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Article

The Influence of Seasonal Effects on Railway Vertical Track Modulus

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Abstract: Adequate vertical track support is essential for safe and efficient railway operations. Insufficient support leads to distorted track geometry, increased dynamic loads, component stress, poor ride quality, rolling stock damage, and derailment risks. Current inspection practices focus on assessing the condition of the track components and geometry, rather than the root causes of degradation. To improve this condition, this study presents the use of a methodology that utilizes an autonomous vertical track deflection measurement system mounted on a loaded rail car (36 tonnes/axle) to support track maintenance decisions in a heavy haul railroad located in southeast Brazil. The system continuously measured substructure stiffness along the railway line. Over one year, data were collected from over 8000 km of track. The study highlighted seasonal effects on track degradation over time, identifying areas with significant deflections and high deflection rates, which contribute to issues such as differential settlement and reduced lifespan of track components. Additionally, the study revealed seasonal effects, with deflections peaking during wet weather and decreasing during dry cycles. A method to classify weak track areas was developed, facilitating monitoring and enabling more effective maintenance planning, contributing to the reduction of overall track maintenance costs and enhancing safety and operational efficiency.

Keywords: seasonal effects on railway; track degradation; track modulus; railway maintenance

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1. Introduction

Mounting pressure to enhance axle loads and reduce maintenance costs will see more railway operators, globally, significantly investing in research as well as technologies that support the evolution to a strong and durable track structure. Safety and cost have always been the primary concerns. The quest for safe and cost-effective railway transportation has driven improvements in materials and processes that have provided a track structure with increased reliability and durability.

The influence of track substructure, and its importance to overall track performance, is a widely discussed topic for railways that use ballast and subballast as interface layers between the sleepers and the subgrade. According to Selig and Waters [1], a conventional railway track construction comprises both superstructure and substructure components. The superstructure includes the rails, fastening systems, and sleepers, whereas the substructure is made up of the ballast and subballast, subgrade, and drainage arrangements. Drainage, in particular, has high importance on track performance due to the influence of water on geotechnical components [1,2].

Good track support is characterized by strong resistance of the ballast, subballast, and subgrade layers to plastic deformation and by the elastic deflection under rolling load being small and reasonably uniform along the track. Support stiffness that is variable along the track causes deformation and damage with each cycle of stress and strain for virtually every track component [2]. Vertical stiffness is a fundamental performance parameter for railway tracks, essential for advances in railway engineering [1–7].

State-of-the-art methods for measuring track stiffness include both traditional standstill measurements and continuous measurement techniques. The efficient and accurate measurement of track stiffness is of significant theoretical and practical importance. The continuous measurement methods for vertical stiffness have advanced significantly in recent years and have gained prominence for assessing the support conditions of the track, as they reflect the supporting performance over a large extent of the track with agility [7]. Among the most relevant continuous measurement concepts, the method of static stiffness under dynamic load through measuring the vertical rail displacement using a laser/camera measurement system stands out. This method was initially created at the University of Nebraska at Lincoln in collaboration with the Federal Railroad Administration (FRA) [7,8]. Currently, this method is capable of evaluations at speeds of up to 100 km/h, having improved in accuracy due to enhanced displacement measurement. This was the method chosen for this study, having also been successfully used in other studies on heavy haul railways previously [9,10].

Although it has not yet been applied in high-speed rail, this method is widely applicable to freight railways, especially heavy haul railways, with operational speeds between 50 and 80 km/h. These railways are responsible for a significant portion of global freight movement, particularly in the USA, Canada, Australia, China, Brazil, South Africa, India, Sweden, Norway, and Russia. Due to heavy loads, exceeding 25 tonnes per axle, and high annual traffic density, heavy haul railways experience high rates of track degradation. Therefore, they require a supplementary evaluation method that goes beyond geometric or visual assessments of track condition.

The application of this methodology to passenger railways is also relevant, as support instability is one of the most significant causes of degradation in these railways [1,2]. Although there are limitations on the testing speed, this method aids in identifying zones with higher maintenance recurrence for track components. Examples of such issues include excessive geometric corrections, frequent replacement of rails, fastenings, and sleepers, as well as unexpected rail fractures that cause traffic interruptions or even accidents. In summary, investigating the root cause of failures enables a predictive maintenance plan, rather than merely correcting events after they occur.

Track geometry recording systems are used by railroads to make continuous measurements of the track geometry parameters in order to monitor the existing functional condition of the track and to minimize the impact of rough track. Comparison of the measured geometry parameters to allowable track safety standards determines the need for maintenance intervention or slow order [11,12]. These inspections evaluate the condition of the track components, rather than the root cause of the degradation impacting the track component condition. Although it is the most required and the most common way to identify problems in track conditions that directly impact geometry, it is difficult to determine the underlying cause(s). This is because geometry defects are a symptom rather than a source of the recorded deficiency.

For this reason, the main purpose of this research is to use an emerging technology that records continuous vertical track deflection measurements to map the stiffness condition over long distances and quantify the influence of substructure on track performance. This includes the generation of geometry irregularities and deterioration of track condition. Due to climate change over recent years, there has been an increase in rainfall indices, as well as recurring substructure problems on the MRS Logistics lines. Despite constant maintenance, the number of mud spots has progressively increased each year, along with rail fatigue at these locations, leading to more frequent speed restrictions and increased fuel consumption.

This research presents the results of track vertical deflection measurements and track modulus evaluation over more than 8.000 km of track, captured every 0.30 m, to evaluate the seasonal effects and degradation of the track over time. The data come from four high-traffic subdivisions and map the stiffness condition along the track. The data included in this study consist of one year of measurements. This research is a part of extensive project in which the two main objectives are to focus on the root cause of the problem to guide the maintenance plan and assess the effectiveness of remediation methods used to enhance the performance of track lines operated by MRS Logistics railroad.

Even though it was not designed for heavy haul operations, with most of its lines constructed over 100 years ago and a route characterized by sharp curves that connect the mountainous region to the ports of southeastern Brazil, MRS stands out for its good operational and safety indices, being recognized as one of the leading heavy haul railways.

Substructure Considerations

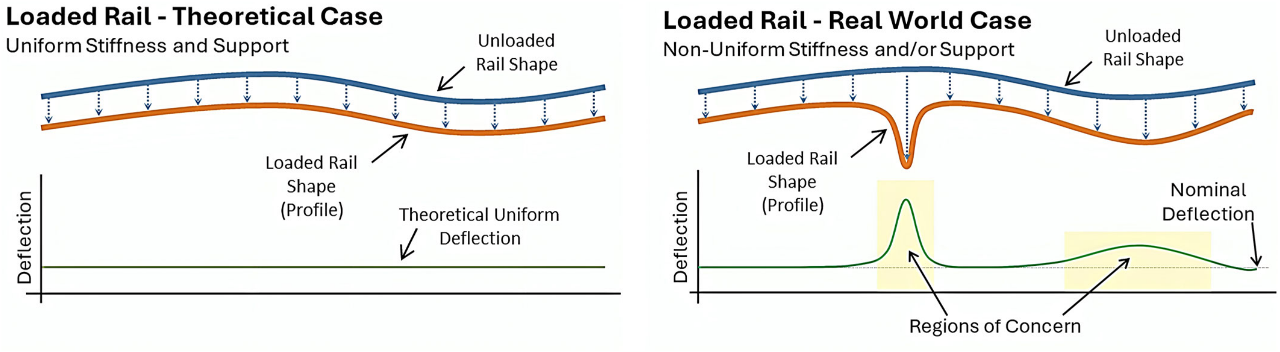
In an evolving industry, track engineers must identify and address key drivers of substructure issues with effective solutions, rather than relying on routine maintenance. They face the challenge of limited maintenance windows, due to high traffic, which risks the quality of repairs due to inadequate time for comprehensive action. Building on the importance of timely and root cause-focused repairs amid limited maintenance opportunities, it is crucial to understand that the substructure plays a foundational role in track performance. Many substructure problems are geotechnically related, often affected by water. Thus, ensuring the substructure's integrity is paramount, as it directly influences the track's overall functionality, the efficacy of its components, and the safety and reliability of passing vehicles. This underscores the need for precise, effective substructure maintenance strategies.

After substructure problems manifest on the track surface, the track condition tends to decrease rapidly as each passing wheel load deforms the track more. The critical stage where track support becomes increasingly more problematic is when the ballast–sleeper interface is affected, and in particular, when a sleeper cavity develops. Most fouling material is generated due to ballast deterioration, which occurs near the track surface where the loads are highest. Fine particles from the subgrade can also migrate upwards into the ballast layer, especially if the subgrade is not adequately sealed or if water flow through the track structure is not properly managed. Poor drainage of fouled ballast often traps water in the sleeper cavity creating a mud spot, as presented in Figure 1.

Figure 1. Example of severe mud spot.

The unsupported or "hanging" sleeper is a particular problem for track substructure performance because the lack of vertical support produces a dynamic impact component under wheel loading. This results from the rapid vertical movement of the sleeper that impacts the ballast surface. The low vertical track support, as evidenced in a mud spot zone, can generate premature failure of track components.

The condition of the track substructure is typically assessed using the track modulus, a single parameter that represents the combined effects of all track substructure components beneath the rail [3]. The track modulus is the coefficient of proportionality between the rail deflection and the vertical contact pressure between the rail base and track foundation [3]. In other words, the track modulus is the supporting force per unit length of rail per unit rail deflection [1]. Both low track modulus and significant variations in track modulus are undesirable [4,5]. Additionally, significant and abrupt variations in track modulus, such as those frequently observed near bridges, crossings, tunnels and joints increase the dynamic load [6,13] and affect the life of railway system components (track and rolling stock). Figure 2 presents the representation of track theorical deflection.



(**a**) (**b**)

Figure 2. (**a**) Theoretical track deflection; (**b**) real deflection (courtesy of Harsco Rail).

Track modulus is often used as a measure of track quality. In general, a higher track modulus is believed to represent a better track foundation. However, an excessively high modulus can result in fatigue, fractures, and excessive vibrations [1]. Hay [14] recommended a minimum value of 14 MPa for a track modulus to ensure satisfactory performance of railway track, which is the same value suggested by American Railway Engineering and Maintenance of Way Association manual [15]. Raymond [16] suggested that the optimum track modulus is over 34 MPa and under 69 MPa. Ahlf [17] suggested a track modulus value under 14 MPa was poor, a track with a track modulus above 28 MPa was good and values in-between this range ($14 < u < 28$ MPa) was average. According to Roghani [9], a relatively high track modulus is beneficial as it offers adequate track resistance to applied loads and results in reduced track deflection and decreased track deterioration. Heelis et al. [18] suggest that track with a consistent and high track modulus will permit increased train speeds, thereby enhancing both performance and revenue.

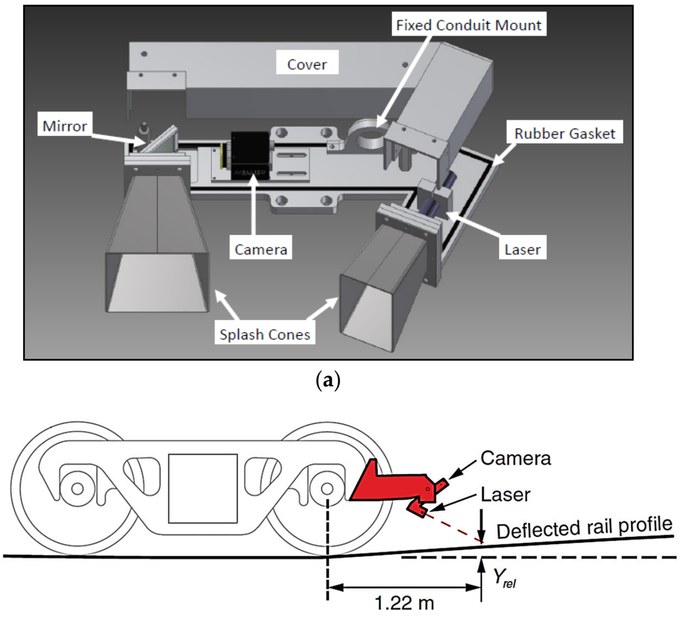
2. Methodology

2.1. Stiffness Investigation on MRS Logistics Network

Located in the southeastern region of Brazil and covering the most industrialized area, MRS Logistics is a privately owned company operating one of the most important railroads in the country. With over 20,000 wagons and 700 locomotives, the company carried 200 MGT last year, with iron ore representing more than 70% of this volume. The company is divided into four sections with a total of approximately 1.700 km of track. Most of the high traffic volume is carried on the 900 km, 1600 mm gage section, with 136 RE rails and wooden sleepers. The company is currently undergoing an increase in axle load from 32.5 tonnes to 36 tonnes while doubling consist lengths to 272 wagons and also increasing speed.

In order to improve railroad safety and prioritize maintenance, MRS invested in inspection technologies such as track geometry measurement systems, ultrasonic test cars, rail inspection vehicles, and wayside systems; however, it was also necessary to evaluate the substructure condition. The technology for measuring vertical track deflection used in this research allows railways to monitor the vertical track support and perform intervening maintenance to reduce adverse damaging effects. As previously mentioned, the MRail vertical deflection measurement method employed in this research for measuring vertical track modulus was initially created at the University of Nebraska at Lincoln in collaboration with FRA [7,8]. Currently, the MRail system is provided by Harsco Rail and it measures vertical track deflection, making use of in-service vehicles. MRail Vertical Track Deflection Technology is already in service and has been tested on Class 1 railroads in North America. The system collects data autonomously and continuously whenever the vehicle is in operation.

The MRail system employs a laser camera sensor head that casts a laser line across the rail head and translates its position in the camera's field of view into vertical deflection (YRel) (see Figure 3). The camera takes pictures at a frequency of 90 frames per second. Track deflection measurements from this system are referred to as YRel, because they reflect the relative vertical deflection of the track between where it contacts the wheel and a distance of 1.22 m from the nearest wheel of the loaded truck [9]. The calculation of YRel assumes an unloaded condition and the system is calibrated before use according to the operational characteristics. The distance of 1.22 m from the nearest wheel is a compromise between maximizing the distance from the wheel at which the measurement is taken and the increased vibration that occurs due to a longer and heavier beam [8,9]. The data are transmitted via cellular modem and is analyzed remotely, with timely turn-around of valuable track support information. Figure 3 shows the system configuration installed in a gondola car and the details of the laser/camera system.



(**a**)

(**b**)

Figure 3. (**a**) MRail system configuration; (**b**) system installed in a bogie frame [9].

The complete MRail system consists of a pair of laser/camera sensor heads, one installed on either side of the car, allowing for measurement of both rails. The MRail system is autonomous and collects and stores track deflection data (and associated GPS coordinates) on board the instrumented car. The characteristics of the car used on MRS are detailed in Table 1.

Table 1. MRS ore car characteristics.

Car Weight (Tonnes)	Number of Axles	Wheel Diameter (mm)	Length over Couplers (mm)	Truck Spacing (mm)	Axle Spacing (mm)
144	4	914.4	10,490.2	6248.4	1828.8

The seasonal measurement campaigns were defined to cover the dry season, the "in-between" or transitional season, and the wet season of the region. The breakdown of data collection campaigns was as followed:

- Dry season—July 2017
- "In-between" season—September to October 2017
    - Inspections occurring during the transition from dry to wet seasons
- Wet season—November 2017 to February 2018
- Dry season—July 2018

Data were gathered using a system in which the instrumented ore car operated within a dedicated train consist across ten specified cycles. Each cycle encompassed a complete loop from the iron ore mining areas to the ports. To compensate for potential data capture gaps inherent to autonomous systems, the system conducted multiple runs over the route during each measurement campaign (season).

System calibration is crucial for achieving accurate data with the MRail system, which converts pixel values to YRel. Calibration should be performed during initial installation, post-maintenance, after significant periods of non-use, between critical testing periods, and annually. The calibration process involves positioning the MRail-equipped car on a stiff support, such as a machine shop, where YRel measurements should be near zero. The laser arc position in the camera's field of view is verified and adjusted. A special calibration plate with known step heights is used to determine the relationship between arc location and YRel. This relationship is tested by moving the MRail car over the shop floor and processing the data, ensuring YRel values remain consistent with zero.

2.2. Determining Track Modulus through MRail Data Analysis

MRail measures relative deflection of the top of rail under moving load. As such, it offers the ability to estimate track modulus of the underlying substructure. Track modulus can be defined as the linear elastic support stiffness for a beam (rail) continuously supported by an elastic foundation (BOEF). BOEF theory has several assumptions and shortfalls; however, BOEF remains the predominant theory used in track component design and stress analysis [19]. Figure 4 below shows a typical BOEF model.

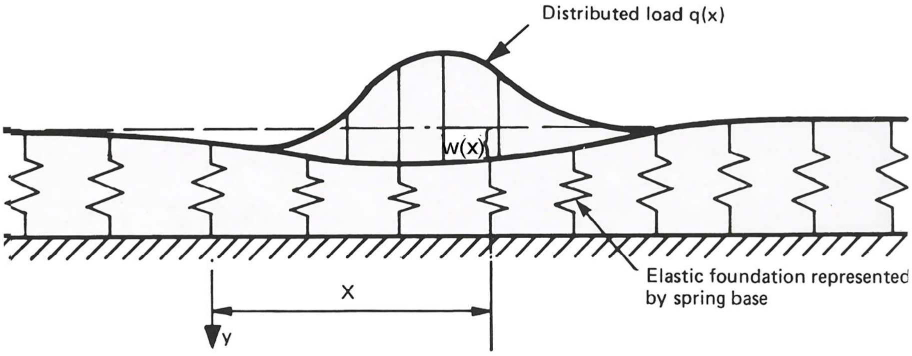


Figure 4. Beam on elastic foundation (BOEF) model.

The defining differential equation and solution for deflection for a standard BOEF model under a point load (single wheel) is shown according to the equation below:

$$\begin{gathered} \mathrm{EI}\frac{d^4w(x)}{dx^4} + kw(x) = q(x) \\ w(x) = \frac{P\beta}{2k}e^{-\beta|x|}[\cos(\beta|x|) + \sin(\beta|x|)] \\ \beta = \sqrt[4]{\frac{k}{4\mathrm{EI}}} \end{gathered} \quad (1)$$

where w(x) = rail deflection at location x; P = wheel load; k = track modulus or stiffness; E = rail modulus of elasticity; I = rail moment of inertia.

To better understand the nominal deflection values, this solution can be applied for multiple wheels using linear superposition and summing solutions. This is required when analyzing the MRail data as adjacent wheels influence overall deflection and resulting YRel results. When considering the solution algorithm above (Equation (1)) for multiple wheels, 136 RE rail, and a uniform track modulus of 24 MPa, a typical deflection plot for uniform track modulus can be created (Figure 5). Note that the individual wheel deflections of each axle of the instrumented wheel bogie are summed for the overall track deflection.

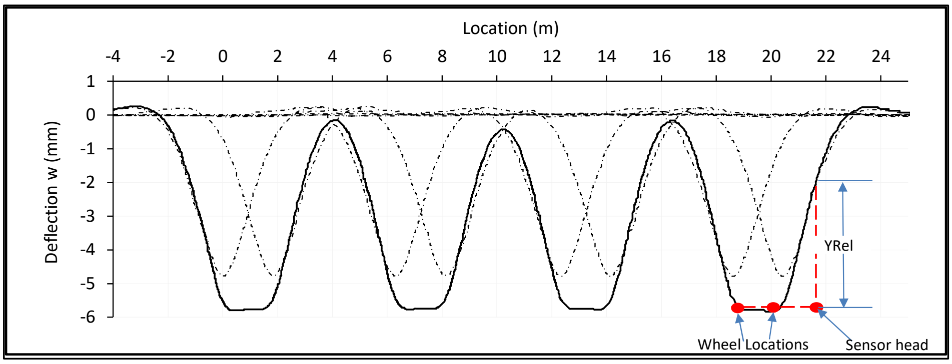


Figure 5. BOEF deflection of instrumented MRS wagon bogie and location of YRel measurement.

From Figure 5, it can be seen that a maximum rail deflection of 5.8 mm will occur between the axles of the instrumented bogie (near but not directly under the wheel). The maximum deflection will be directly related to the track modulus, or support stiffness. Figure 5 also shows the YRel measurement based on the laser line location cast by the MRail system sensor head. The dashed red line represents the YRel measurement, which in this case is 3.8 mm.

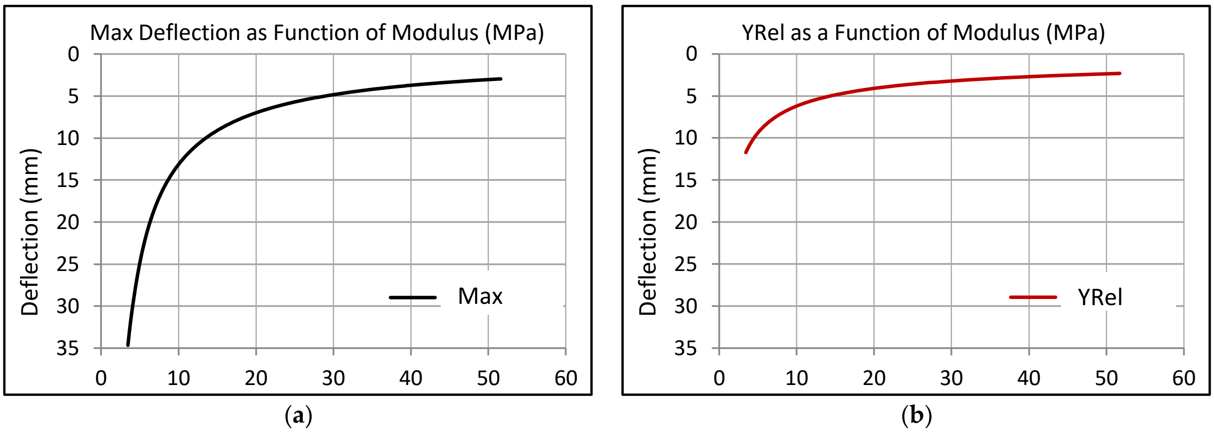
As shown in Figure 5, the red lines depict the MRail system and resulting YRel measurement from the measurement consist. That figure shows the deflection “plot” for a time slice of the train on the track (at a specific location), i.e., how the rail would deflect along the track’s longitudinal axis from the adjacent wheels of two cars. As the train moves down the track, this deflection “plot” moves as well (and may vary as a function of support stiffness variations), and the YRel measurement captured for each point along the track is the peak deflection at that point in track. The point captured by the MRail system for each time slice (approximately 30.5 cm of train travel) defines the deflection “map”, or maximum value at that time slice and corresponding location on the track. Thus, for uniform support stiffness, the applied load, and constant rail section, the resulting deflection “map” (measured YRel at each point along the track) would be a constant value.

Figure 6 shows the variation of expected maximum rail deflection as a function of track modulus. This figure shows the extreme deflection conditions that can exist for softer tracks. It is important to note that due to the extent of the deflection (influence away from the wheel), the measurement that is captured by MRail is not exactly the total deflection, but it is related to the deflection. Considering variations in track modulus, Figure 6 also shows expected YRel results (as a function of track modulus) for uniform track stiffness. Note that YRel values of 10.2 mm on soft track correspond to actual maximum track deflection values in excess of 31.8 mm.

Note that analysis for Figure 6 considers the deflection of the rail under the moving instrumented ore car weighing 144 tonnes operating at an average collection speed of 60 kph and for 136 RE rail section. These characteristics corresponded to the majority of the conditions evaluated in the MRS network. Using the information in Figure 6b, it is possible to develop an equation for estimating modulus (k) from YRel:

$$k = 198.06\text{YRel}^{-1.642} \tag{2}$$

Note that this equation is in metric units, where YRel is in millimeters and k is MPa.



(**a**) (**b**)

Figure 6. Deflections versus track modulus (**a**) maximum; (**b**) relative YRel.

To estimate the track modulus from deflection map, it is recommended that the YRel data be evaluated over a length of track (approximately 5 to 50 m). Thus, the YRel data should be smoothed using a low-pass filter prior to assessing track modulus. It is important to note that negative YRel values must be ignored. Also, dynamic impact loads resulting in spikes in YRel (and resulting low modulus values) must be ignored. These issues are associated with significant local changes in modulus, and this level of detail is currently unavailable. The variations that can arise during normal modes of testing are a function of the change in support stiffness, i.e., the track is not being uniformly supported, variations in the applied dynamic vertical loading, and/or changes in the rail section (including reduced section due to rail wear). This will result in stretches of track that are fairly uniform with spikes showing softer sections of track.

In reality, the support stiffness is not constant. In fact, the load may have a dynamic augment, and the rail section could change (or be worn). Thus, a typical YRel plot shows variation in the deflection "map" (as shown in Figure 7 below). Figure 7 also shows the track modulus analysis related to the same section of track evaluated for YRel. Note the variation in YRel, which clearly shows that the support stiffness is not uniform (and in fact the load and rail section properties may vary).

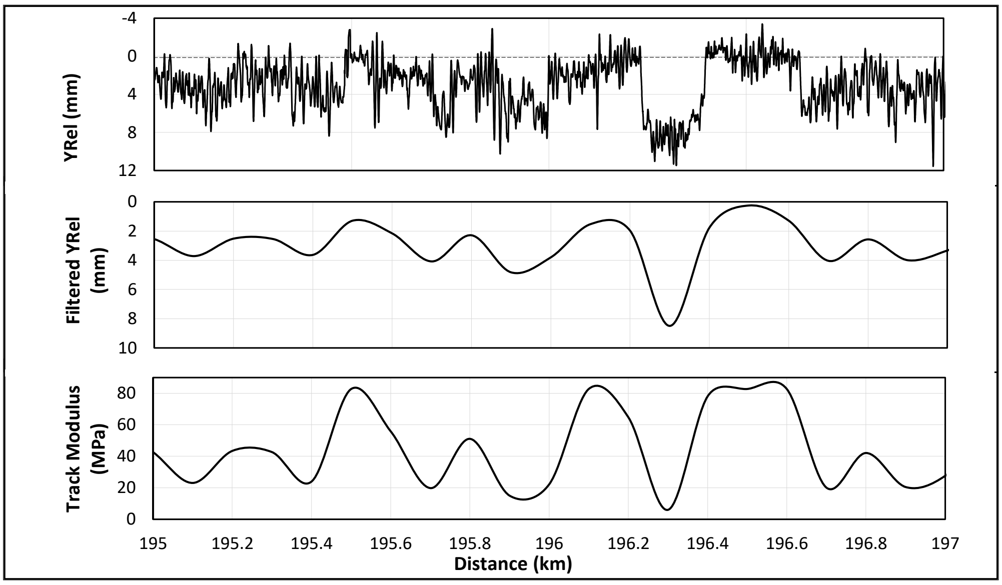


Figure 7. Track modulus analysis for 2 km of track.

Note that the representation of track modulus used was calculated by Equation (2), and the relationship was the same presented in Figure 6.

3. Results

3.1. Analysis of Seasonal Effects on Vertical Track Deflection

This section presents findings from the analysis conducted over a one-year period, spanning July 2017 to July 2018 for the entire track, focusing on the inspection and data gathering activities. Specifically, Figure 8 illustrates the average track modulus values, depicted graphically for each observed cycle. These results are aligned with the methodology outlined in the preceding sections of the article, ensuring consistency in the data analysis process. This visualization aids in understanding the variability and trends in the track modulus values across different cycles, providing insights into the structural integrity and performance of the tracks under study.

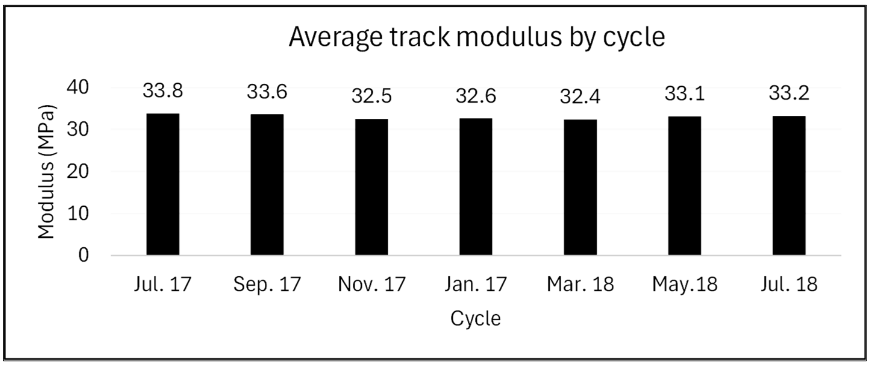
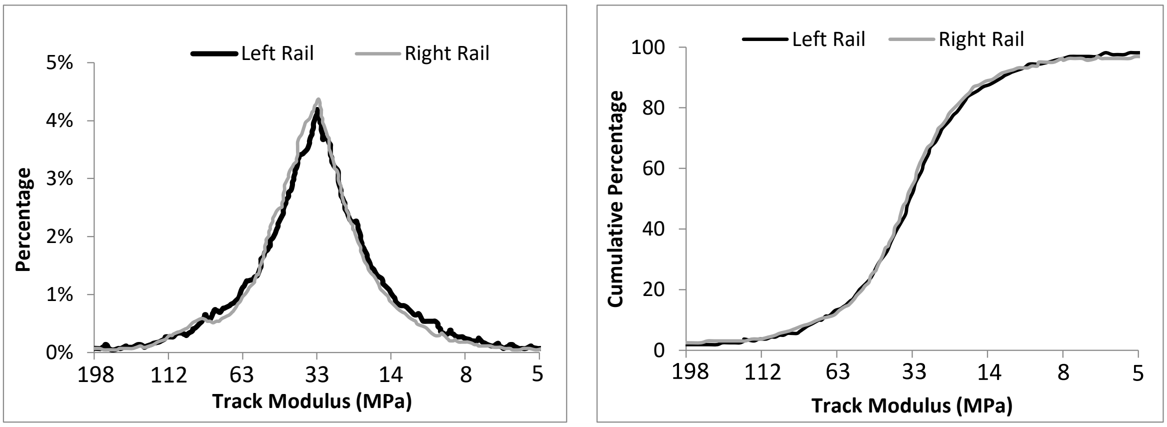


Figure 8. Average track modulus by cycle.

As can be seen from Figure 8, the overall average modulus is approximately 33 MPa. The distribution of track modulus measurements and its cumulative distribution for all of the measurements is shown below in Figure 9 for each rail side.



(**a**) (**b**)

Figure 9. (**a**) Track modulus distribution; (**b**) track modulus cumulative distribution.

It can be seen from Figure 9 that the distributions for each rail side are nearly identical as expected. YRel greater than 5.1 mm (corresponding to a modulus of 14 MPa or less) account for approximately 11% of the overall measurements. Thus, if YRel > 5.1 mm is considered soft track, then 11% of the track exhibits soft behavior. This percentage corresponds to almost 100 km of the line. Note that this is based on a 100 m average of YRel values. Local (single or multiple contiguous measurements) exceptions are handled separately.

One of the primary purposes of this study was to evaluate the seasonality effects on track support using deflection data. The track modulus distributions were developed individually for each of these cycles and are shown in Figure 10.

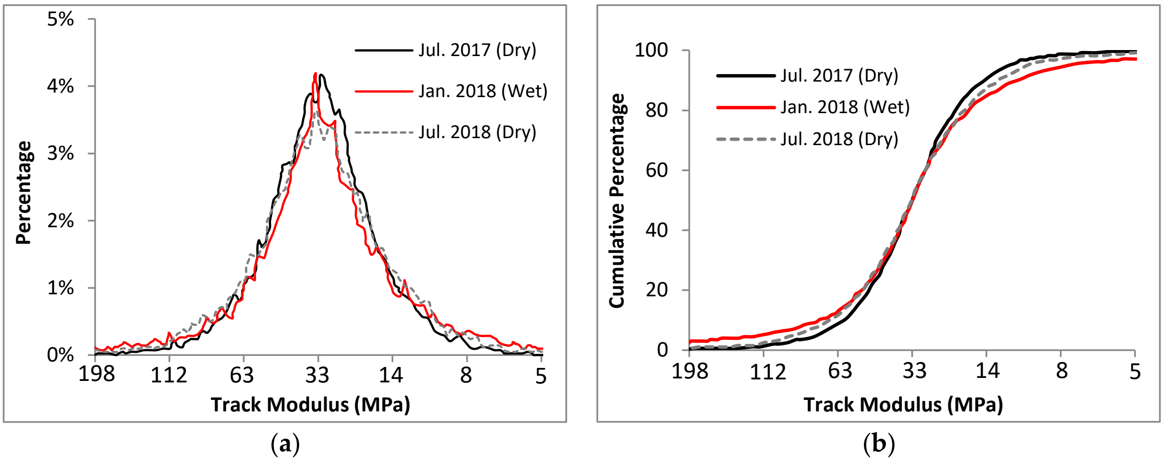


Figure 10. Season evaluation (**a**) modulus distribution; (**b**) modulus cumulative distribution.

Figure 10a showed (for the left rail) that the average track modulus value is nearly the same for each cycle, approximately 33 MPa, with a deflection of 3 mm. This is as expected, since seasonal effects will not affect the majority of the track, but only a subset. This is seen on the right side "tail" of the distribution, where cycle January 2018 (wet) extends further to the right. This indicates a certain percentage of modulus values larger than the dry cycles' values. The seasonal effects can be better visualized in a cumulative distribution plot as shown in Figure 10b. Figure 10b shows that for the wet season (cycle Jan. 2018) a larger percentage of higher modulus values exist.

Figure 11 below shows the seasonality effects on track support. It can be seen that all three cycles had approximately 50% of their values near the expected mean of 33 MPa. This indicates they behave the same on average. However, the wet season (January) clearly has more instances of higher YRel values than the dry season results. In particular, nearly 14% of the track has a YRel > 5 mm during the wet season, which correspond to track modulus values of 14 MPa, while only 8.2–11.7% of the track exceeds 5 mm during the dry season. In addition, 3.8% of the track exceeds 7 mm (8 MPa) during the wet season, while during the dry season only 0.5–1.5% of the track exceeds that limit. This macro analysis allows for a global understanding of the seasonal effects.

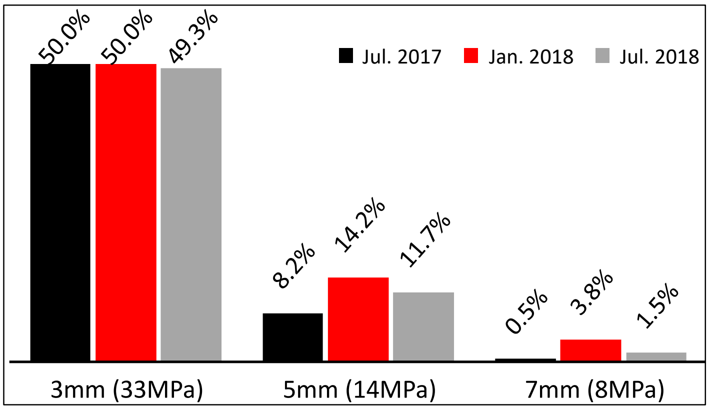


Figure 11. Percentage exceedance by season.

Based on the results presented in Figure 11, it is important to note that while there is some rebounding of the track in softer locations after the wet season, there is some permanent degradation. This is identified by the fact that 0.5% of the observations are considered very soft locations (8 MPa) for the first dry season run. These locations increase to 3.8% during the wet season and drop down to 1.5% during the next dry season. Thus, 1% have experienced degradation during the wet season.

In order to get a better understanding of the variability and seasonality effects, Figures 12 and 13 present the track modulus variations for 5 km of track from KP 41 to KP 45. The wet season clearly showed seasonality effects by the fact that track modulus decreases in wet weather. While track stiffness decreased during the wet season, data showed that track stiffness increased during the next dry cycle (gray line); see Figure 13.

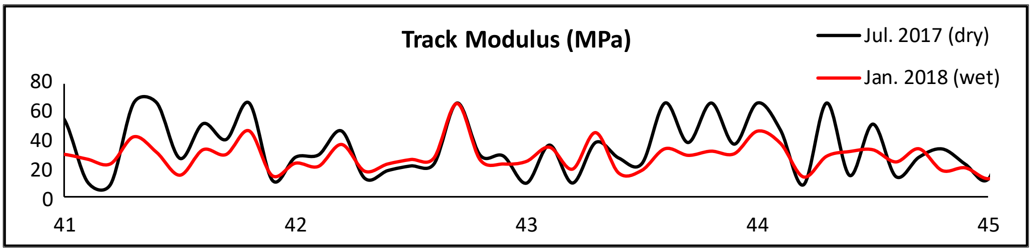


Figure 12. Seasonal variation between dry (Jul. 2017) and wet (Jan. 2018) measurements.

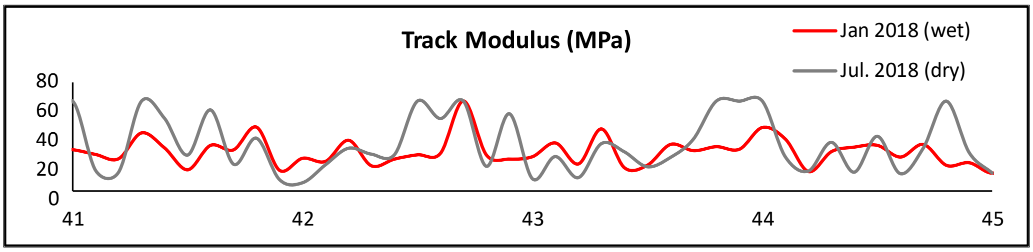


Figure 13. Seasonal variation between wet (Jan. 2018) and dry (Jul. 2018) measurements.

To estimate the track modulus values in Figures 12 and 13 above, the YRel data were evaluated over a length of 20 m and smoothed using a low-pass filter prior to assessing track modulus using Equation (2). The wet cycle clearly shows the variability, as well as the isolated locations of significant deviation. The pattern of variability is evident in that some locations show similar changes between runs, and softer and stiffer sections of track can easily be seen. In addition, the average track modulus for these three cycles, from km 41 to km 45, was 41.3 MPa in Jul. 2017 (dry), 30.8 MPa in Jan. 2018 (wet), and 39.8 MPa in the next dry cycle (Jul. 2018).

The seasonal effects could also be analyzed by the track geometry defect evaluation during a year before and a year after the stiffness campaigns. The geometry measurements utilized in this analysis comprised gage, alignment, and surface parameters including profile, crosslevel, and warp. A track geometry defect exists when the measured values of track geometry exceed threshold values set based on regulations, in this case FRA [20]. The threshold value considered a defect is determined by an assigned class of track, where the class is established to limit train speeds according to match the track's condition. The number of defects in Figure 14 below is a sum of all class defects. Note that the sections evaluated in this study consisted of Class 3 and 4 tracks.

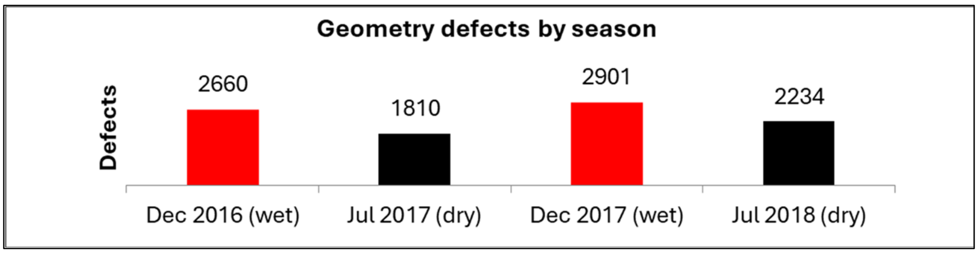


Figure 14. Number of geometry defects by season.

Figure 14 clearly shows the increase of geometry defects during the wet season, which is related to the variation in track stiffness during this period. This fact is associated with changes in subgrade condition due to the moisture variation and the excess of contamination existing in the ballast of most of the studied track sections. Note that the 2018 dry season shows an increased number of defects with is most likely related to the track degradation.

3.2. Mud Spot Identification

This section of the research is a part of a project to identify track mud spot locations correlating track vertical deflection signatures through MRail data (YRel). The subject focus of this research effort was to classify mud spot conditions with their impact on track maintenance, and more importantly its potential for track safety improvement. Mud spots are a very common problem where water, through capillary action, is "pumped" from the subgrade into the ballast by sleepers that move down under axle loads and then back upwards after the axle has passed over the sleeper. The sleeper acts like a piston pump as the rail elasticity springs the sleeper upward after the axle load passes. The mud mixed in with the ballast causes several problems that increase derailment risk including less stable muddy ballast, significant vertical track deflection, increased rail stresses (and increased risk of a rail break), areas where timber sleepers rot quickly, poor gauge holding stability due to rotting sleepers, poor lateral resistance for track alignment, higher risk of sun kinks from poor lateral resistance, and poor surface.

The biggest problem with mud spots is that there are too many for any railroad to repair 100% of the total. The need is to have a low-cost and fast way to evaluate the severity of each mud spot. Roadmasters inherently know where their mud spots are located and in general perform repetitive maintenance to fix the symptoms and not the root cause of the problem. This maintenance is expensive and requires track time. If the severity for each mud spot were quantified, maintenance could be prioritized. The method to quantify the severity of each mud spot is to analyze the data from the MRail Vertical Track Deflection System as well as other railway track and operating data such as: in site visual inspections, geometry, etc.

Figure 15 shows an exception associated with a spike in YRel used during the development of the model. Investigation of this location revealed this to be an area of fouled ballast. The data from the location presented was extracted for the left rail and a plot of YRel for the surrounding area.

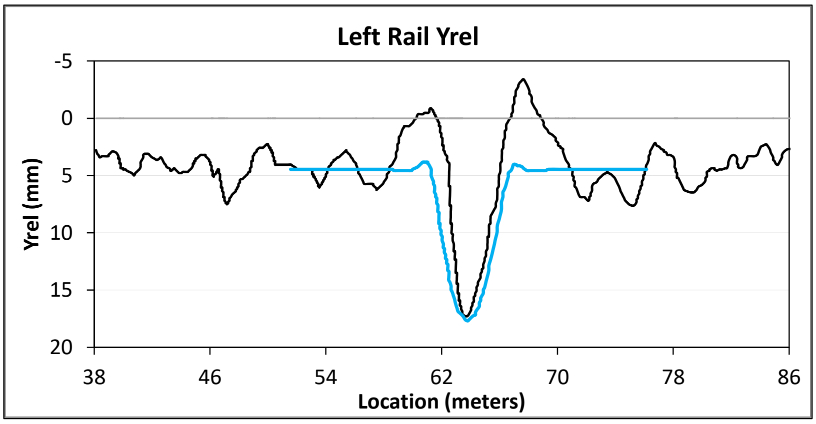


Figure 15. YRel and BOEF output for the mud spot location used in model development.

Figure 15 shows a unique YRel signature of the mud spot. The surrounding locations have a mean YRel of 4.3 mm, a peak YRel of 17.8 mm in the center of the mud spot, and an average minimum value of −2.5 mm in the uplift zone. The mud spot YRel map has a length of approximately 5 m in the uplift zone and 4 m at the mean location. Note that this graph depicts the maximum YRel at each measurement location (every meter) as the inspection vehicle moves down the track.

It is important to understand the derivation of YRel and its relationship to deflection. In an ideal situation, i.e., uniform track support, the track will behave as a beam (rail) continuously supported by an elastic foundation (everything below the rail) subjected to sequential point loads (passing wheels) as described in the previous section. The solution for the deflection of a beam continuously supported by an elastic foundation is given by Equation (1). Using linear superposition, the deflection of the rail can be determined for an applied truck load of two wheels. Typical results for the deflection were presented in Figure 5. It can be seen from this figure that the individual deflection waves from each wheel combine to provide the rail deflection under two adjacent axles on a bogie. This rail deflection shape can be seen at any point along the track and is dependent on the support stiffness and applied load, along with the rail properties.

Figure 5 also showed the projection of the measurement system and graphically how YRel is derived from the actual deflection curve. This can be represented mathematically as follows:

$$\mathrm{Yrel} = \frac{5}{3}\mathrm{w}(\text{inboard wheel} = 0) - \frac{2}{3}\mathrm{w}(\text{outboard wheel} = 1.83) - \mathrm{w}(\text{sensor head} = -1.22) \tag{3}$$

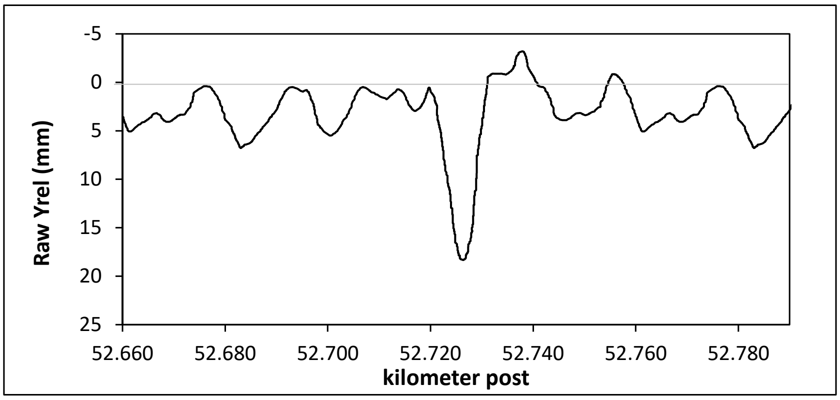
where w(x) = rail deflection at location x. Note that the above is for uniform stiffness, and as mud spots are evaluated, stiffness will have abrupt changes.

Considering the model depicted in Figure 5, the rail deflection can be modelled using beam on elastic foundation theory, and the modelled YRel value can be calculated from Equation (3) for each measurement location. The rail deflection curves can be converted to YRel plots using the equations presented previously. The YRel map for the mud spot shown is overlaid with a modelled (blue line in Figure 15) YRel map using BOEF model for a parent track stiffness of 24 MPa and mud spot of 5 m length and mud spot stiffness 3.5 MPa. While not a perfect match to the BOEF model, Figure 15 shows how the BOEF model closely matches the measured YRel data. It should be noted that the lift regions which flank the peak deflection are not seen in the BOEF model. This is due to the BOEF model's assumption that the beam is connected to the foundation. This connection drastically minimizes any uplift. In reality, the rail is not fully fixed with the substructure and rail lift is expected.

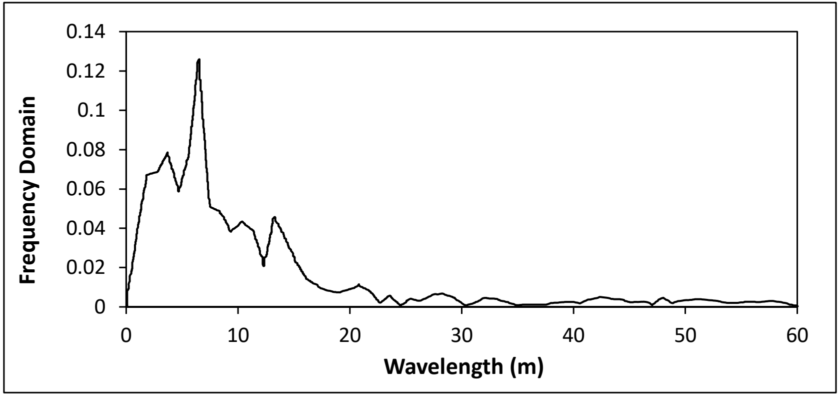
In order to facilitate production analysis, an algorithm for automatically identifying potential mud spots was develop using signal processing techniques of the YRel signature. After a series of analyses using BoEF to correlate measured YRel data to mud spots, the signature shown in Figure 15 proves fairly consistent, and depending on mud spot severity, will show changes in length and peak values. Machine learning techniques and other advanced data science techniques can be applied for identifying this signature.

The chosen method for determining a "soft" location was to use fast Fourier transforms (FFTs). The signature shown in Figure 15 (peak YRel with two uplift values) provides a unique signature that can be evaluated. In order to identify this signal, moving windows of YRel data were transformed into the frequency domain using FFT. Windows were required in order to isolate a specific signal response associated with one mud spot candidate and not the frequency spectrum of the entire dataset. Initial signal analysis was conducted using 130 m windows (to account for uplift zones of 6 m mud spot).

Figure 16a shows an example of a 130 m YRel data window being converted into the frequency domain using an FFT. In the frequency domain, the signal was analyzed to identify the presence of a significant low frequency response. After complete processing, this window was flagged as a potential mud spot candidate. As can be seen, the YRel data show the expected response (large peak flanked by minor uplift deflection signals) and the frequency domain contains a significant low frequency response. This approach allows us to automatically find the location with the associated YRel signature that can be correlated to mud spots. This flagged signature can now be prioritized for severity, as the length and maximum YRel will vary for each mud spot.



(**a**)



(**b**)

Figure 16. (**a**) Example of a 130 m YRel data; (**b**) fast Fourier transform of YRel data.

This analysis can be applied in real time as well. Figure 17 shows 500 m of data and identified mud spots (highlighted with red dots).

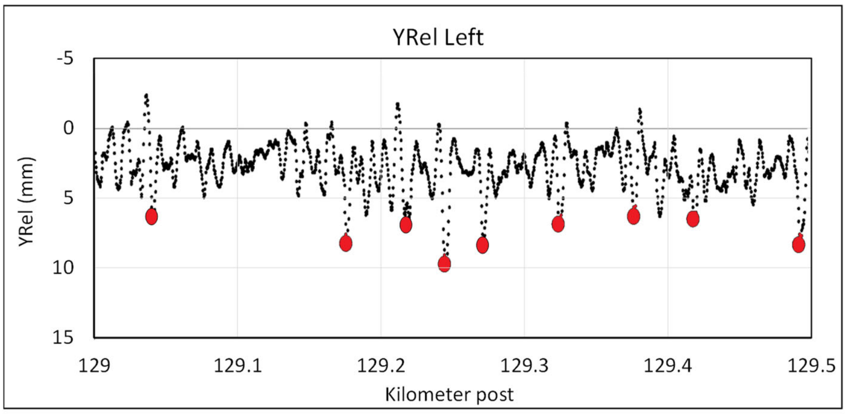


Figure 17. Mud spot identification for 500 m of data.

Note that the YRel signature associated with a mud spot may also be associated with other soft support conditions in track. These may come from consecutive sleepers that are plate-cut or excessively decayed, hanging sleepers, or other localized soft support conditions. Thus, the identification of localized soft support conditions in track is important, whether it be from a mud spot or other cause. In order to limit the analysis to just mud spots, visual inspection and validation of the locations were performed. In addition, the algorithm may not identify newly formed mud spots until they reach peak deflection values that exceed the limits of detection.

Another way to visualize the mud spot location along the track is presented below. Figure 18 shows the GPS coordinates of identified mud spots in MRS Corridor 1 from

June 2017 and February of 2018 (the last measurement in wet season). The figure below clearly shows the evolution of mud spots in this specific corridor by the difference of severity related to the size and the peak of deflection of each mud spot. This location did not receive appropriate substructure maintenance activities during this period of analysis, which facilitated the comparation of seasonal effect and mud spot growth.

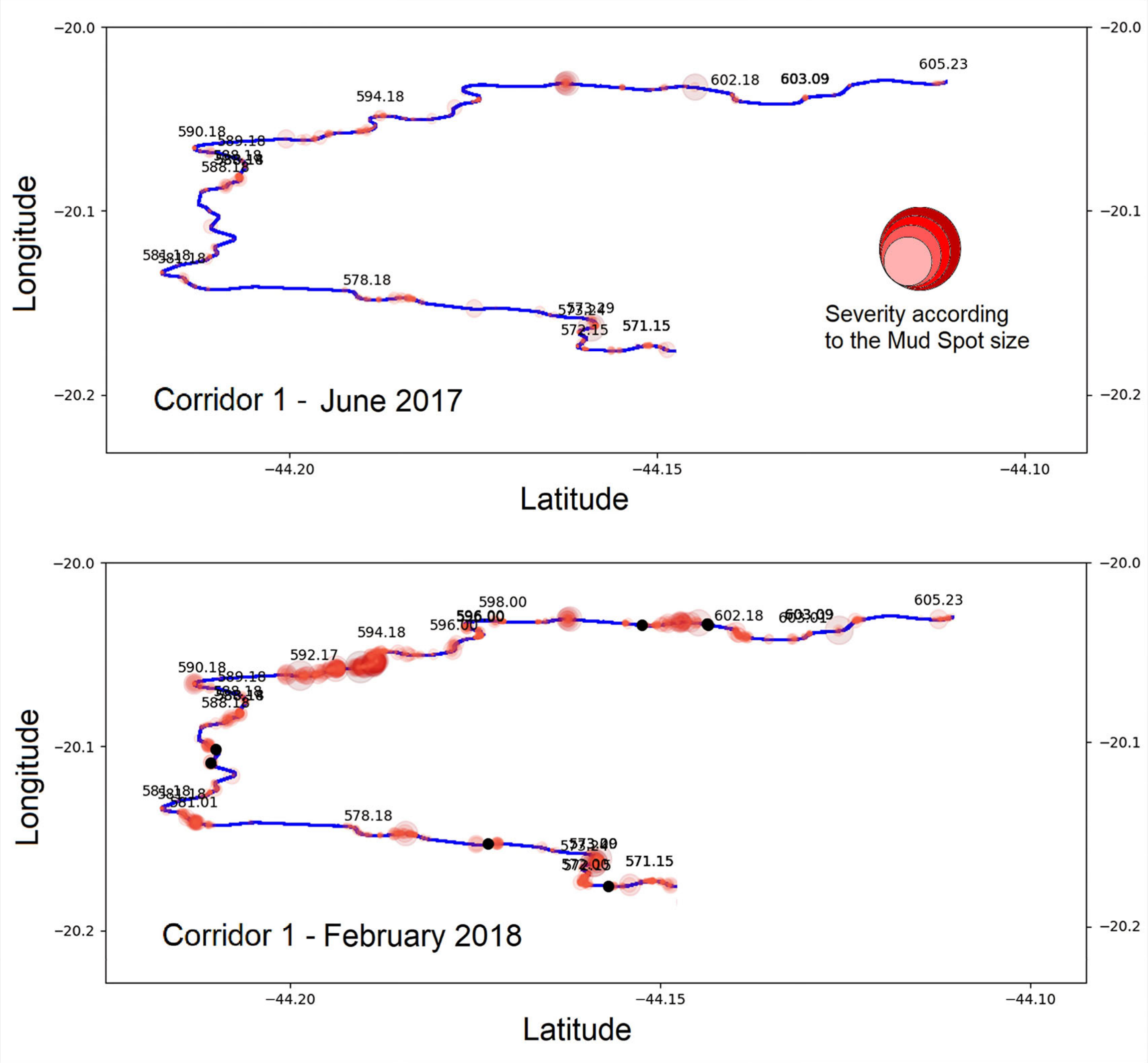


Figure 18. GPS coordinates of the mud spot variation in MRS Corridor 1.

Utilizing the FFT approach to identify mud spots, roughly 900 km of MRS vertical deflection data were processed through the steps outlined above. A total of 497 signals were flagged to match the potential signal of a mud spot. Each signal was processed to identify its central deflection zone and total widths as well as its localized mean deflection and its maximum deflection. A histogram of full signal widths is shown in Figure 19. It can be seen that most signals had a total width of between 9 and 18 m. Full width includes the uplift zones and central deflection zone.

The analyses discussed previously have played a crucial role in prioritizing the maintenance plans for MRS in the years following the project, with a particular focus on preparations for the rainy seasons. The results of the analyses were correlated with other inspection methods to define the most appropriate action plan. Areas with a high concentration of mud spots, covering approximately 34 km (3.8%), with track modulus below 8 MPa, underwent total track renewal and subgrade restoration, as they required drainage and reinforcement interventions. These areas consistently exhibited low support capacity. Additionally, these locations had higher superstructure component degradation, including sleeper replacement and fastener and rail fatigue. Locations with frequent tamping and high geometry degradation, accounting for approximately 10.4% (94 km) of the track, were associated with areas of low support and were designated for the initial phase of the ballast cleaning project. These locations, with a track modulus between 14 MPa and 8 MPa, showed significant variation in support between seasons, as ballast contamination retained water during the rainy period, reducing track modulus and causing geometry degradation.

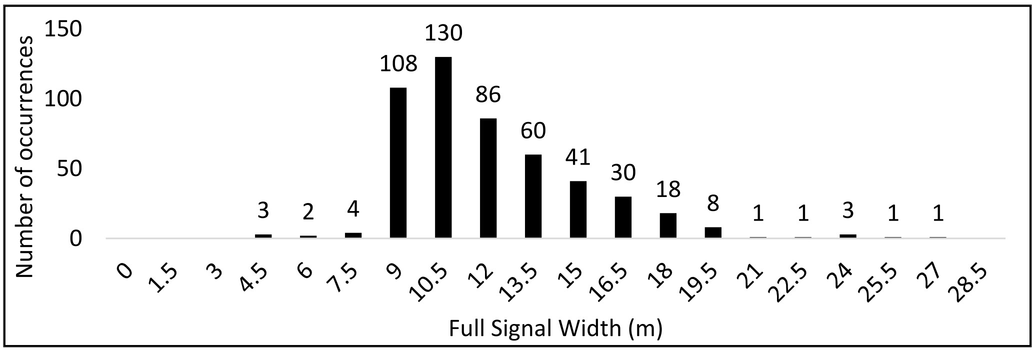


Figure 19. Distribution of identified full signal widths.

In addition to areas with low track modulus, locations with high modulus variation over short distances were also evaluated, particularly those at tunnel entrances, bridges, and level crossings. Approximately 100 points required intervention, with 30 needing immediate action due to high dynamic impact. Interventions included bridgehead replacement and complete restoration of level crossings. This plan was based on an integrated analysis of multiple systems. During one of the measurement campaigns, the MRail instrumented train was also equipped with an instrumented wheelset system to correlate measurements. This approach enabled the identification and treatment of the most critical locations for load impact.

These examples illustrate how the strategic approach led to a reduction of more than 50% in the number of defects on the permanent way in the following years. Additionally, it contributed to a notable decrease in the frequency of derailments, with the most recent incident occurring in December 2019.

4. Discussion

In the railway sector, concerns have been raised regarding the effective evaluation of track substructure conditions and the transformation of results into practical analysis for maintenance planning. Continuous measurement methods for vertical stiffness have advanced significantly in recent years [7]. This research presents the application of this technique with a new approach to interpreting data, particularly for the automatic identification of mud spots. Similarly to the findings of Roghani [9], this research demonstrated that the vertical continuous track deflection measurement system was effectively utilized in extensive testing to assess the influence of substructure components on track performance. The system successfully identified soft conditions beneath the track, providing critical data for maintenance planning and enhancing overall track stability [10].

This work differentiates itself from previous studies by the repeatability and periodic inspections of the same railway section, with the aim of producing a degradation trend and feeding a predictive maintenance model. This model combines the assessment of seasonal effects during periods of heavy rainfall with railway maintenance. By identifying critical locations early, it is possible to organize a maintenance plan focused on the root cause of the problem and to schedule the most appropriate sequence of maintenance activities, rather than merely correcting the problem's effects, which results in higher maintenance costs. Since substructure maintenance activities require greater preparation, it is crucial to anticipate their potential effects on the superstructure.

Some other opportunities for data analysis could be developed using this initial mud spot study to establish an appropriate guideline risk. Mud spots will inherently differ in length and support stiffness; i.e., the YRel map will have varying peaks and lengths over the peaks [21]. In addition to the size and location, a relationship using the bending stress and the deflection at the specific mud spot could be applied to improve the risk analysis and better support the maintenance plan activities. This, in effect, is a measure of the severity of the mud spot. This analysis could be associated with the flexural stress the rail experiences due to significant increases in deflection and provide a suitable measure of risk. There are additional opportunities to extend this research by developing risk-based inspection frequency algorithms to optimize inspection intervals, thereby limiting the risk of defect formation. Furthermore, collecting additional data and employing advanced machine learning techniques can enhance the development of degradation models.

5. Conclusions

The purpose of this research was to examine MRail vertical track deflection data and associated track support information to show both macro- and micro-level seasonality effects on 900 km of the MRS Logistics network. Locations were identified with large deflections and large deflection rates that can lead to differential settlement, increased dynamic loading, increased bending stress in rails and sleepers, fouled ballast, and failed subgrade. In addition to evidence of degradation over time, the results of this analysis showed seasonality effects, highlighted by increases in peak vertical deflection during wet weather. On a macro level, data indicate a decrease in track stiffness during the wet season, followed by a rebound in stiffness during the subsequent dry cycle. On a micro level, analysis reveals that approximately 34 km of track exhibits a significantly low track modulus (below 8 MPa) during the wet season. These low stiffness areas, spanning more than 900 km, also correlate highly with the presence of track defects. Therefore, precision in the maintenance plan is crucial for effective intervention and long-term track integrity. Moreover, the observed low stiffness is associated with an accelerated rate of degradation in these areas.

By characterizing the vertical track support characteristics of their network, MRS Logistics was able to understand its operational limitations, such as the viability for increasing axle load and speed, as well as provided an understanding of the substructure condition and maintenance requirements. Further, MRS Logistics was able to use vertical track deflection data, in a developed mud spot model, to determine priority maintenance areas. Results of this work were an important part of MRS's decision to implement an undercutting and subgrade restoration program on their network.

In conclusion, this study suggests that by using MRail to understand vertical track deflection, potential problems can be monitored, and maintenance planned for such activities as surfacing, ballast cleaning, undercutting, sleeper replacement, and joint maintenance. Ultimately, the cost of track maintenance can be reduced by quantifying the track formation condition and allowing track maintenance personnel to plan for preemptive, rather than reactive, maintenance activities.

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