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Identifying Precursors to Track Buckling for Development of a Continuous Monitoring System Using Track Geometry Measurement Data

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Abstract

The East Japan Railway Company is committed to preventing track buckling incidents through track maintenance and to ensure safe and punctual transportation. To prevent such incidents, the maintenance department conducts inspection of continuous welded rail (i.e., inspection to estimate rail axial force based on rail-creep measured relative to fixed points along both sides of the track) and performs restressing of continuous welded rail as necessary. The aim of this maintenance work is to provide appropriate tension to the rails, thereby preventing track buckling in periods of extreme heat and rail breakage that may occur in the colder winter months.

However, these inspections alone have not been sufficient to eliminate the occurrence of track buckling within our jurisdiction. Consequently, this study was to investigate the practicality of monitored alignment data to identify precursors to track buckling as a supplementary measure.

Analysis of alignment data showed trends of increasing irregularities with rising seasonal temperatures, enabling accident prevention before track buckling occurs. A business intelligence (BI) tool based on these findings has been implemented in our service area, and this paper describes its role in the overall management system.

Keywords: track buckling, rail stress, monitoring, alignment, restressing, continuous welded rail, business intelligence tool

1. Introduction

The railway industry in Japan is facing a complex set of challenges, including a labor shortage driven by the shrinking working-age population, an aging infrastructure, and the constant need to maintain safety. In track maintenance, decisions on whether repairs are required and how to prioritize work are made after reviewing vast amounts of inspection data, but ultimately depend on the engineer's final judgment, meaning that the current management approach relies heavily on experience and intuition. It will be essential to establish next-generation management of railway assets apart from such an experience-dependent decision-making process, with a shift toward making investments and maintenance-related decisions in line with Condition-Based Maintenance (CBM).

The East Japan Railway Company (hereafter "the company") is also accelerating its transformation toward CBM as a means of maintaining safer and punctual transportation service. As track buckling incidents are a direct source of severe transportation disruptions, their prevention is among the company's highest priorities. Traditionally, the maintenance department has periodically conducted inspection and restressing of continuous-welded rail — readjusting rail tension where necessary — as a preventative measure to track buckling. However, due to factors such as increased occurrence of extreme heat spells in the summer due to climate change, periodic inspections as have been conventionally conducted are not able to fully address or eliminate issues of track buckling over the extended area of our jurisdiction.

Against this background, this study focuses on utilizing data collected at close intervals to detect alignment irregularities, obtained from a track geometry measurement system (Figure 1) developed by the company to supplement conventional Time-Based Maintenance (TBM). This paper presents the results of a study showing that it is possible to identify precursors to track buckling by capturing trends of increasing irregularities in alignment associated with rising ambient temperatures. This paper also introduces a case study of a BI tool developed as a core enterprise system to embed these findings into field-level decision-making, discussing a new management framework that does not solely rely on experience or intuition.

Figure 1: Track geometry measurement device.

2. Overview of the Track Geometry Measurement Device

The track geometry measurement device developed by the company is installed underboard of passenger train cars for short-interval measurements of day-to-day changes in track geometry. The measurement interval ranges from approximately once per day to once every seven days, while on major lines measurements are conducted as frequently as once per day. The point of this study in particular is to utilize data obtained from the device and investigate its potential to properly identify precursors to track buckling.

3. Characteristics of Track Buckling Incidents

Due to the fact that continuous-welded rail is constrained by sleepers over extensive sections, significant axial force is generated within rails as a result of changes in ambient temperatures. Particularly high compressive forces act on the rails during extreme spells of heat. Forces exceeding the lateral ballast resistance provided by the ballasted track trigger track buckling incidents, where rails bulge suddenly in a lateral direction. To prevent such incidents, the company strives to maintain safety through axial force management via continuous-welded rail (CWR) inspections – a form of TBM management – as well as track reinforcement such as ballast replacement and repairs to the rail-fastening system. However, maintaining perfect track geometry across all lines within the wide area of our jurisdiction is extremely difficult in practice. Thus, the complete elimination of track buckling remains an ongoing challenge.

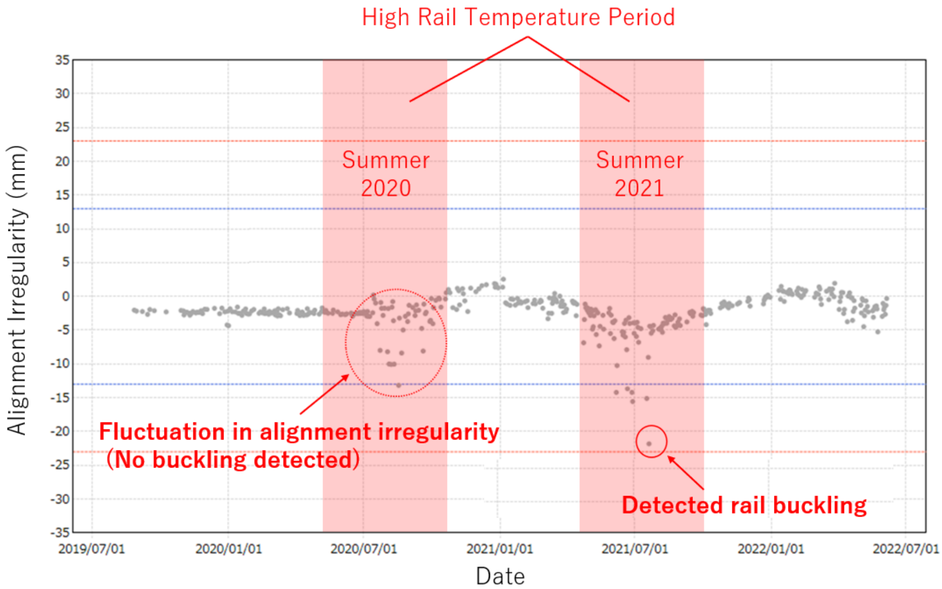

Figure 2: Locations of rapid increases in alignment irregularities under extreme heat

Therefore, this study focuses on the data of irregular alignment obtained from the track geometry measurement device as a means to monitor vast areas more efficiently. Figure 2 is a graph showing alignment irregularities at points where track buckling has occurred on our lines. Analysis of actual cases confirms that as excessive axial force is generated in the rail by rising ambient temperatures, and as it approaches the limit of the lateral ballast resistance force, a specific behavior occurs; namely, a gradual increase in alignment irregularity – precursive to the final buckling. In this paper, we identify this characteristic seasonal increase in displacement as a "precursor" and examine the effectiveness of an analytical method in preventing incidents.

3. Methodology

The period of analysis established for this study to identify precursors to track buckling was from January 2021 to May 2022, selected to include both periods of severe winter cold and of extreme heat, to verify the effect of annual rail temperature fluctuations on track geometry. In Japan, ambient temperatures typically rise significantly after May. Therefore, from the perspective of accident prevention, it is only necessary to evaluate the presence of precursors using data acquired beginning directly before this period. Accordingly, the analysis continued up to May to verify the validity of a practical predictive model. In the analytical graphs presented later, data up to September 2022 is also displayed to verify the progress and effectiveness of the measures implemented.

The threshold for extracting precursor locations was set at 5mm or higher. This value was established to grasp initial behavior leading to track buckling while excluding errors in measurement and other minor displacements not subject to maintenance. The specific extraction logic involved the calculation of the median, maximum, and minimum values of alignment irregularity during the period of analysis. Points satisfying either of the following conditional expressions were selected for detailed investigation.

$$|A_{max} - A_{med}| \geq 5mm \quad or \quad |A_{min} - A_{med}| \geq 5mm$$

wherein A_{max}, A_{min}, and A_{med} represent the respective maximum, minimum, and median values of the alignment irregularity during the period of analysis. This calculation allows for quantitative extraction, whether alignment irregularities resulting from sudden diversions from track geometry or gradual seasonal increases.

4. Analysis Results of Precursors to Track Buckling

Figure 3 shows the resulting spatial distribution from analysis of the alignment irregularity within the target section. The solid black line in Figure 3 represents the median value of alignment irregularity, and the yellow-shaded area represents the range of fluctuation from minimum to maximum values. The vertical axis denotes alignment irregularity in millimeters (mm), and the horizontal axis represents distance from origin in meters (m). This graph exemplifies that areas in yellow where alignment irregularity remains stable and unaffected by fluctuations in ambient temperature remain narrow, while wider areas show significant fluctuation.

However, the fluctuations in this spatial distribution include not only behavior related to ambient temperature but also changes in displacement associated with maintenance work, such as track leveling. Therefore, it is not possible to definitively identify a precursor to track buckling based on Figure 3 alone. Consequently, in this study, points where the fluctuation of irregularity exceeded the 5 mm threshold in the spatial distribution were selected for extraction. For these points, a time-series analysis, as shown in Figure 4, was conducted to determine whether the observed behavior was a definitive precursor.

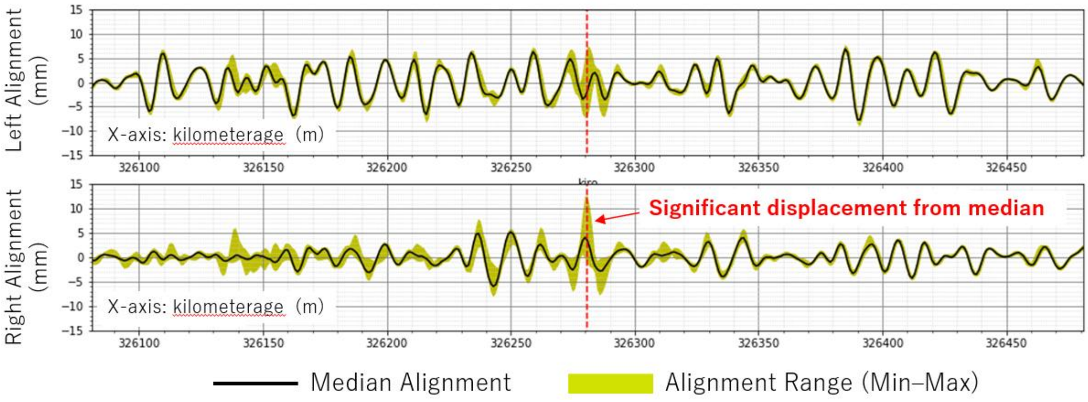

Figure 3: Graph of median values and fluctuation range of alignment irregularity

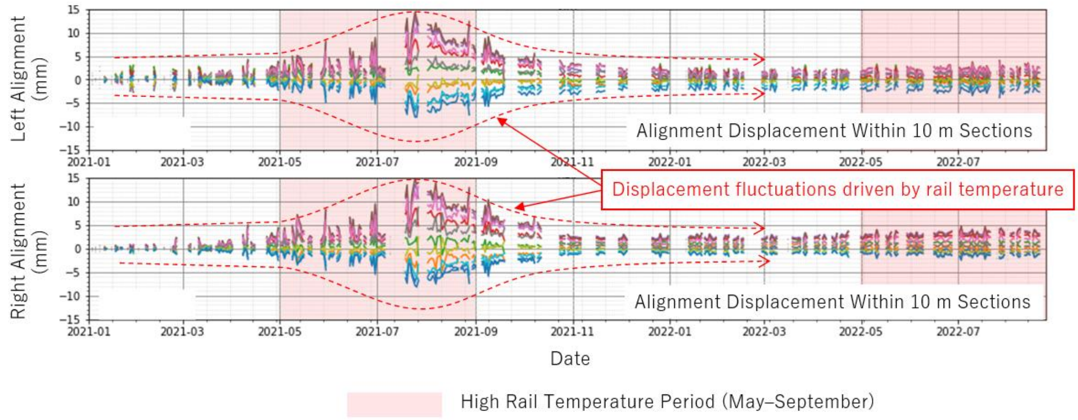

Figure 4: Time-series graph of precursors to track buckling.

Figure 4 shows a time-series transition of alignment irregularity at a point where significant fluctuations were observed. In this figure, the values are calculated as "relative displacement" to improve the visibility of track behavior linked to ambient temperature fluctuations based on the measurement values from the start of the analysis in January 2021. Each plot in the graph represents distribution of alignment irregularity within a 10-meter segment centered on the target point, i.e., 5 meters either way from the point of distance from origin.

Reviewing the time-series transition, it can be observed that displacement remained generally stable from January to April in 2021. During the period from April to October in 2021, corresponding to a period of temperature rise and extreme heat, a trend was confirmed in which alignment irregularity increased in synchronization with the rise in rail temperature. The increase in displacement became particularly pronounced after May, suggesting that the increase in axial force of rail due to ambient (rail) temperature has a direct impact on the progression of track irregularity.

From October 2021 through the colder winter months, behavior was confirmed in which irregularities in alignment contracted and regressed toward their baseline, linked to the drop in rail temperature following lowering ambient temperatures. Factors for such seasonal displacement fluctuations are inferred to be excessive axial force of rail occurring due to improper restressing of continuous-welded rail (incorrect neutral temperature), or insufficient lateral ballast resistance force. Maintenance work aimed at optimizing the rail's axial force and reinforcement of lateral ballast resistance force at such locations may help to suppress creeping displacement before track buckling occurs.

Investigation was actually conducted on-site, as shown in Figure 5, and the presence of deficient ballast shoulders and ballast breakdown suggested that lateral ballast resistance force had been physically reduced. Ballast exchange for track reinforcement work was thus implemented based on these results. Based on data review, Figure 4 shows that no fluctuations in alignment irregularity associated with the rise in rail temperature were observed following improvements, even as temperatures began to rise in May 2022 and periods of extreme heat continued into September, subsequently verifying effectiveness.

These results demonstrate that the use of monitor data to focus on the details of fluctuation of irregularities, it is possible to perform capture of precursors to track buckling quantitatively. Furthermore, we can conclude that appropriate track improvement work to points specifically identified as precursive would be extremely effective in preventing track buckling incidents.

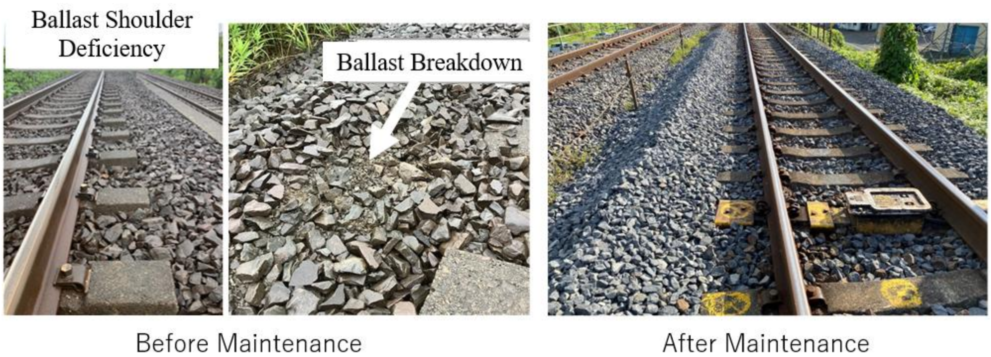

Figure 5: Status before and after maintenance work (ballast spreading)

7. Continuous Monitoring of Track Buckling Precursors via BI Tool

The methodology described in the previous section is used to estimate locations where track buckling is a concern before the onset of rising temperatures, therefore positioned as an approach in preventive maintenance.Even after the onset of warming temperatures, track condition may change with time, and also pre-warming rail temperature (rail axial force) may not have revealed any signs of buckling due to track resistance from the stabilizing effect of the lateral ballast.

To address these challenges, a business intelligence (BI) tool was developed based on this methodology to enable continuous monitoring of points precursive to track buckling. Figures 6 and 7 show parts of the tool's user interface (UI) screens.

©Mapbox, ©OpenStreetMap, [National Land Numerical Information (Railway Data)] Processed and created based on data from the Ministry of Land, Infrastructure, Transport and Tourism (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N02-v2_3.html)

Figure 6. Visualization of points with track buckling risk using GIS data

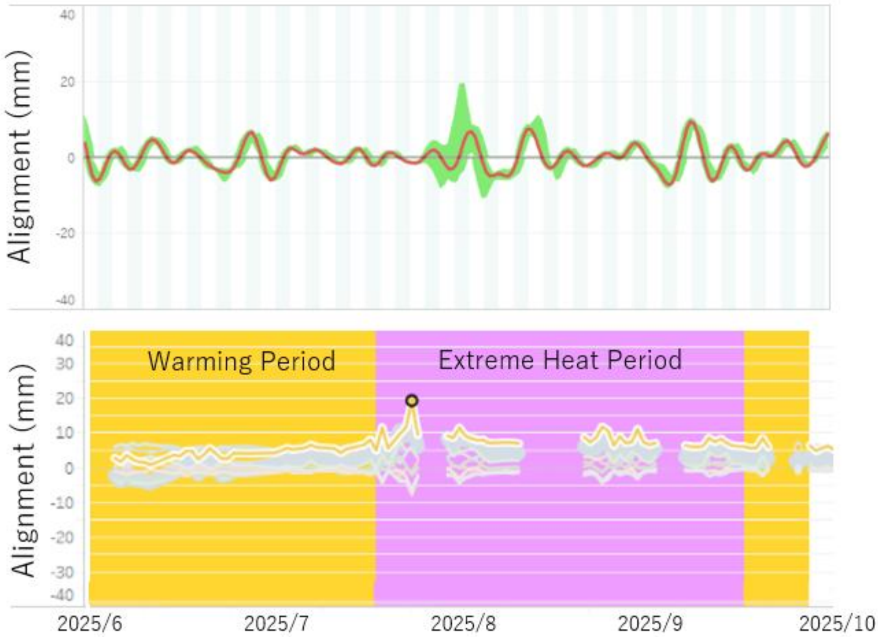

Figure 7. Fluctuation and time-series graphs of alignment irregularity

We will omit the details of Figure 7 as it overlaps with similar content of the previous section. In Figure 6, fluctuation in irregularity is classified into six levels of 5 mm increments and visualized on the GIS as risk levels. It should be noted that the risk levels shown in Figure 6 include the effects of maintenance work; therefore, it is necessary to verify whether or not a high-risk level is actually caused by a rise in rail temperature.

The flow is structured so that high-risk locations are first identified from a bird's-eye view using Figure 6, followed by a detailed status confirmation of those specific points as in Figure 7. The use of this tool has made it possible to efficiently capture and manage precursors to track buckling.

This methodology and the BI tool have been rolled out within the company. Although application is currently limited to line segments where the track geometry measurement device has been implemented, the management of track buckling has improved significantly compared to previous conventional methods. It can be concluded that this system greatly enhances safety and reliability in transportation.

8. Conclusion

This study confirmed that it is possible to identify precursors to track buckling by focusing on data of alignment irregularity obtained from the track geometry measurement device and capturing the gradual growth in displacement associated with rising rail temperature.

The methodology extracts points with a high risk of track buckling by performing analysis prior to seasonal warming and is positioned as a new approach in preventive maintenance. However, it is also known that track geometry can change with time, even after the onset of rising temperatures, and that potential points of risk may exist where precursors have not manifested themselves as irregularities in alignment, as lateral ballast resistance force remains dominant under conditions of lower rail temperature (axial force of rail), such as just before the summer season.

To address these challenges, a BI tool was developed and implemented to enable continuous monitoring at points precursive to track buckling. The tool’s GIS (Geographic Information System) screen allows for a bird's-eye view of "risk levels;" classified into six stages in 5 mm increments based on the range of fluctuation range of irregularity. This is followed by a close examination to determine whether or not the increase in displacement at a given location is caused by rising rail temperatures. By establishing a flow that combines a "global overview" via GIS with "individual detailed analysis" via time-series charts, it has become possible to efficiently and accurately extract and manage truly high-risk locations from among the vast volume of data.

This methodology and the BI tool are currently being rolled out across the company’s line segments where the track geometry measurement device has been implemented. Management of track buckling has improved significantly through the utilization of monitoring data, compared to previous conventional methods, greatly reinforcing safety and reliability in transportation. Moving forward, we aim to further refine the analytical algorithms and integrate data with other maintenance items from the perspective of asset management, striving for the advance of Condition-Based Maintenance (CBM) within the company.

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