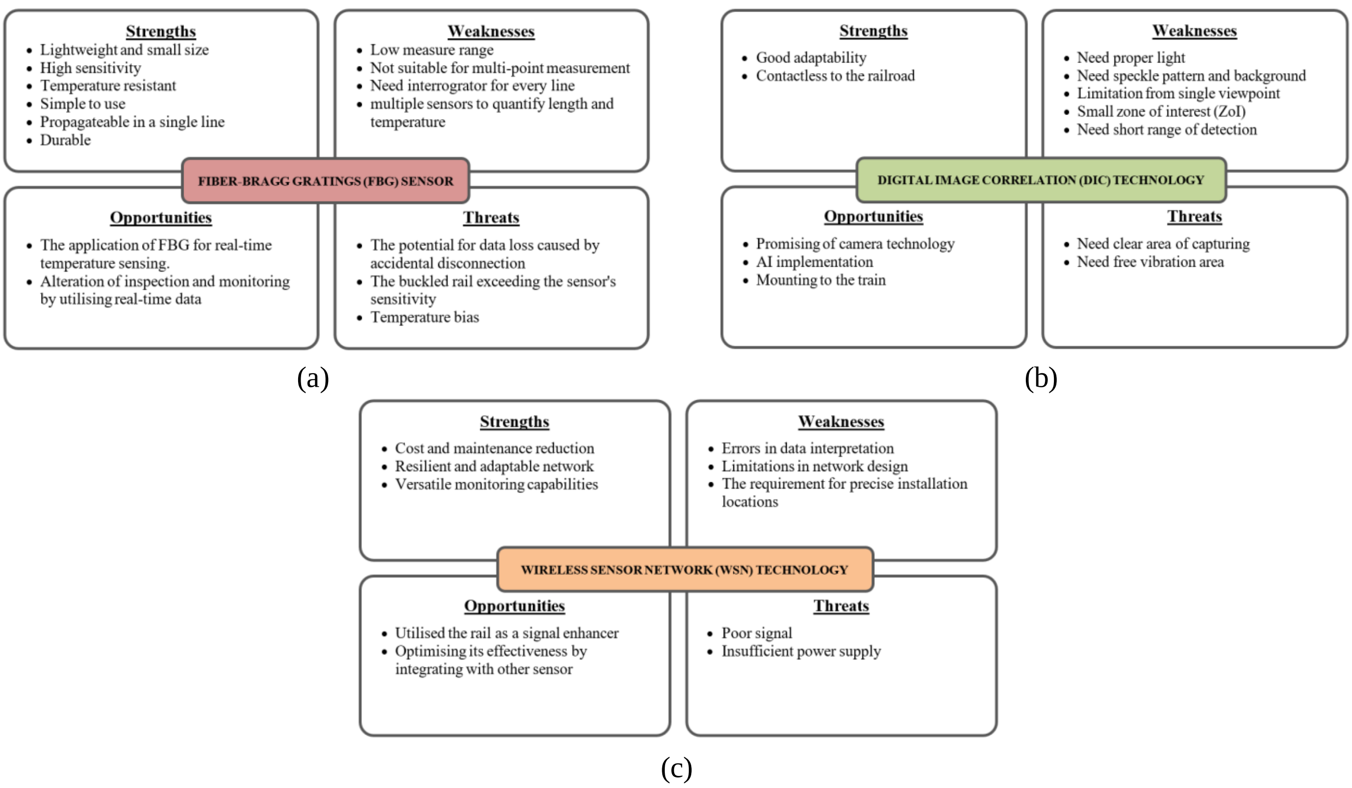


Figure 5. The SWOT analysis of (a) FBG, (b) DIC, and (c) WSN.

3.4 Multi-criteria Decision Analysis of Rail Buckling Technologies

Table 1. The comparisons of rail buckling detection technologies.

Parameters	Fibre Bragg Gratting	Digital Image Correlation	Wireless Sensor Network
Accuracy	High sensitivity (Xiong et al., 2019). Low Measure Length (Pereira et al., 2024).	High precision. Low area of interest.	Depend on sensor applied. Could be customized as the purposes.
Cost-Effectiveness	The effectiveness enhanced by the strong multiplexing capabilities (Catalano et al., 2014).	Need additional treatment (which incurs costs) (Meyer et al., 2021). Low cost-effetivenes for static monitoring.	High cost effectiveness (Bilodeau et al., 2010).
Complexity	Require multiple integrators for lengthy line (Pereira et al., 2024).	Need proper source of light (Knopf et al., 2021). Need Speckle pattern as the pretreatment (Meyer et al., 2021). Need additional background (Omondi et al., 2016).	Rely on signal and hard to implement in tunnel or restricted area.(Hodge et al., 2015;Hoult et al., 2009). Rely on battery or other power supplies (Hodge et al., 2015).
Durability	Compact Dimension (49-120mm) (Li et al., 2017). Can be utilised in tunnels (Xiong et al., 2019). Temperature Resistant (Xiong et al., 2019). Exelence resistant (Chan et al., 2021; Pereira et al., 2024 ;Tam et al., 2005).	Vibrations may have an impact on the process of collecting data (Meyer et al., 2021) Need extra maintenance considering camera is a sensitive instrument	Reliable transmission (Zhao et al., 2022). Reducing the system failure (Bilodeau et al., 2010).
Power Consumption	Low energy consumption	The power consumption is relatively large when using two cameras and other instruments continuously.	Energy Efficiency (Shin and Park, 2007).
Monitoring and data collecting	Need complex demolulation for real time monitoring (Xiong et al., 2019)	Only detecting from a sight view (Omondi et al., 2016) Need close proximity to the object	Flexible adaptation (static / dynamic monitoring) (Hodge et al., 2015). Flexible data collection (periodic / real-time monitoring) (Hodge et al., 2015). Worldwide accessibility (Zhao et al., 2022). Possibility of misinterpretation data (Hodge et al., 2015).
Adaptability	Multiplex numerous sensors up to 100 FBGs (Tam et al., 2005) Also could sensing the temperature altogether (Wang et al., 2021) Could supporting intelligent railway monitoring (Chan et al., 2021)	High versality (Gehri et al., 2020) Contactless (Sabato and Niezrecki, 2017) Rely on the camera specification (Sabato and Niezrecki, 2017) AI integration adaptation (Kumar et al., 2023)	Interconnecting sequences of sensors (Bilodeau et al., 2010; Hodge et al., 2015). Self organization (Shin and Park, 2007). Scalability (Shin and Park, 2007).

The best decision could be selected by using the Multi Criteria Decision Analysis (MCDA) to generate the analysis. One of the most popular MCDA theory is the Analytic Hierarchy Process (AHP). Several factors are required to develop an effective system for rail buckling detection. These metrics could be established as guidelines for selecting the most appropriate technologies for rail buckling detection in UK railway systems. Saaty (1990) recommends that the consistency ratio (CR) should be 10% or lower to optimize results, requiring recalculation if the CR exceeds 0.1. The weighting score can be derived by comparing one criterion against another. Saaty (2008) presents a 1-9 scale for analysis, where 1 denotes equal relevance, 1/9 signifies minimal importance, and 9 indicates significant importance of criteria. After calculating the weight factor for every criteria, the consistency ratio is 0.027. The result could be shown in the Figure 6 below.

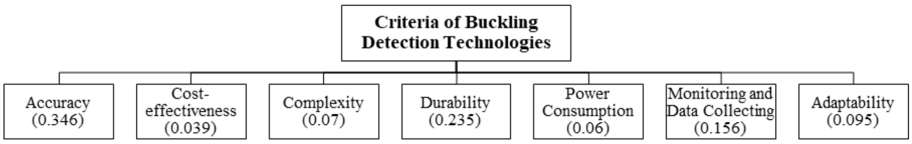


Figure 6. The weight of criteria.

By using the weighting factor of every criteria, the pairwise comparison between the technology options could be obtained. The FBG sensor is identified as the most suitable technology for integration into the UK train network, with a value of 0.435. The WSN is assigned a secondary priority, with a value of 0.367. The minimum score is achieved by employing the DIC, which accounted for 0.198. FBG and WSN are particularly well-suited for integration into the UK train system as rail buckling detectors. According to the MCDA result, the FBG is known as the most precise system that may be adapted to include several sensors, leading to improved efficiency. Following a thorough evaluation, it has been concluded that the optimal detection method for adoption in the UK railway system is a combination of Wireless Sensor Networks and FBG technology. Moreover, WSN can be effortlessly integrated with additional sensors, such as strain gauges, accelerometers or LVDTs, to address various detection needs, including structural health monitoring (SHM) of tunnels, railroads, and bridges. Moreover, the detection duration can be modified to improve efficiency, considering that the buckling process is not instantaneous. Consequently, periodic monitoring may provide a more beneficial alternative.

4 CONCLUSION

Rail buckling poses a significant risk to UK railway lines in the next decades. The maximum rail temperature will rise along with the anticipated maximum air temperature. The highest temperature in the UK regions during summer shows a consistent and gradual increase from 2030 to 2070. The UK stations also observed a rise in the highest recorded air temperature between 2021 and 2080. The temperature rise was mainly concentrated in the southern region of the UK, with an almost 10^{o}C increase.The largest surge takes place in the southern region of the UK. In order to surpass the point at which buckling occurs and pose a risk to the safety of train operations in the UK regions. Hence, it is imperative to employ sensing technology that is appropriate and efficient for implementation on UK railways. Rail buckling can be prevented through the implementation of mitigation measures. Inspection and monitoring are effective methods for implementing this mitigation. Nevertheless, the utilisation of sensor technology has the potential to substitute inspection efforts and enhance efficacy through more rigorous monitoring. This study specifically examines three technologies with significant potential for implementation in the United Kingdom: Fibre Bragg Grating (FBG), Digital Image Correlation (DIC), and Wireless Sensor Networks (WSN). The appropriate utilisation of sensor technology on tracks in the UK region involves the implementation of a combination of WSN along with strain gauges and FBG.

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