TRENDING AND CORRELATION ANALYSIS OF PERFORMANCE INDICATORS FOR MEASURING AND MONITORING RAIL PROFILE WEAR

By

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ABSTRACT

This thesis develops a comprehensive understanding of rail profile performance indicators (PIs), their temporal trends and the relation between them. The increasing demand for freight and passenger rail transportation accentuates the need for regular and timely rail maintenance, particularly rail grinding. To enhance the efficiency and effectiveness of maintenance activities, meaningful PIs must be developed and monitored. Despite general recognition of the benefits of adopting performance-based rail monitoring and management programs, knowledge gaps remain in terms of: (1) the selection of relevant indicators of rail condition and performance; (2) deterioration rates and the thresholds that trigger maintenance interventions; and (3) the effectiveness of rail grinding in prolonging the life of rail assets. This research partially fills these knowledge gaps.

This research develops a new algorithm in MATLAB© to: (1) automate the extraction, compilation and screening of historical rail profile data, (2) calculate multiple rail profile PIs over multiple years, (3) store the calculation results, and (4) analyse them using qualitative (i.e., temporal trending graphs) and statistical tools (i.e., Spearman correlation technique). The algorithm enables user flexibility in the definition of temporal periods to evaluate performance before and after maintenance interventions. Moreover, it improves analytical efficiency and enables customization of analysis steps and results.

The trending and correlation analyses integrate industry-standard PIs (head loss, gauge wear, vertical wear, and grind quality index) with newly-developed PIs (average rail profile, lateral contact position, and contact radius). There appears to be a strong agreement

between head loss and vertical wear; however, other performance indicators truly measure unique aspects of rail profile performance and should be considered alongside each other.

The findings provide some evidence of the value of maintenance interventions—quantified in terms of the lower grind quality index over time. However, additional information on rail maintenance (time and level of effort) and operations (e.g., tonnage and number of passes) is required to develop more conclusive insights. Also, the trends for certain PIs reveal the pending need for replacement when the PIs approach relevant condemning limits. This information supports more proactive and effective rail maintenance intervention decisions.

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DEDICATION

This work is dedicated to my lovely parents for their motivation, inspiration and support.

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1 INTRODUCTION

1.1 Purpose

The purpose of this thesis is to develop a comprehensive understanding of rail profile performance indicators, the relation between them, and their temporal trends. This understanding supports rail profile performance monitoring, maintenance, and management. A comprehensive study of performance indicators related to rail profile maintenance practices revealed seven indicators of particular relevance to this research:

- average rail profile
- head loss
- gauge wear
- vertical wear
- grind quality index (GQI)
- contact radius
- lateral contact position.

The thesis analyzes trends and relationships evident for these indicators using a time-series rail profile data set. When validated through industry experts, the results support more data-driven rail maintenance decisions.

1.2 Need and Background

Relative to other freight transportation modes, railway transportation is particularly well-suited for hauling heavy commodities over long distances (Olkhova, et al., 2017). For passenger transportation, railways enable efficient movement of people between major origin-destination (O-D) pairs, and effectively serve as urban transit systems. In some cases, intercity rail services are competitive with short-to-medium haul air transportation (Xia & Zhang, 2016). According to the International Union of Railways (UIC) Synopsis (2019), approximately 9 billion tonnes of freight and 30 billion passengers were transported by railway globally in 2019.

As one of the major industries in Canada, railways carry approximately 84 million passengers and 70% of all freight hauled between cities each year (Railway Association of Canada). The Canadian rail transportation industry generated roughly $9.5 billion from its freight sector and $500 million from commuter and passenger services in 2011 (Transport Canada). Recent rail statistics in Canada reveal an increasing trend in total volume of rail freight transportation (Figure 1). The total freight volume transported by rail in Canada increased from 268 to 312 million tonnes from 2010 to 2017 (Statistics Canada, 2019).

While intercity passenger rail transport is relatively uncommon in Canada, several major cities (e.g., Toronto, Montreal, Vancouver, Calgary, Edmonton, and Ottawa) utilize metro or rail transit systems as a primary means of accommodating urban passenger transport demand.

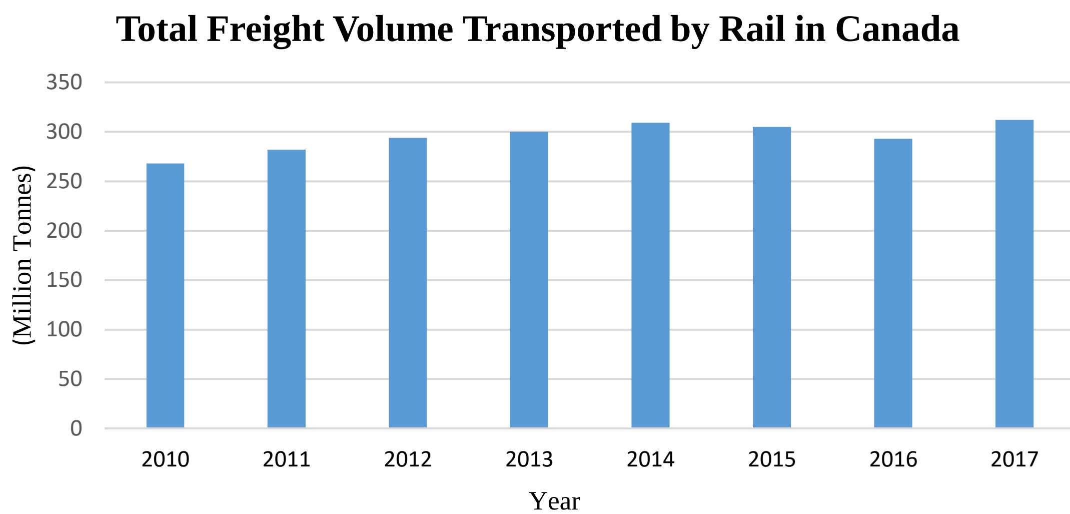
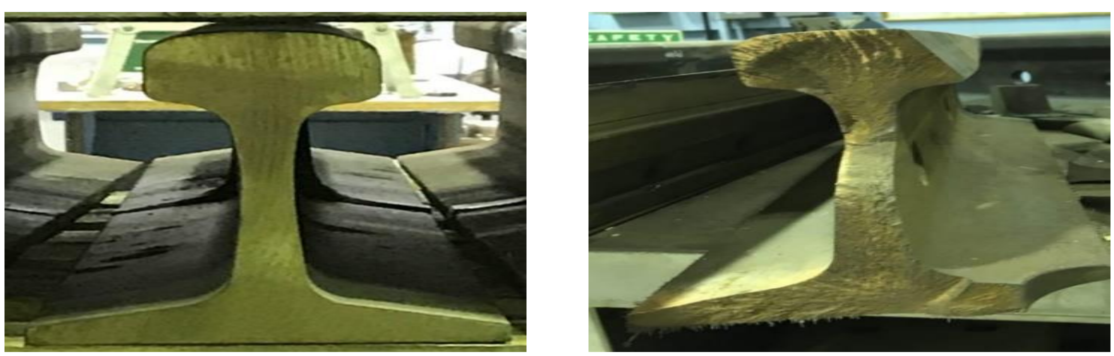


Figure 1. Total Freight Volume Transported by Rail in Canada (Million Tonnes)
Data Source: Statistics Canada (2019)

As railway transportation demand increases, rail infrastructure requires investment to accommodate this demand (National Infrastructure Commission, 2017). More traffic leads to more rail deterioration, as illustrated in Figure 2. Deterioration manifests as various types of rail and wheel failures and ultimately causes safety hazards and economic loss. Regular rail maintenance programs, however, can mitigate these issues (NSW Transport Railcorp, 2012)



(a) **(b)**

Figure 2. Illustrative Example of (a) an Unworn Rail Section and (b) a Deteriorated Rail Section.

It is crucial to manage the contact interface between the wheel and rail to optimize performance of a rail transportation system. This involves regular maintenance (e.g., lubrication, rail grinding), which is an essential part of railway asset management (Lewis & Olofsson, 2009). Railways invest considerable resources in the maintenance and management of rail assets. According to Transport Canada (2017), Canadian railways invest approximately $1.8 billion (20% of their revenue) into infrastructure. To support maintenance and management decisions, it is necessary to monitor the condition of rail infrastructure (Stenström, et al., 2012).

Assuring and improving railway performance relies on measuring and analyzing the rail condition as generally recommended by the DMAIC (Define, Measure, Analyze, Improve and Control) cycle (Sokovic et al., 2010). In order to enhance the efficiency and effectiveness of maintenance activities, performance indicators must be taken into consideration. Focusing on performance indicators has proven beneficial in monitoring rail infrastructure and improving rail safety and productivity (Kaplan and Norton, 1992, 1993).

Despite the general recognition of the benefits of adopting performance-based rail monitoring and management programs, knowledge gaps remain in terms of: (1) the selection of relevant indicators of rail condition and performance; (2) deterioration rates and the thresholds that trigger maintenance interventions; and (3) the effectiveness of rail maintenance (in particular rail grinding) in prolonging the life of rail assets. This research aims to fill these knowledge gaps by quantifying rail profile condition over time.

1.3 Objectives and Scope

This research has four objectives:

1. to review available performance indicators and identify appropriate measures for detailed analysis,
2. to determine and verify methods to calculate performance indicator values,
3. to develop and analyze temporal trends in performance indicators used to monitor and manage rail profile performance and identify the effectiveness of rail grinding activity, and
4. to investigate the potential relationships between performance indicators through a correlation analysis.

The methodology developed by this research is applied using data from a closed-loop, heavy haul Canadian short-line railroad with uniform traffic. The data were collected by optical rail measurement devices on 100 miles (160 km) of track over the 17-year period between 1995 and 2012, inclusive. While aspects of the analysis and conclusions comprising this thesis pertain uniquely to the examined rail property, the methodology is generic and applicable to any rail property (freight or passenger) with a rail profile monitoring program.

1.4 Approach

This thesis focuses on developing an understanding of various rail profile performance indicators and their application in rail maintenance programs. Analysis of trends and relationships amongst the indicators supports this understanding. The thesis develops an algorithm in MATLAB® to export, screen, manage, and analyze rail profile data available within Holland®'s Rangecam Office and Grind Analyst® software.

Developing an understanding of rail wear mechanisms, rail profile data acquisition, rail maintenance procedures, and most notably the different rail profile indicators underpins the analysis in this thesis. Moreover, to fulfill the objectives, the research necessitated the integration of practical rail knowledge with MATLAB programming and statistical analysis skills. The MATLAB algorithm automatically evaluates the eligibility of track segments for analysis, calculates performance indicator values, and plots segment-by-segment temporal trending graphs for each performance indicator. The algorithm integrates commonly used rail profile indicators (head loss, vertical wear, gauge wear, and GQI) with newly developed indicators (average rail profile, lateral contact position, and contact radius). The correlation analysis utilized SPSS® software.

1.5 Thesis Organization

This thesis comprises five chapters, including this introductory chapter. Chapter 2 provides a summary of the findings of the literature review. Specifically, it discusses:

- common rail defects,
- rail asset management and rail maintenance programs, and
- rail profile and rail maintenance performance indicators.

Chapter 3 describes the data structure and the algorithm that was developed to extract data, analyze rail profile performance indicators, and store the results. It also outlines the methodology for the correlation analysis.

Chapter 4 discusses data verification and validation, presents the results of the trending and correlation analyses of the selected rail profile performance indicators, outlines analytical limitations, and discusses the implications for managing rail grinding program.

Finally, Chapter 5 summarizes key research contributions and findings and makes recommendations for further research.

2 LITERATURE REVIEW

This chapter summarizes the findings of the literature review. Specifically, it discusses:

- common rail defects,
- rail asset management and rail maintenance programs, and
- rail profile and rail maintenance performance indicators.

2.1 Rail Defects

This section describes the findings from literature review of the deterioration mechanisms that affect a rail's life cycle. While the literature uses various and inconsistent terminology to describe these mechanisms, this thesis adopts the general concept of "rail deterioration" to describe those mechanisms that negatively affect rail life.

According to the Rail Defects Handbook (NSW Transport Railcorp, 2012), a rail's lifespan is determined by three factors:

1. *Wear* occurs both laterally and vertically on the railhead surface and gauge side. The magnitude and rate of rail wear depends on the nature of wheel/rail interaction and rail maintenance practices (e.g., rail grinding, lubrication).
2. *Plastic flow*, also known as mechanical deformation, occurs on both high and low rails in curves and is particularly common on curves carrying high axle loads.
3. *Rail defects* occur in all rails due to a wide range of reasons, such as the rail manufacturing process, cyclical loading, impacts from rolling stock, rail wear, and plastic flow.

It is crucial to address a rail defect in a timely manner to prevent rail failure or expensive rail maintenance (NSW Transport Railcorp, 2012). According to Zarembski (2010), rail wear and rail fatigue are two main rail deterioration phenomena, which may lead to rail replacement. These phenomena may be interrelated. For example, the fatigue rate could be affected by rail wear due to rail stress growth. Table 1 provides a list of subcategories of these two rail deterioration phenomena.

Table 1. Subcategories of Rail Wear and Rail Fatigue (Zarembski, 2010)

Rail Wear	Rail Fatigue
1. Side wear	1. Transverse defects
2. Gauge-face wear	2. Detail fractures
3. Head wear	3. Horizontal split head
4. Railhead profile deterioration	4. Vertical split head
	5. Rolling contact fatigue (RCF)
	6. Surface spalling, shelling, and corrugation
	7. Squats and tache ovals

There are a wide range of rail defects in practice; however, Table 2 provides common rail defects that can be addressed by rail grinding (NSW Transport Railcorp, 2012, International Heavy Haul Association, 2015, Magel, 2011). These common defects are:

- rail corrugation
- rolling contact fatigue (RCF)
- squat defects
- vertical split head
- horizontal split head
- wheel burn

Table 2. Common Rail Defects and Treatments

Defect	Characteristics	Treatments
Rail Corrugations	• Rail corrugations are cyclic, vertical, wave-shaped patterns on the railhead surface • Two categories of rail corrugation may develop : (1) short pitch corrugations are developed under light axle loads and caused by various types of wear from the sliding action of the wheel on the rail: and (2) long pitch corrugations are developed under high axle load and caused by plastic flow. • Rail corrugations might cause deterioration rates of the track and rolling stock to increase, leading to rapid infrastructure deterioration, (e.g., RCF, ballast degradation)	• Use higher strength rail steels. • Use improved wheel and rail profiles to provide a reasonably large contact band. • Implement better rail pads to reduce the track roughness. • Perform regular maintenance, particularly rail grinding and lubrication of the rail gauge face and wheel flange. • Make adjustments to vehicle suspensions. • Superelevate curves.

Defect	Characteristics	Treatments
Rolling Contact Fatigue (RCF)	• RCF refers to a range of defects caused by stress at the wheel-rail interface. • There are three categories of RCF that occur in the gauge side of the rail: • Gauge corner checking, which occurs on the rail surface and is common in sharper curves • Shelling, which originates internally and is common in high rails of curves • Running surface checking / Flanking, which occurs on the rail surface of high and low rails in curves • RCF is common on most of the rail systems and is a globally recognised issue.	• Use higher strength rail steels • Use cleaner rail steels • Improve wheel and rail profile to provide a reasonably wide running band • Improve rail field stressing procedure • Optimise rail grinding / rail maintenance programs • Improve wheel-rail lubrication • Apply ultrasonic rail testing to detect defects correctively • Develop crack initiation modelling capabilities • Grind rails to remove fatigued material • Replace rails

Defect	Characteristics	Treatments
Squat Defects (Head Checks)	• Squat defects refer to initial small cracks on the rail surface that extend in two steps and are caused by high contact stresses at the wheel–rail interface or surface irregularities. • There are two categories of squat defects, based on the zone of rail in which they occur: (1) running surface squats, which occur in the contact band and often appear in a double-sided kidney shape; and (2) gauge corner squats, which occur mostly close to the gauge side and originate from the cracks that already exist. • Squat defects first extend down from the surface to a depth of 4-6 mm under the rail surface. Then, the cracks spread laterally and longitudinally. • They can occur on either or both rails from all types of traffic (passenger/freight/mixed), regardless of the properties of the rail.	• Use head-hardened rail. • Use the wire feed process for head repair welding. • Replace rails. • Perform rail grinding. • Perform running band management.

Defect	Characteristics	Treatments
Vertical Split Head	• Vertical split head refers to the vertical separations that split a railhead in two parts. • The visual characteristics of large vertical split head defects include: (1) a dark crack on the running surface; (2) a widened rail head and contact band along the defect; and (3) a rust streak in the head/web fillet region. • It occurs in a significant length close to the centre line of rails. • It is invisible in small or medium sizes; however, it can be recognized when sufficiently large. • Older rails that were not produced by continuous casting are more prone to this type of defect.	• Use cleaner rail steels. • Apply ultrasonic rail testing to detect cracks and irregularities before they reach a critical size. • Perform rail grinding. • Reduce the levels of applied nominal, dynamic and impact wheel loadings. • Reduce the levels of wheel hollowing.

Defects	Characteristics	Treatments
Horizontal Split Head	• Horizontal split head refers to longitudinal-transverse fatigue cracks in the railhead that expand horizontally and split the railhead in two parts. • The visual characteristics of large horizontal split head defects are: (1) a dark crack on the field zone of the running surface; (2) a widened rail head and the contact band along the defect; (3) a horizontal crack, followed by a rust streak below the top of the railhead on the field side.is invisible in small or medium size; however, it can be recognised in large size. • It is caused by expanding the existing seam in the rail steel. • It occurs in the rail's field zone, expanding both across and along the rail head. • Older rails that were not produced by continuous casting are more prone to this type of defect.	• Use cleaner rail steels. • Apply ultrasonic rail testing to detect cracks and irregularities before they reach a critical size. • Perform frequent rail inspections and rail grinding. • Reduce the levels of applied nominal, dynamic and impact wheel loadings.

Defects	Characteristics	Treatments
Wheel Burn	• Wheel burns, also known as engine burns, refer to the running surface defects that are caused by continuous slipping of the locomotive wheels on the rails (locomotive wheel spinning). • Wheel burns occur when the adhesion limit is exceeded. • They may happen while rolling stock is in motion, causing an extended length of damaged surface. • They occur in pairs of opposite directions on the two rails. • They are similar to small squats if they are small in size. • The wheel burn can cause cracks that might cause transverse defects.	• Minimize influencing operational factors. • Implement several recommended lubrication procedures (e.g.. avoiding excessive lubricant pumping) • Clean the rail surface using high pressure spray water. • Apply ultrasonic testing to detect the defects before they reach a critical size. • Perform subsurface inspections and rail grinding. • Use AC traction motor locomotives.

Source: Adapted from Rail Defects Handbook (NSW Transport Railcorp, 2012), International Heavy Haul Association (2015), Magel (2011)

2.2 Rail Asset Management and Maintenance Programs

This section provides a detailed description of rail asset management practices and concepts, some examples of commercial rail asset management software, rail grinding practices, and some international examples of the application of rail grinding within rail maintenance programs.

2.2.1 Rail Asset Management Practice

An asset is defined as a potential or actual value of an organisation (ISO 55000 Clause 3.2.1). The scope of assets covered by a particular asset management system depends on the organization's decisions and policies. Currently there is a need to improve consistency among organizations. According to UIC (2010), through the European Commission 5th Framework Programme, a scope of assets has been proposed to promote consistency among rail organizations. Table 3 lists the items included in the scope of assets defined in UIC Lasting Infrastructure Cost Benchmarking (LICB) project.

Table 3. Scope of Assets Included in the Asset Management System Defined by UIC

Assets	Sub-Assets / Description
Ground area (right-of-way)	
Track structures	Track, track bed, etc.
Engineering structures	Bridges, culverts, overpasses, tunnels, etc.
Highway-rail crossings	All the assets included for the purpose of road traffic safety assurance
Superstructure	Rail infrastructure including rails, grooved rails, sleepers, ballast, etc.
Access way for passengers and commodities	Access by road is also included
Safety, signalling and telecommunications installations	Includes all the installations on the open track, in stations, and in marshalling yards, etc.
Lighting installations	These are included as they contribute to safety
Electric power supply for train haulage	Sub-stations, supply cables between sub-stations and contact wires, catenaries

Source: Adapted from International Union of Railways (UIC) (2010)

ISO 55001 Clause 4.4 describes asset management as a set of coordinated activities performed by an organisation to understand and protect the asset's value. However, a more detailed definition of this concept is required for the purpose of communicating with the public (Hastings, 2015). According to Hastings (2015), asset management is defined as the set of activities that helps an organization with identifying required assets, managing funding, purchasing assets, managing asset maintenance, and renewing required assets. Asset management is the interface between the technical and business sections of an organization that, when integrated, provides the organization with the assets necessary for effective operation (Hastings, 2015). McElroy (1999) explains the term "asset management" from a transportation perspective. Asset management is necessary as a systematic approach through "maintaining, upgrading and operating physical assets cost-effectively" in order to enable the transportation system to operate in an optimal way (McElroy, 1999).

Although the concept of asset management system is widely accepted, implementation has been a challenge for transportation infrastructure asset owners and managers. Parlikad et al. (2016) categorize the challenges that the transportation industry encounters when maintaining, monitoring, and managing their assets (Parlikad et al., 2016):

- "asset performance monitoring and prediction,
- data management,
- optimizing investment/expenditure, and
- organisational culture change."

The solutions suggested by Parlikad et al. (2016) to address these challenges are classified into four groups (see Table 4).

Table 4. Solutions to Address Challenges in Transportation Infrastructure Maintenance

Solutions	Examples
Models and tools	• Long-term investment planning • Infrastructure performance simulation platform
Integrated solutions	• Integration of enterprise information systems for real-time risk analysis • Integrating data from multiple data sources
Guidance	• Integrating ISO 55000 with other quality management frameworks • Generic whole life asset information requirements register
Methodologies	• Incorporating sustainability • Effective sensing strategy

Source: Adapted from Parlikad et al. (2016)

Regardless of the type of asset considered, information management significantly influences effective decision-making (Vanier, 2001). Realizing this, many agencies have begun to consider data as an asset unto itself (International Transport Forum, 2018). The importance of data holds whether asset management focuses on “repair and renew” (the general focus of most North American agencies) or “design and build” (Vanier, 2001; Johnson and Clayton, 1998).

In North America, freight rail properties have sometimes abandoned rail lines as a means of managing assets (Too E., 2010). While controversial, this strategy has enabled railways to reduce operating costs (Law et al., 2004).

2.2.2 Rail Asset Management Software

Zarembski (2010) describes the implementation of rail inspection and monitoring technologies and software to support rail asset management. Specifically, rail maintenance planning and management based on rail condition optimizes the maintenance process and minimizes rail maintenance costs. The data obtained by this process is then applied within the new generation of rail asset management software. This software comprises the following four categories (Zarembski, 2010):

- Rail relay planning software: The need for rail replacement arises mainly because of rail wear and rail fatigue. This type of software is capable of scheduling and planning rail replacement. Zeta-Tech’s RailLife is an example of this type of software that evaluates the rate of fatigue and rate of wear using Weibull techniques to forecast the rail life of each track segment.
- Rail lubrication monitoring software: This type of monitoring software shows the effectiveness of rail lubrication. The software enables users to compare the actual rate of wear with the anticipated rate of wear. This capability helps practitioners locate and evaluate the effectiveness of lubrication on the segment at which the rate of wear is relatively high.

- Rail grinding management software: This software consists of management modules that cover concerns associated with rail grinding (i.e., managing removals, controlling rail surface defects, and maintaining the rail profile).
- Rail test management software: This software is beneficial for monitoring rail fatigue development and the risk of broken rail. Also, this software is used to evaluate the effectiveness of ultrasonic tests.

Holland's Rangecam© Office software supports railways with various tools for monitoring and managing rail infrastructure (e.g., rail measurement and rail replacement forecasting). While providing rail condition assessment tools, Rangecam also enables railways to forecast the time when the worn rail requires replacement. Rangecam is equipped with reporting, planning and visualizing tools to provide rail condition reports, develop rail replacement plans, and graphically illustrate the location of rails using mapping tools. More information about Rangecam is available on Holland's website (Holland LP, 2016).

2.2.3 Rail Grinding

Rail grinding is the process of surface removal on rails using a series of grinding stones to reshape the rail profile to a desired profile (Kumar, 2006). Rail grinding consists of two different strategies (Sroba & Roney, 2003):

- Corrective grinding is the process of ensuring the removal of surface defects, often through multiple passes of rail grinding.
- Preventive grinding is the process preventing the extension of rail surface defects through a single pass or sometimes multiple rail grinding passes.

Table 5 illustrates the characteristics of these two strategies (Kalousek, 1989; Kumar, 2006; Magel et al., 2003; Sroba & Roney, 2003).

Table 5. The Characteristics of Corrective and Preventive Grinding

Grinding Strategies	Characteristics
Corrective grinding	• Requires heavy and deep cuts • Performed usually once a year • May require multiple passes
Preventive grinding	• Requires light and thin cuts • Performed frequently • May only require a single pass • Performed at a speeds up to 8-10 mph • Economically efficient grinding approach

The initial reason for developing rail grinding was to remove the corrugation from the top of rail. However, this resulted in various railhead deformations, including squared railhead, flattened top, and sharp corners (Magel et al., 2003). Cannon et al. (2003) indicate that, since 1980, the main application of rail grinding has transitioned from corrugation removal to the removal and/or control of RCF defects.

Rail grinding has become complex and advanced in practice since the time that it emerged. For example, rail grinding requires the use of high-accuracy, laser-based technology to obtain rail profile measurements (Zarembski, et al., 2005). Magel et al. (2003) explain how a combination of theory and field experience has led to the advancement of rail grinding practice. For instance, as described by Zarembski (2013), grinding practice involves the passage of a sequence of multiple grinding stones, with the profile created by each stone becoming the profile to be ground by the subsequent stone. In fact, the performance of each stone affects the performance of subsequent stones. Consequently, as explained by Zarembski (2013), it is important to quantitatively evaluate the performance of different grinding patterns and practices; such evaluation is a data-intensive effort.

2.2.4 Rail Maintenance Practice – International Case Examples

Different countries have different approaches to rail maintenance practice. The following points provide illustrative case examples of rail maintenance practices in North America, Australia, Sweden and South Africa.

- **North America (Magel et al., 2003):**

  Magel et al. (2003) provide a brief history of the development of rail grinding practice in North America. The authors mention that the profile grinding technique at the initial stages of its development focused on field side relief of the low rail. Canadian National Railway used to rely on performing heavy grinding on specific rails exhibiting cracks to inhibit crack spreading. However, this approach affected the rail shape, requiring an expert to perform pre-testing and post-testing to ensure the actual railhead matched the desired railhead. Quality assurance at that time depended on the decisions made by the rail grinding supervisor. Therefore, a set of eight rail templates were introduced in 1991 with different degrees of relief on each side of the rail.

  Magel et al. (2003) explain how the combination of theoretical developments and experiences gained from practice have contributed to distinguishable changes in grinding practice applied in the North American railway system. The practice used to be corrective, involving multiple passes only once a year based on the rail surface appearance. More recently, in some cases, practice has evolved into preventive grinding, which involves light, single passes and frequent grinding at a speeds up to 8-10 mph. North American railways have not only concentrated on grinding enhancements, but have also made efforts to improve rail steels, particularly steel cleanliness during rail manufacturing (Magel et al., 2003).

- **Australia (Schoech, Fröhling, & Frick, 2009):**

  Rail grinding has been implemented in Australia since the mid-1970s and featured a variety of strategies and technologies. Rail grinding used to be executed through manual inspection and multiple operations (multiple passes) based on the rail grinding supervisor’s judgment. The experiences from rail grinding in Australia in 1978 showed that improvements could result from shifting the rail contact band. For instance, the gauge-face contact would be reduced while improving the wheelset curving ability by shifting the high rail contact band to the gauge side and the low rail contact band to the field side (Magel et al., 2003). The idea of distinguishing and prioritizing areas based on their track segment’s characteristics (e.g., curvature) provided a pragmatic schedule for rail grinding depending on the availability of capacity (Schoech, Fröhling, & Frick, 2009).

  One of the weaknesses of the Australian experience was the lack of appropriate knowledge in rail maintenance and information recording. This problem has been solved by the application of technology that enables timelier before-and-after rail profile measurements (Schoech, Fröhling, & Frick, 2009).

- **Sweden (Schoech, Fröhling, & Frick, 2009):**

  The Swedish Rail Administration invests significantly in rail maintenance, including annual grinding and lubrication. Although rail grinding is now widely accepted as a part of maintenance practice, it used to be neglected before 2001. Rail grinding is executed differently based on the nature of the track segment and the season. Curves are ground every year, while the grinding process is performed on tangents once every three years. Grinding is also done on switches (both the main and diverting tracks) every year. This process requires elevating the switch-rail during the process, which improves the contact condition in the zone between the switch-rail and stock-rail. A specific annual budget has been allocated to grinding practices since 2001 (Schoech, Fröhling, & Frick, 2009).

- **South Africa (Schoech, Fröhling, & Frick, 2009):**

  According to Schoech, et al. (2009), there is a wide range of externalities affecting the rail grinding practices on South Africa's heavy haul lines (Transnet Freight Rail), including variations amongst contractors and available equipment. Transnet Freight Rail aims to achieve low-contact stress, good curving performance, high-speed lateral stability, and surface defect removal. The company's success in achieving these objectives indicates how effective the grinding practice is. In addition, its efficiency depends on the way that grinding strategies affect grinding costs.

  In 1996, a new wheel profile was designed and implemented that led to the design of a new rail-grinding template. The grinding process at that time was based on the supervisor's decision whether to concentrate the process on the gauge corner or the top of the rail. However, a wide range of problems occurred, including flange wear and severe RCF on rails in turnouts. The new wheel and rail profiles along with more attention to the grinding strategy has brought success in Transnet Freight Rail's rail maintenance practice. Moreover, in 2004, the company began using a turnout grind machine in turnouts to address surface fatigue on turnout rails.

2.3 Performance Indicators

2.3.1 Key Concepts

Measuring and analyzing rail asset condition is fundamental for rail asset management. Within the commonly applied DMAIC (Define, Measure, Analyze, Improve and Control) cycle (Sokovic et al., 2010), performance indicators are introduced to improve the efficiency and effectiveness of rail maintenance practices. Performance indicators have proven to be beneficial in supporting preventive rail maintenance, monitoring rail infrastructure, and improving rail safety and productivity (Kaplan and Norton, 1992, 1993, Vanderwees, 2018; Stenström, 2014).

According to Tzanakakis (2013), an indicator is a numerical explanation of how a process performs during a specific time. Regardless of the application context, performance indicators commonly track progress in the following categories:

1. Efficiency
2. Effectiveness
3. Productivity
4. Budget/profit
5. Quality of working life
6. Innovation
7. Quality

Key performance indicators (KPIs) are those performance indicators (PIs) that are vital for a company (or other entity) to achieve success in its business or mission. They are developed for various reasons, for example, to prioritize processes that require improvement and to carry out trending and temporal analysis (Tzanakakis, 2013).

In addition to the topical categories for performance indicators listed above, Stenstrom et al (2013) classify performance indicators as (Stenstrom, et al., 2013; Stenstrom, et al., 2014):

- those related to financial, technical, health, safety, and environmental performance (i.e., analogous to topical categories),
- those which are leading, coinciding, or lagging; and
- individual or composite.

Leading, lagging, and coincident indicators are introduced through an input-process-output (IPO) model and are defined based on the time of a process (before/during/after) being considered (Stenstrom, et al., 2013). According to findings of Stenstrom et al. (2013), technical PIs and health, safety, and environmental indicators that signal potential future events are examples of leading indicators. The PIs used in condition monitoring (e.g. monitoring inspections and sensors) to measure the events at the same time that they are occurring are categorised as coinciding indicators. Finally, economical and soft PIs (e.g., questionnaires) that measures the events that have already occurred are interpreted as lagging indicators. Saisana and Tarantola (2002) indicate that composite indicators are the mathematical aggregation of more than one individual indicator.

2.3.2 Performance Indicators in Rail Maintenance

Stenstrom et al. (2012) review existing research papers, technical reports and documents on performance indicators in European railway systems. This review identified and categorised rail infrastructure indicators and compared these with the indicators identified by European Standards EN 15341. According to the authors, railway infrastructure indicators comprises two categories—managerial and condition indicators—with each category comprising various subcategories (Table 6).

Table 6. Subcategories of Rail Infrastructure Managerial and Condition Indicators

Rail infrastructure Indicators	Subcategories
Managerial indicators	Technical, organisational, economic, health/safety/environmental
Condition indicators	Substructure, superstructure, rail yards, electrification, signalling, information communication technologies

Source: Adapted from: (Stenstrom, et al., 2012)

The rail infrastructure indicator categories suggested by Stenstrom et al. (2012) are almost the same as the three categories developed by the British Standards (EN, BS. 15341: 2007). Managerial indicators encompass technical criteria that relate to reliability, availability, and maintainability, while condition performance indicators include indicators such as those based on rail profile measurements and profile quality indices (Stenstrom, et al., 2012).

From the perspective of rail infrastructure maintenance, a wide range of performance indicators are observed. According to the British Standards (EN, BS. 15341: 2007), rail maintenance performance indicators are generally categorized into three different groups:

- economic,
- technical, and
- organisational

Economic performance indicators mainly include costs and values. For instance, some performance indicators are utilized in life cycle analysis, such as the cost of down time, failure rate, and repair time (INNOTRACK, 2009). Technical performance indicators consider technical aspects of the maintenance performance at the work site. The number of failures, number of maintenance activities, damages to environment, are examples of this type of indicator. Finally, organisational indicators are those related to operations and resources, such as the number of internal maintenance personnel, direct/indirect maintenance personnel, and work shifts (EN, BS. 15341: 2007).

2.3.3 Performance Indicators Related to the Rail Profile

This thesis focuses on developing an understanding of performance indicators related to the rail profile. This section provides a series of templates to describe selected rail profile performance indicators currently used or being developed in North America. The performance indicators include:

- Grind Quality Index (GQI) [Profile Quality Index (PQI)]
- Surface Damage Index (SDI)
- Rail Corrugation Index (RCI)
- Equivalent Grinding Index (EGI)
- Average Rail Profile
- Head Loss
- Vertical Wear
- Gauge Wear
- Lateral Contact Position
- Contact Radius

Note that the SDI, RCI, and EGI are relatively new indices being developed in the industry. They have been included in the templates below, but are not considered further in the analysis within this thesis.

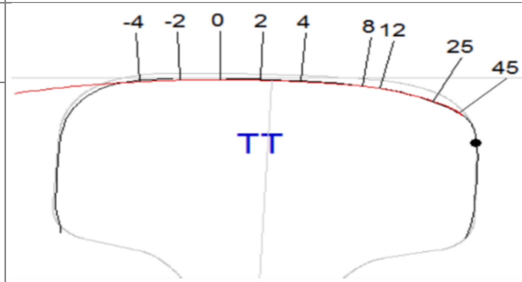
As shown in Figure 3, the templates include the following information:

1) *Performance Indicator*, which identifies the name of the PI.
2) *Developer*, which includes the citation of the main references developing the PI
3) *Illustration*, which provides an illustration of the PI
4) *Formula - Algorithm*, which provides a brief understanding of how the PI is measured
5) *Characteristics*, which provides information on usage and technical aspects of the PIs
6) *Application*, which describes the application of the PI in the railway industry

7) *Description*, which provides a brief description of the PI through a review of literature

<table>
<tr><td>1) Performance Indicator</td><td>2) Developer</td><td>3) Illustration</td></tr>
<tr><td></td><td></td><td rowspan="2"></td></tr>
<tr><td colspan="2" rowspan="3">4) Formula - Algorithm</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry ☐
Developed in Research ☐
Under development ☐
Segment-based ☐
Profile-based ☐
Unit ☐</td></tr>
<tr><td colspan="3">6) Application</td></tr>
<tr><td colspan="3">7) Description</td></tr>
</table>

Figure 3. Template Used to Describe Rail Profile Performance Indicators

1) Key Performance Indicator	2) Developer	3) Illustration
Grind Quality Index (GQI) Profile Quality Index (PQI)	Various	 Source: Adapted from Rangecam 12.3 RPR Office System

4) Formula – Algorithm

a) Advanced Rail Management and Holland LP

GQI = $(|Extreme\ Gauge\ zone| + |Gauge\ Zone| + |Centre\ Zone|) * 1000$

b) Palese et al., 2004

GQI = 100 * (Ab / Aa + Ab)

Aa: area of the difference profile above the acceptance envelope

Ab: area of difference profile below the acceptance envelope

c) AREMA Standards (2009)

Rail Profile Quality Index (RPQI) =

$100 - (100/2)\sum_{I=1}^{n} TWF$[1] $(xi).D$[2](xi)

Segment RPQI (SRPQI) =

$(\sum_{j=1}^{M} LWF$[3]$j\ .RPQI)/\sum_{j=1}^{M} LWFj$

5) Characteristics

Utilized in Industry	■
Developed in Research	
Under development	
Segment-based	■
Profile-based	
Unit	NA

6) Application

The application of GQI [PQI] is to ensure quality in rail grinding. GQI, as a quality control tool, illustrates the effectiveness of grinding practice in reshaping the rail profile to the desired template. While indicating the health of the rail head, GQI enables railways to compare the shape of rail profile "before" and "after" the grinding program to determine the effectiveness of the grinding practice. In addition, GQI can be used to prioritize rail segments for grinding and to determine the amount (depth) of grinding that is required for each rail segment.

7) Description

GQI and PQI are rooted in the same definition (Vanderwees, 2018). Zarembski, et al. (2005) define GQI as a tool to illustrate how close the actual rail profile shape is to the desired rail profile before and after grinding. As such, it helps assess the effectiveness of rail grinding (S. Regehr, et al., 2017). While various methods exist for calculating GQI, they are developed based on the same approach. This includes normalizing the top of the actual and template profile (template alignment), followed by measuring the difference between the two profiles (Magel et al., 2018).

(a) Advanced Rail Management and Holland LP determine GQI by measuring the difference between actual and template profiles at three different zones; this approach is commonly used in North America (Magel et al, 2018). GQI varies between 0 to ∞. The value of zero for GQI is ideal, meaning that the shape of the actual rail completely matches the template.

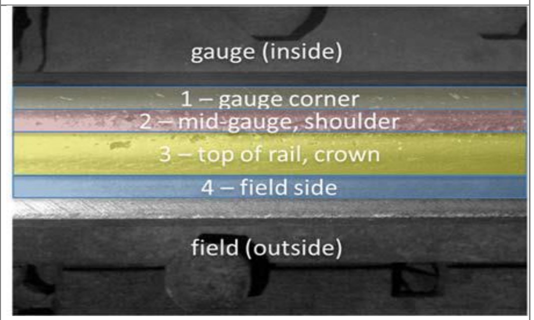
(b) Palese et al. (2004) measure GQI as the vertical deviation of the measured rail from the template in a specified range known as the "acceptance envelope" (Magel et al, 2018).

(c) The AREMA Standards consider the ideal GQI value at 100 (Magel, et al., 2018; AREMA Standards, 2009). AREMA Standards (2009) introduce the RPQI as either the vertical or "along lines normal to the template" (see the illustration) difference between actual and desired rail profiles. Using a longitudinal weighting function, SRPQI can be measured based on the RPQI for the rail segment.

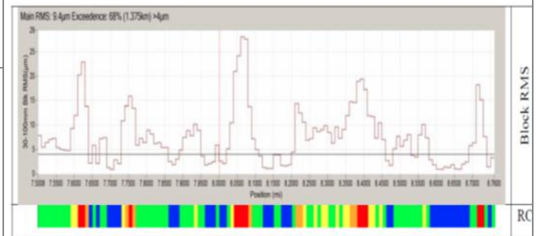
1 TWF: Transverse Weighting Function

2 D: Difference in all zones across the rail head

3 LWF: Longitudinal Weighting Function

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Surface Damage Index (SDI)</td><td>Magel and Oldknow (2018)</td><td rowspan="2">

Source: Adapted from (Magel and Oldknow, 2018)</td></tr>
<tr><td colspan="2" rowspan="2">4) Formula – Algorithm
The process of estimating surface quality in current practice mainly includes estimating the crack depth from the collected data. For instance, the surface images collected by machine vision systems need interpretation to estimate the crack depth. Also, the same process is required to estimate crack depth from the crack length data collected by eddy current systems.</td></tr>
<tr><td>5) Characteristics
Utilized in Industry
Developed in Research
Under development
Segment-based
Profile-based
Unit NA</td></tr>
<tr><td colspan="3">6) Application
According to Magel and Oldknow (2018), the application of the current practice in estimating the surface quality is to classify surface condition in order to support the preparation of a rail grinding plan.</td></tr>
<tr><td colspan="3">7) Description
Magel and Oldknow (2018) describe the opportunity for estimating and implementing a new SDI made possible by the development of machine vision tools and electromagnetic measurement systems. Britain and North America have made significant effort to quantify an estimation of crack characteristics based on the images collected from the rail surface (Magel and Oldknow, 2018). Magel and Oldknow (2018) explain a British framework, named “Blue book”, to determine the crack depth based on visual evidence. The image provided on the top right corner reveals a translation technique to determine the damage depth from the rail surface photographs.</td></tr>
</table>

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Rail Corrugation Index (RCI)</td><td>Magel and Oldknow (2018)</td><td rowspan="2">

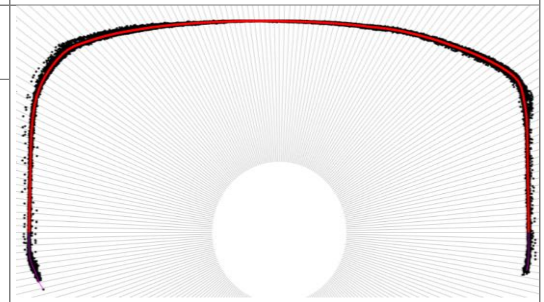
Source: Adapted from (Magel and Oldknow, 2018)</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm

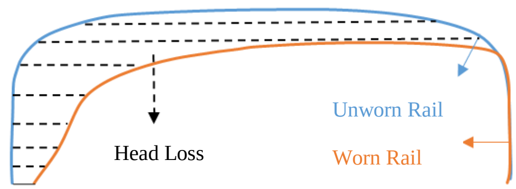
While various RCI estimation methodologies exist, the following formula is designed for use with data produced by a corrugation analysis trolley. It depends on the RMSBlock[1] and tolerance (TOL[2]) levels:

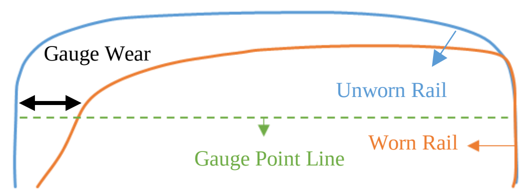
RCI = 100 * [1 – (RMSBlock – TOL)/(6 * TOL)]</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry: ■
Developed in Research: □
Under development: □
Segment-based: ■
Profile-based: □
Unit: NA</td></tr>
<tr><td colspan="3">6) Application
The main application of the RCI is in rail grinding quality control. According to Grassie, et al. (1999), the quality of grinding can be measured through estimating and monitoring RMS amplitude of the irregularities along the rail surface, considering specific limits.</td></tr>
<tr><td colspan="3">7) Description
According to Magel and Oldknow (2018) and Grassie, et al. (1999), surface irregularities trigger rail corrugation and noise, which causes complaints from residents alongside rail lines. Controlling rail corrugation through a preventive rail grinding program can address the associated problems with rail corrugation and reduce maintenance costs (Magel and Oldknow, 2018; Grassie, 2005, Grassie, et al., 1999). Grassie (2005) provides a detailed description of various measurement techniques and technologies for measuring and characterizing rail corrugation, including the corrugation analysis trolley (CAT). A more detailed description of CAT is provided by Grassie (1999). The image provided on the top right corner reveals the “block RMS values” reported by CAT. Magel and Oldknow (2018) suggests that an RCI be developed based on the measured depth of the corrugation with some allowable threshold.</td></tr>
</table>

[1] RMSblock = Root Mean Square for a specific length of track (block)
[2] TOL = Tolerance value

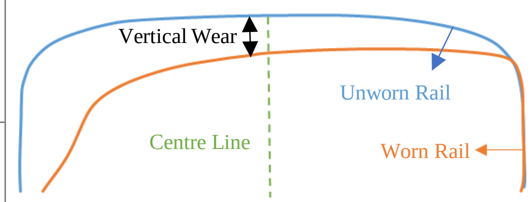
<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Equivalent Grinding Index (EGI)</td><td>NA</td><td rowspan="2">NA</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm
The following formula combines the PQI, SDI and RCI in a way that enables the grinding manager to decide the importance of each PI by assigning weighting coefficients:
$EGI = (W_{PQI} * PQI + W_{SDI} * SDI + W_{RCI} * RCI) / (W_{PQI} + W_{SDI} + W_{RCI})$</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry □
Developed in Research □
Under development ■
Segment-based ■
Profile-based □
Unit NA</td></tr>
<tr><td colspan="3">6) Application
The main application of the proposed EGI is to help decision makers, particularly grinding managers, consider the nature and timing of rail maintenance activities (Magel and Oldknow, 2018).</td></tr>
<tr><td colspan="3">7) Description
According to personal communications with railway experts, EGI is a new concept in railway asset management, which is under development. Magel and Oldknow (2018) mention the need to explore the trade-off between PQI, SDI and RCI. The reason for this need is that these PIs have different implications leading to specific decisions. For instance, on a particular segment, different values for PQI, SDI and RCI could imply different actions. EGI combines these PIs, assigning weighting coefficients to achieve a single value that can help grinding managers with the process of decision-making.</td></tr>
</table>

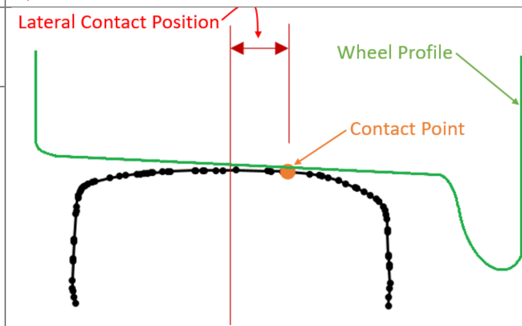
<table>
<tr><td>1) Key Performance Indicator</td><td>2) Developer</td><td>3) Illustration</td></tr>
<tr><td>Average Rail Profile (ARP)</td><td>(Regehr et al., 2017)</td><td rowspan="2"></td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm
1) Prepare array of x,y-coordinates for all rail profile
(2) Normalize x,y-coordinates in the y-dimension
(3) Create array of polar coordinates based on x,y-coordinates
(4) Depict a polyline connecting adjacent coordinates
(5) Superimpose radial lines and find their intersection points and polyline
(6) Calculate the mean of the intersection points</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry
Developed in Research
Under development
Segment-based
Profile-based
Unit: NA.</td></tr>
<tr><td colspan="3">6) Application
The application of ARP is to improve current practice in selecting a measured rail for GQI calculations. In other words, ARP improves “the objectivity and repeatability of the decisions that support rail-grinding activities”.</td></tr>
<tr><td colspan="3">7) Description
In practice, a profile located near the midpoint of a segment is usually selected as representative of the segment, which is a subjective approach. An Average Rail Profile is developed to represent the rail profile of each rail segment. This representative approach calculates the mathematical mean of a considerable number of rail profile coordinates using an automated procedure. Regehr et al. (2017) developed the ARP to provide a repeatable procedure to determine a representative rail profile for a segment, with the view that such a measure would support the planning and monitoring of rail grinding activities. While the current approach in practice is subjective and encounters several limitations because it is not repeatable, the procedure to determine the average rail profile is objective. To determine the ARP, an array of x,y-coordinates of all measured rail profile coordinates in a segment is created. Each profile is then vertically normalised to superimpose the rail profiles on one another (illustrated with black dots in the figure in the top right corner). The x,y-coordinates are then transformed to θ,ρ-coordinates to generate a polyline connecting adjacent coordinates and calculate the arithmetic mean of θ,ρ-coordinates to reach the average rail profile. One of the differences between this indicator and other PIs studied in this thesis is that the ARP represents a shape described by x,y-coordinates, rather than a numerical value. Therefore, further effort is required to transform the ARP into a single value to facilitate numerical analyses and make the indicator more broadly applicable.</td></tr>
</table>

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Head Loss</td><td>AREMA Standards (2009), Holland LP</td><td rowspan="2">
</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm
(1) Superimpose the measured rail on the standard unworn rail
(2) Calculate the area of intersection of two rails</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry ■
Developed in Research □
Under development □
Segment-based ■
Profile-based ■
Unit: %</td></tr>
<tr><td colspan="3">6) Application
Head loss is a measurement value that compares measured rail parameters to a superimposed unworn rail template. Head loss is expressed as a percentage difference to the unworn template of gauge, vertical and field wear combined.</td></tr>
<tr><td colspan="3">7) Description
Railhead loss may cause a derailment (Cannon D.F., 2003; Magel, 2011); therefore, it is important to measure and control this phenomenon using a PI. Head loss is an indicator showing the changes in the area of the railhead. The calculation of the difference between the rail head area of the measured rail and standard unworn rail results in head loss (AREMA Standards, 2009). This PI is displayed as a percentage, which differs from the vertical wear and gauge wear calculated in inches or mm. Head loss can be reported on a segment or profile basis. One of the limitations of this PI is that the calculation of railhead area is not always reliable in showing the changes in the railhead as a result of wear. In other words, various phenomena (e.g., plastic flow) cause rail to wear in different ways, which may not be captured by the head loss indicator. Industrial Metrics / Holland LP (2012) introduces a procedure to minimize the effect of plastic flow in the railhead area calculation. This procedure superimposes the measured rail on the standard unworn rail and then the intersection of these two rail profiles is calculated as the railhead area of the worn rail. Therefore, this method eliminates a part of the measured railhead that is outside of the gauge face of the standard rail’s perimeter.</td></tr>
</table>

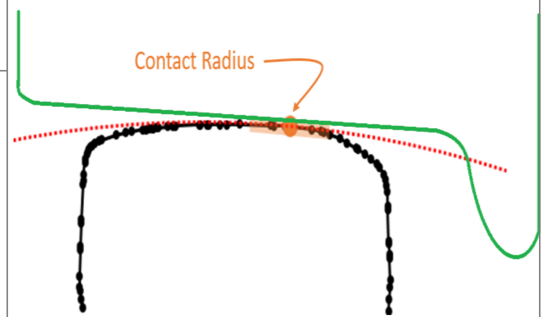
<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th colspan="2">3) Illustration</th></tr>
<tr><td>Gauge wear</td><td>AREMA Standards (2009), Holland LP</td><td colspan="2" rowspan="2">
</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm

(1) Draw the virtual line of gauge point line (worn/unworn rail).
(2) Find the gauge point (floating-point/fixed-point).
(3) Calculate the horizontal difference between the worn and unworn rail profiles at the gauge point.</td></tr>
<tr><td colspan="2">5) Characteristics</td></tr>
<tr><td>Utilized in Industry
Developed in Research
Under development
Segment-based
Profile-based
Unit</td><td>■
□
□
■
■
mm. [in.]</td></tr>
<tr><td colspan="4">6) Application
The main application of measuring and monitoring gauge wear is to prevent derailment (S. Kweens, personal communications, 2019).</td></tr>
<tr><td colspan="4">7) Description
Gauge wear is a PI that is developed to measure wear on the gauge face of the rail. It is defined as the horizontal distance between the actual and unworn rail profile at a specific point (known as the gauge point). Gauge wear measurements may be provided in two different ways: for segments or individual profiles. When reported as a segment-based indicator, a mean gauge wear may be calculated for analysis. The unit for measuring this PI can be inches or millimeters. Two methods can be used to measure gauge wear. The first method, known as ‘floating-point’, measures the gauge wear referencing a distance (5/8 inch in North America) below the top of the worn rail. The fixed-point method measures the gauge point referencing the top of unworn rail (AREMA Standards, 2009). Industrial Metrics / Holland LP (2012) defines the gauge point as the intersection of the gauge point line and the gauge face of the rail. The default settings for gauge wear measurement in Rangecam© use “floating-point”.</td></tr>
</table>

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Vertical wear</td><td>AREMA Standards (2009), Holland LP</td><td rowspan="2">
</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm
(1) Find the intersection of centerline and rail head
(2) Calculate the vertical difference between worn and unworn rail at the intersection point</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry
Developed in Research
Under development
Segment-based
Profile-based
Unit — mm. [in.]</td></tr>
<tr><td colspan="3">6) Application
Vertical wear is a key indicator to monitoring for the evaluation of rail grinding programs.</td></tr>
<tr><td colspan="3">7) Description
Vertical wear measures the vertical change in the top of the rail. Vertical wear shows the vertical difference between the top of the measured rail and the unworn standard rail at a specific point. The point is defined as the intersection of the vertical centerline and the top of the rail (AREMA Standards, 2009). The vertical wear is both profile and segment based. The unit for measuring this PI can be inches or millimeters.</td></tr>
</table>

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Lateral Contact Poistion (LCP)</td><td>Vanderwees (2018)</td><td rowspan="2">

Source: Adopted from Vanderwees (2018)</td></tr>
<tr><td colspan="2" rowspan="2">4) Formula – Algorithm
(1) Data setup
(2) Determine railhead slope, limit and middle points
(3) Determine the best curve fit to railhead
(4) Determine the lateral contact position and contact radius based on findings in (2) and (3)
(5) Plot the railhead profiles</td></tr>
<tr><td>5) Characteristics
Utilized in Industry □
Developed in Research ■
Under development □
Segment-based ■
Profile-based □
Unit mm.</td></tr>
<tr><td colspan="3">6) Application
According to Vanderwees (2018), the lateral contact position provides an understanding of a rail profile’s characteristics and the interaction between the rail profile and the wheel. The lateral contact position can be applied to the wheel-rail interface monitoring and management tools in the industry. In other words, the industry would benefit from this PI in improving proactive maintenance practice. Lateral contact point can quantify and depict the wheel-rail contact. This enables the use of temporal trending graphs to demonstrate the effectiveness of rail grinding as well as to predict rail condition.</td></tr>
<tr><td colspan="3">7) Description
The lateral contact point is a rail profile performance indicator that numerically quantifies and graphically illustrates the rail and rolling stock wheel contact point (Vanderwees 2018).
Vanderwees (2018) explains that the effort to develop the lateral position of the contact point is rooted in previous efforts by Hornaday (2006, 2010) and Abadpour & Alfa (2007). Vanderwees (2018) developed a method, based on rigid contact theory and accounting for the cant angle and the wheel tread slope, to locate the lateral contact point on the top of rail. The algorithm developed to calculate this PI uses the rail profile x,y-coordinates that are collected by optical rail measurement technology. This indicator has only been applied to tangent segments.</td></tr>
</table>

<table>
<tr><th>1) Key Performance Indicator</th><th>2) Developer</th><th>3) Illustration</th></tr>
<tr><td>Contact Radius (CR)</td><td>Vanderwees (2018)</td><td rowspan="2">

Source: Adopted from Vanderwees (2018)</td></tr>
<tr><td colspan="2" rowspan="3">4) Formula – Algorithm
(1) Data setup
(2) Determine railhead slope, limit and middle points
(3) Determine the best curve fit to railhead
(4) Determine the lateral contact position and contact radius based on findings in (2) and (3)
(5) Plot the railhead profiles</td></tr>
<tr><td>5) Characteristics</td></tr>
<tr><td>Utilized in Industry ☐
Developed in Research ■
Under development ☐
Segment-based ■
Profile-based ☐
Unit mm.</td></tr>
<tr><td colspan="3">6) Application
According to Vanderwees (2018), measuring the radius of the railhead at the point of contact (i.e., the contact radius) provides a better understanding of a rail profile’s characteristics and the interaction between rail and the wheel. Contact radius can be applied to the wheel-rail interface monitoring and management tools used in the industry. In other words, the industry would benefit from this PI in improving proactive maintenance practice. The contact radius can quantify and depict the wheel-rail contact. This enables the use of temporal trending graphs to demonstrate the effectiveness of rail grinding as well as to predict the rail condition.</td></tr>
<tr><td colspan="3">7) Description
The contact radius numerically quantifies the radius of the railhead at the point of wheel-rail contact (Vanderwees, 2018). Vanderwees (2018) explains that the effort to develop the contact radius is rooted in previous efforts by Hornaday (2006, 2010) and Abadpour & Alfa (2007). The algorithm to calculate this PI uses the rail profile x,y-coordinates collected by optical rail measurement technology. The contact radius is observed based on a selected number of points around the contact point located on the rail profile (Vanderwees, 2018).</td></tr>
</table>

2.4 Summary

The literature review revealed the following key findings and knowledge gaps:

- The literature defines rail deterioration mechanisms with different but interrelated terminologies and subcategories (e.g., rail wear, plastic flow, rail fatigue, and rail defect). While different rail deterioration mechanisms require different treatments, rail grinding is one of the most common treatments applied in the industry.
- The literature demonstrates the importance and challenges of implementing asset management concepts within railway maintenance programs. Asset performance monitoring and prediction (for example, based on trend analysis) and data management are two key challenges identified in literature and practice.
- The literature discusses a number of rail maintenance software tools and case examples. The software tools are capable of estimating, predicting, and monitoring rail deterioration rate. In addition, they support execution of maintenance activities (e.g., rail grinding and lubrication), quality control, and management.
- While discussing the key concepts and different categories of performance indicators, the literature revealed that measuring and monitoring the performance of an asset and performing quality control on maintenance activities (e.g., rail grinding) is crucial in improving the level of service and life cycle of the rail infrastructure asset.

- Numerous performance indicators are used in the rail maintenance industry. This chapter identified and described the following indicators:

1. Grind Quality Index (used in practice)
2. Surface Damage Index (under development)
3. Rail Corrugation Index (used in practice)
4. Equivalent Grinding Index (under development)
5. Average Rail Profile (developed in research)
6. Head Loss (used in practice)
7. Gauge Wear (used in practice)
8. Vertical Wear (used in practice)
9. Lateral Contact Position (developed in research)
10. Contact Radius (developed in research)

- Although various performance indicators exist (whether they are used in practice, developed in research, or still under development), there is a need to determine the relationships between them and to develop an integrated tool comprising these PIs. Such a tool could support a broader understanding of current rail condition and forecasted future rail condition.

3 METHODOLOGY

This chapter describes the data structure and the algorithm that was developed to extract data, analyze rail profile performance indicators, and store the results. Specifically, this chapter: (1) discusses data structure and preparation, (2) describes the algorithm, and (3) outlines the correlation analysis methodology. The algorithm is developed to be compatible with the data produced by and used within Holland®'s Rangecam Office and Grind Analyst® Software. However, the algorithm runs outside of Rangecam.

3.1 Data Structure and Preparation

This section describes the data structure and preparation required for performing the trending and correlation analyses. The thesis considers four data types:

- rail profile text files
- track segment report Excel® files
- grind quality control report Excel files
- head loss, gauge wear, and vertical wear Excel files

The following sub-sections provide details about extracting the required databases from Rangecam, folder structure and organization, sorting rail profile text files, and determining eligible segments.

3.1.1 Exporting Required Data from Rangecam©

The algorithm exports the four data types listed above (i.e., rail profile, track segment reports, grind quality reports, and statistics on head loss, gauge wear, and vertical wear) from Rangecam to create a database comprising TXT or XLS files in separated folders. Vanderwees (2018) provides a detailed description of rail profile text files and the process of exporting them from Rangecam. In the original process of exporting rail profile data from Rangecam into text files, the user is able to perform rail profile sorting manually or with an automated sorting subroutine. A set of criteria is also considered for segments in order to increase the accuracy of further analysis. Therefore, only those segments that meet the criteria are sorted into segment folders. This thesis updates the work by Vanderwees (2018) to include an automatic procedure to extract and sort the rail profile text files by year. Section 3.2.1 describes this procedure in further detail.

The rail profile database available for this thesis consists of the rail profile text files obtained for roughly 100 miles (160 km) of a closed-fleet, heavy-haul short-line railway in Canada during 14 data collection runs:

- September 1995
- May 1997
- May 1998
- June 2001
- May 2003
- June 2004
- May 2005
- October 2006
- May 2007
- October 2009
- May 2010
- October 2010
- October 2011
- October 2012

On average, each of the 14 data collection runs comprises 130,000 rail profile text files. In total, the algorithm developed in this thesis processes, sorts, and analyzes almost two million rail profile text files.

The track segment report provides detailed information (e.g., geometry, curvature, length) on each track segment (both curves and tangents) and their subdivisions that are available in the database. This report is accessible in Rangecam and is transferable to various formats such as PDF and XLS. This report provides the data required for section 3.2.1 (Sort Rail Profile).

Rangecam performs grind quality calculations, which provide the data required to perform temporal trending analysis of GQI. Rangecam enables users to adjust settings (e.g. grinding plan and grind zone boundaries), execute the calculations for a year of data collection and export the results (i.e., grind quality report) in either TXT or CSV formats using a preferred name on the local computer drive.

The grind quality report comprises the information about grind quality calculation runs (e.g., run date and covered rail mileages), the rail segment information (e.g., mileposts, rail type, rail side, degree and direction of curvature), and the result of calculations for each grind zone (e.g., extreme, gauge, centre and field zone) as well as crown radius. For the purpose of this thesis, the grind quality report is stored in a CSV format within its year of data collection run as its name. The CSV files should be stored in a database folder, named *GQI_Input*, on a specific computer drive accessible for the algorithm to locate the database.

The Rangecam export run enables the user to adjust the export run settings (e.g., selecting a data collection run, spacing and GPS coordinate settings, and formatting such as measurement units) and export the run database in CSV format. The database comprises the data required for temporal trending and correlation analyses of head loss, gauge wear and vertical wear. This includes information about the run (e.g. track code, run date, and railway authority), rail segment information (e.g. rail type, side, and scaled location) and the result of measurements (e.g., vertical wear, gauge wear, and head loss).

The CSV files should be stored with the year of the data collection run as the filename in a database folder (named *HL_GW_VW_Input*) on a computer drive accessible to the algorithm. The database requires reformatting so that it includes only the data required for head loss, gauge wear and vertical wear analysis (e.g. mileposts, side, calculation results).

3.1.2 Folder Structure and Naming Requirements

The rail profile text files exported from Rangecam must be organized using a specific folder structure and naming format, as shown in Figure 4. Data are sorted by year, segment, and the left or right rail. Vanderwees (2018) provides a more detailed description of naming the segment folders and organizing the text files in each folder. For each year, folders include the segment folders and the grind quality control report and the head loss, gauge wear, and vertical wear Excel files.

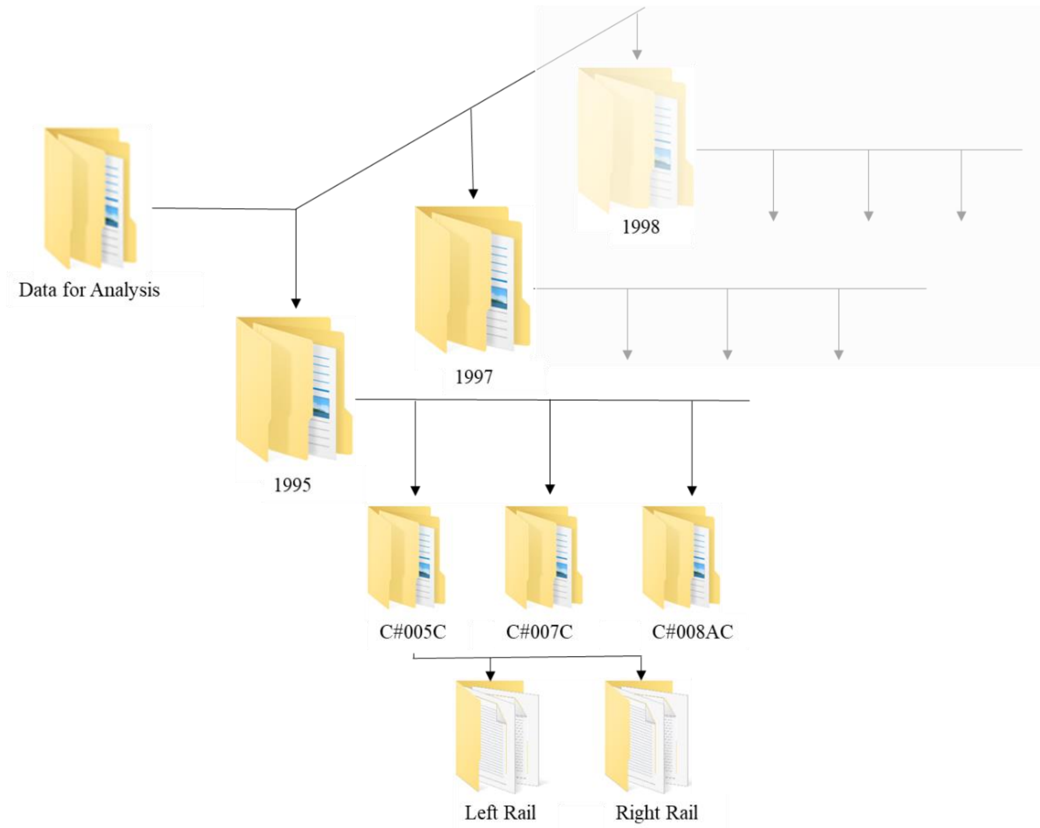


Figure 4. Folder Structure and Naming Format

3.2 Description of the Algorithm

This section describes the algorithm developed for this research. The algorithm provides an automatic procedure to extract historical rail profile data for available track segments, calculate rail profile performance indicators (e.g., head loss, vertical wear), and analyze and store the results of the PI calculations.

The algorithm is developed and tested in MATLAB and runs outside of the Rangecam software suite, but requires four different data outputs from Rangecam. Consequently, the structure of the Rangecam data (see Section 3.1) influences certain steps within the algorithm. The algorithm addresses this by applying adaptations to the data files, which will be discussed in the following sections. Nevertheless, the rail industry can use the concepts this research develops to assist in rail maintenance practices, regardless of the software being utilized.

The algorithm runs a series of functions to analyze PIs extracted from Rangecam, integrates algorithms developed earlier by Vanderwees (2018) and Regehr et al. (2016), and analyzes the results of these two steps. Figure 5 shows a flow chart diagram of the algorithm. At a high-level, the algorithm:

- prompts the user to select a segment type (curve or tangent) for analysis;
- analyzes each rail segment of the selected segment type;
- organizes the data resulting from the analysis and exports it to Excel;
- develops temporal trending graphs, and
- organizes the temporal trending graphs and stores the results.

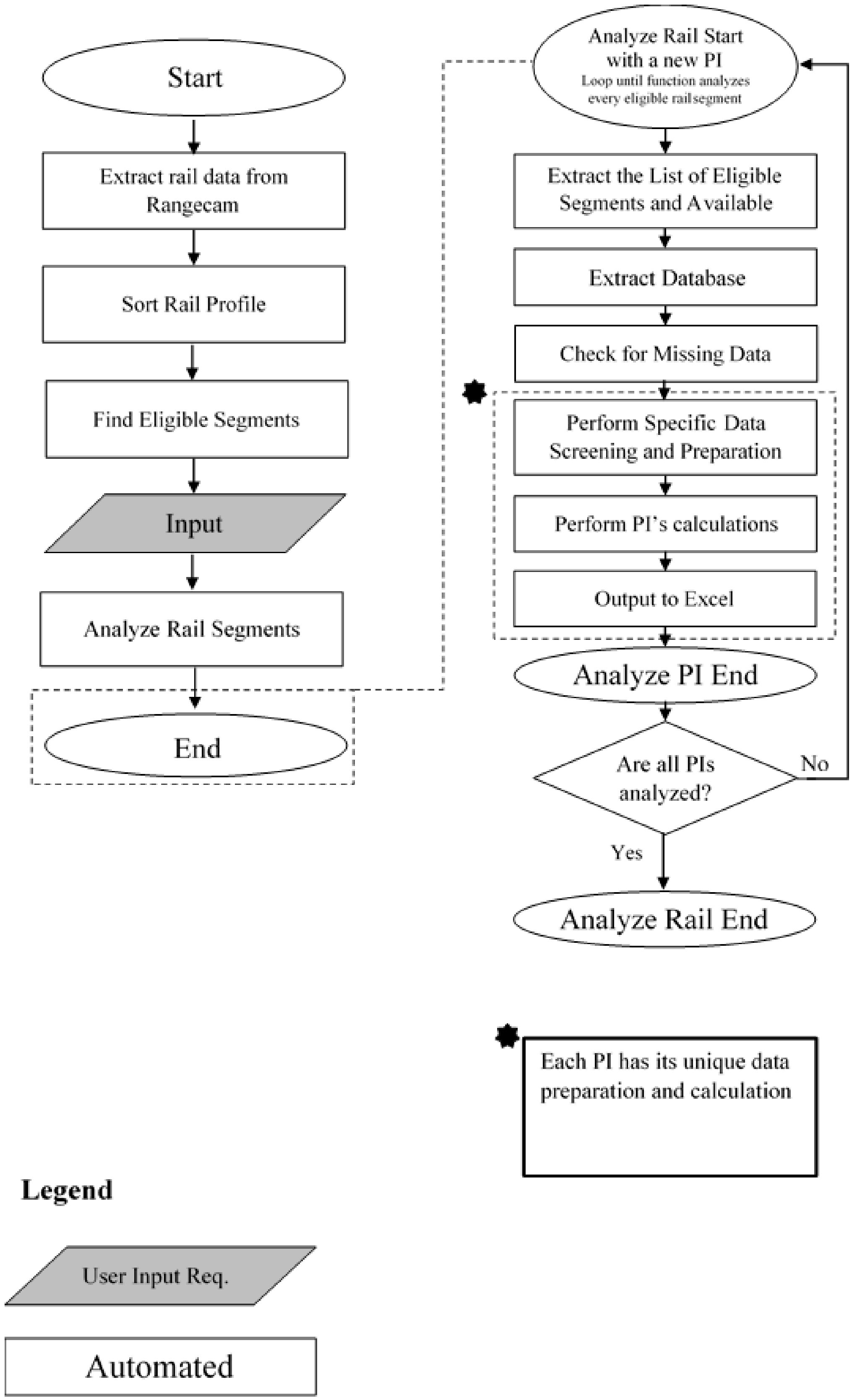


Figure 5. Flow Chart Diagram of the MATLAB Algorithm

For each rail segment, the algorithm:

- extracts the list of eligible segments and available years, rail profile data, and profile-based PIs (e.g., gauge wear, vertical wear, head loss, GQI);
- cleans data inputs for analysis by checking the database for missing data and performs PI-specific data screening;
- calculates each PI for each eligible segment over the available years; and
- organizes and stores the results of the analysis in a database.

To support the ensuing algorithm description, Figure 6 provides a simplified version of the algorithm's main functions. The following sub-sections provide details of each of these functions. Figure 7 illustrates the steps of the *Analyze_Rail_Segments* function described in Section 3.2.4.

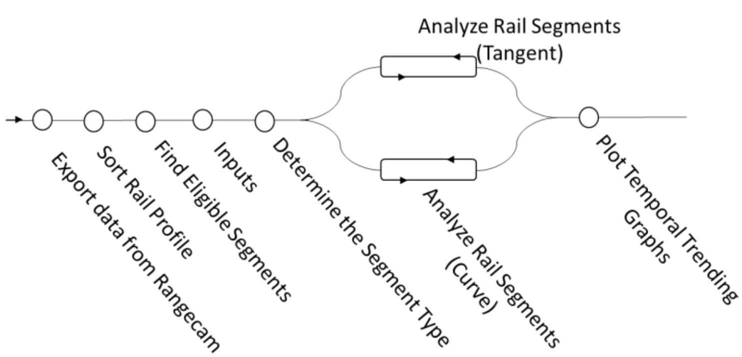


Figure 6. Simplified Flow Diagram of the Algorithm's Main Functions

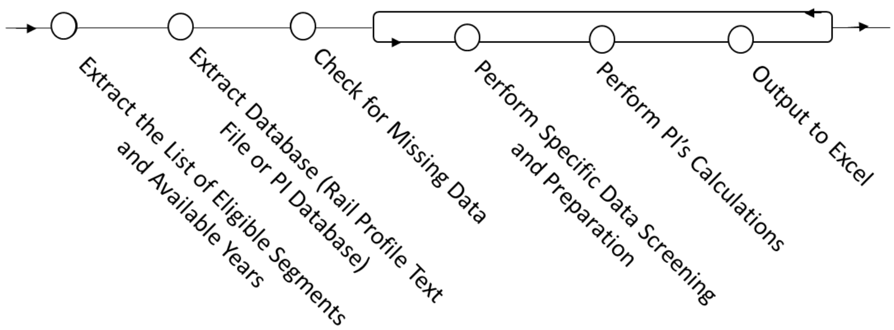
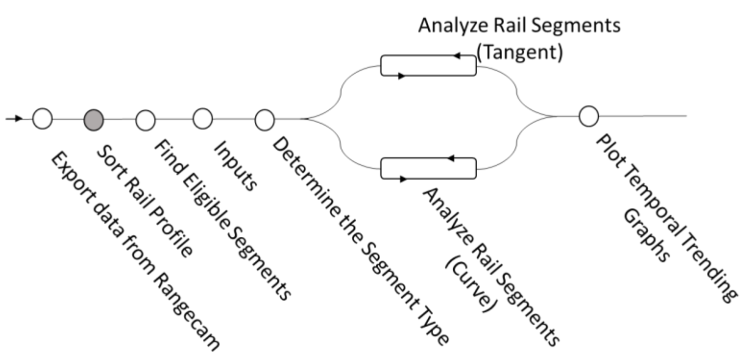


Figure 7. Simplified Flow Diagram of *Analyze_Rail_Segments* Function

3.2.1 Sort Rail Profile



Inputs:

- The list of years under study

Outputs:

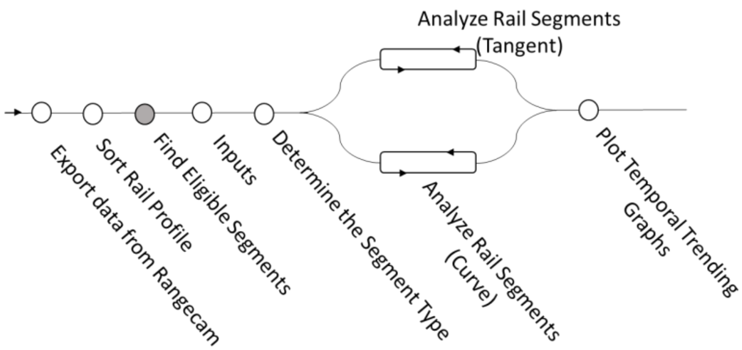
- Curves and tangents folders
- Available year folders
- Segment folders
- Rail folders

Vanderwees (2018) developed the original version of the *Sort_Rail_Profile* function, which required user interaction to select the rail profile database of a specific year. In this thesis, the *Sort_Rail_Profile* function is updated to an automatic procedure so that user interaction is no longer necessary. The function requires the list of years under study to be able to locate the folder of each target year in the database, extract the rail profile text files in each folder, and organize and structure the text files into separated folders based on the segment codes and specifications.

Figure 4 (see Section 3.1.2) illustrates the hierarchical structure of the database provided by the *Sort_Rail_Profile* function. The function uses a control panel to apply a set of criteria defined by Regehr (2016) and Vanderwees (2018) to the rail profile text files. This function is the initial step to determine the eligible segments for analysis. The criteria are listed below:

- **Minimum Number of Profiles**, which ensures that the track segments have at least 30 profile text files in each east and west rail.
- **Allowable Percentage Difference**, which ensures that the percent difference between the number of profile text files existing in the west and east rail is not more than 50%.
- **Maximum Collection Interval**, which ensures that the collection intervals of the rail segments meet the maximum collection intervals reported in the database. Appendix A provides the maximum collection intervals reported in the database.

3.2.2 Find Eligible Segments



Inputs:

- Segments database
- The list of years under study

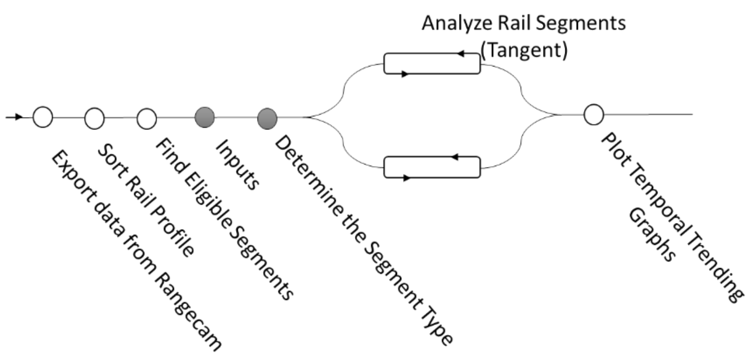
Outputs:

- Segment code
- Number of available years
- Available years

After sorting the rail profile text files, for each year, segment folders are created for those segments that met the eligibility criteria. However, this does not ensure that a segment that met the criteria for a specific analysis year would also meet the criteria in other analysis years. The consistency of the segments over the 14 years of available data is important for analysis accuracy.

This function starts analyzing the available segments that meet the criteria defined in Section 3.2.1 and are already sorted in folders using the *Sort_Rail_Profile* function. The procedure requires the list of the years that data are available as an input. Then, the procedure holds the first segment of the first year database and compares its name with other segment's names in the next year's database. If any segment's name in the second year database matches the selected segment's name, the counter is indexed by one and the procedure moves to the next year's database; otherwise, the procedure moves to the next year's database without indexing the counter. At the end of the procedure, the name of the selected segment, its counter value, and the available years are stored. This algorithm continues until all the segments are counted. Before storing the results in Excel, the algorithm deletes the segments that are unavailable for more than 12 years from the result database. Appendix B indicates the list that is provided using the function described in this Section.

3.2.3 Inputs and Determine the Segment Type



Inputs:

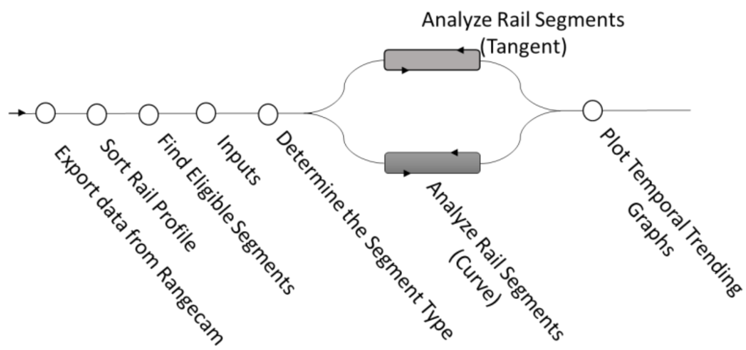
- Not applicable

Outputs:

- Segment type (tangent or curve)

The *Inputs* function prompts the user to select a segment type (either tangent or curve) to start the analysis. The algorithm requires the *Determine_the_Segment_Type* function to be able to continue the process. The purpose of this function is to lead the algorithm through the *Analyze_Rail_Segment* function that requires different databases for analyzing curves and tangents. The *Determine_the_Segment_Type* function enables the algorithm to run the procedures of data extraction and preparation based on the segment type, as tangents and curves have different databases.

3.2.4 Calculating and Analyzing PIs on Rail Profiles and Segments



This section covers four different procedures developed for data preparation and PI calculation, as discussed in sections 3.2.4.1 to 3.2.4.4. Each procedure consists of different functions that are developed to perform data preparation, PI calculation, and storage of the results in Excel. The subsections cover the functions developed for analysis purposes. As shown earlier in Figure 7 for each PI, the *Analyze_Rail_Segment* function screens and prepares the data, performs the calculations needed for that PI, and stores the data in Excel.As discussed earlier, this thesis conducted a comprehensive review of performance indicators related to rail profile maintenance practices. This review revealed seven indicators of particular relevance to this research:

- Average rail profile
- Contact radius
- Lateral contact position
- Grinding Quality Index (GQI)
- Head loss
- Gauge wear
- Vertical wear

Each of these PIs requires a specific type of rail data and a unique calculation methodology. Therefore, different data preparation and calculation procedures are required, based on the PI's specifications, to perform the targeted analysis on rail segments using all the PIs mentioned above. At a high level, the analysis procedure is the same for all seven PIs; however, they differ in their details. The detailed analysis procedures for each PI are provided in sections 3.2.4.1 to 3.2.4.4. The algorithm targets a segment, calculates a specific PI on both the west and east rails of the segment in every year of the available database, organizes and stores the result, and then moves to the next segment. The algorithm continuously performs calculations and analyses for the rail profile PIs using the database that is organized based on a specific hierarchical structure (see Figure 4). Figure 8 illustrates the analysis hierarchy.

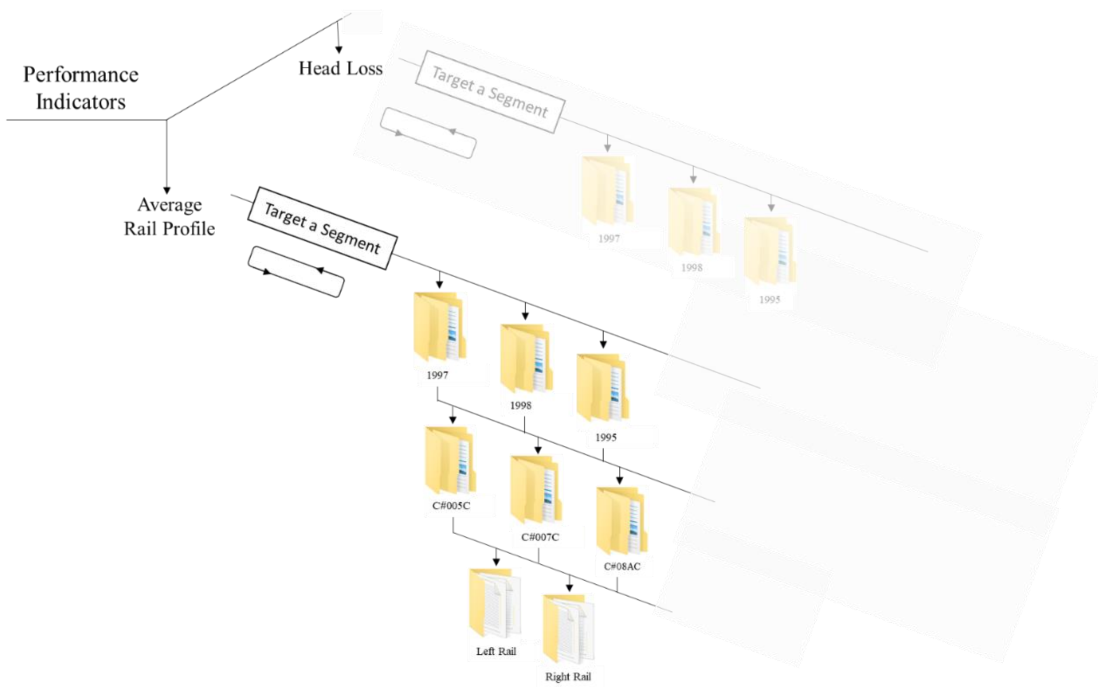
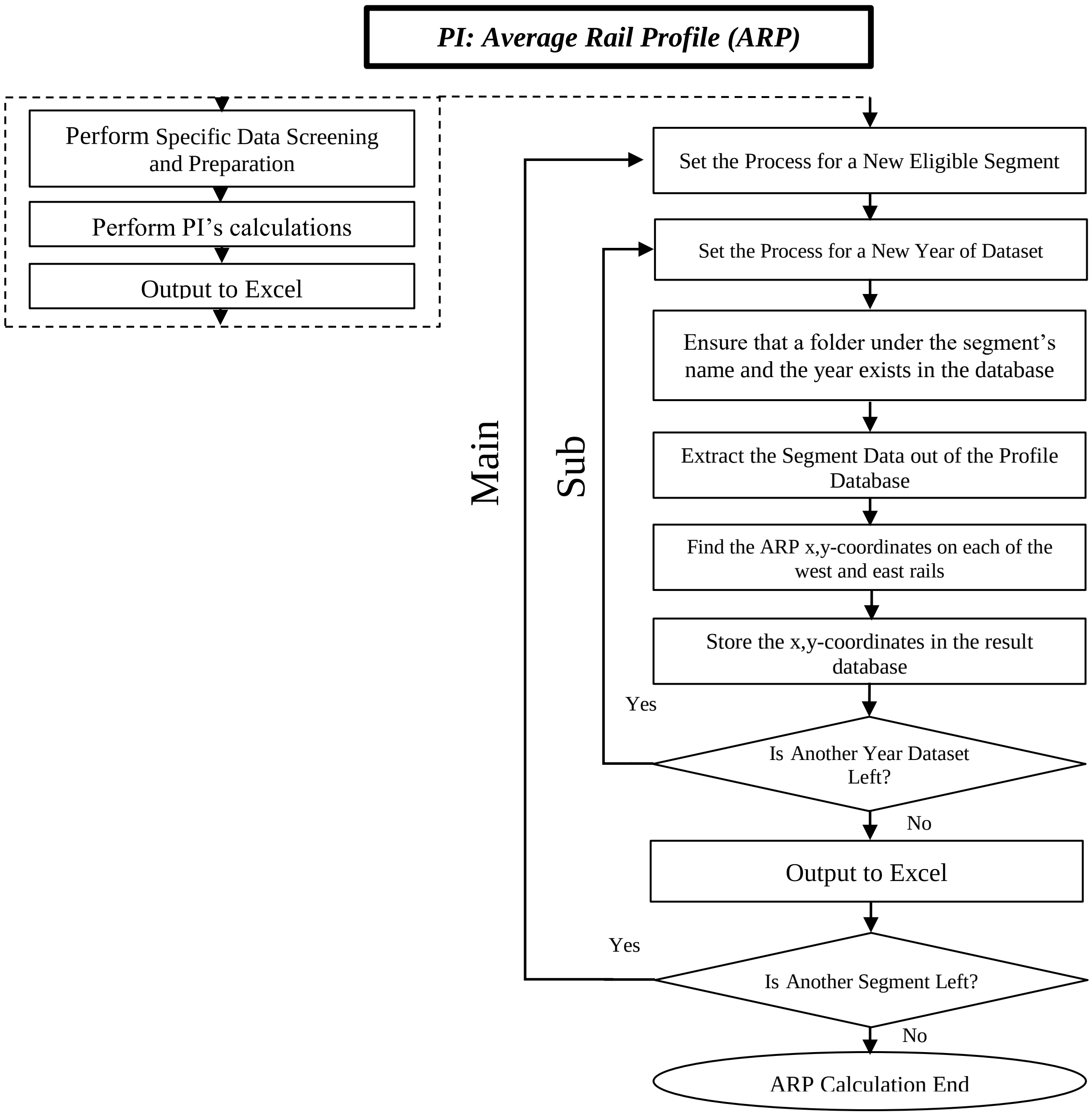


Figure 8. Analysis Hierarchy Performed by *Analyze_Rail_Segment* Function

3.2.4.1 Analyze Average Rail Profile



Inputs:

- List of eligible segments
- Segments database (rail profile text files)

Outputs:

- ARP x, y-coordinates of the eligible segments over the available period of study

This section provides a detailed description of the original procedure for determining the ARP and the set of functions developed and added to the procedure for the purpose of this thesis. The set of functions enhances the original procedure to determine a segment's average rail profile developed by Regehr et al. (2017). The original procedure requires user interaction to locate track and rail segments and a year in the database to start the analysis. This is time-consuming when analyzing multiple segments for many years, as is done in this research. Therefore, this thesis developed an automatic procedure to locate and extract the rail profile text files, perform calculations and analysis on the rail profile data, and organize the results in the Excel database. The procedure consists of two cycles. The main cycle, which targets the segments, ensures that all the eligible segments are analyzed. The sub-cycle, which ensures the analysis of ARP over the years that data are available, controls every step of ARP analysis.

As mentioned earlier, the *Analyze_Rail_Segment* function measures the PIs on both east and west rails of track segments over the years that rail profile data are available in the database (see Figure 8). Therefore, the automatic procedure establishes a framework for targeting the segments from the eligible segments list, and selects a start year within the study period. The first step in the analysis process is to confirm that the previous two steps (targeting a segment and selecting a year) have correctly prepared the folder structure. This ensures that the procedure runs without error. The procedure continues the analysis of the next segment/year in the case that the targeted folder is unavailable, and the user is notified with a prompt statement.

As summarized in Section 2.3.3, the ARP calculation and verification procedure consists of the following six steps (Regehr et al., 2017):

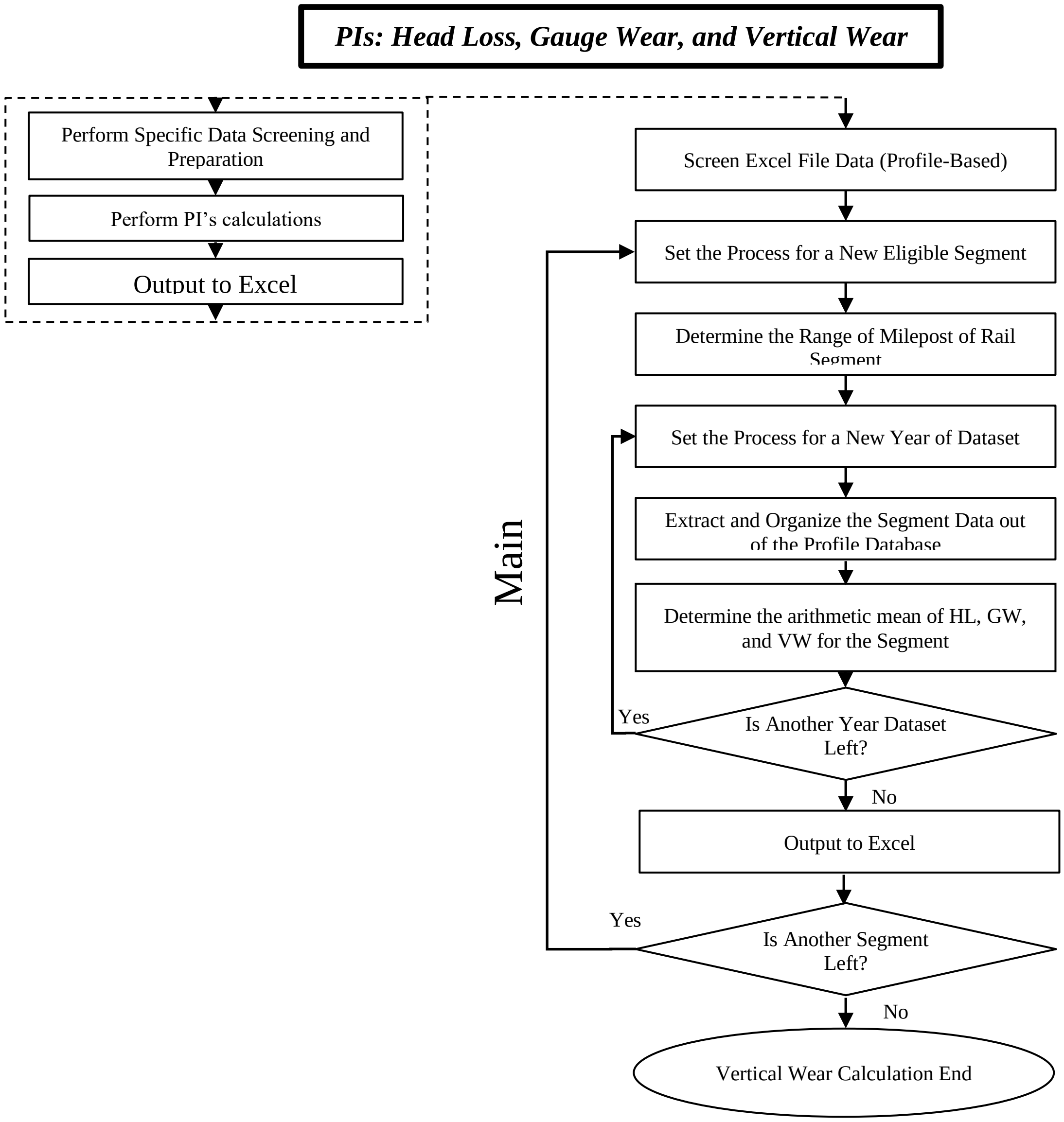
- Step 1. Create an array of x,y-coordinates for all the rail profiles in the targeted segment.
- Step 2. Superimpose the measured x,y-coordinates of rail profiles by normalizing and aligning the coordinates on the vertical axis, which sets y-coordinates to a specific origin while keeping the x-coordinates consistent (i.e., no change in a rail profile's shape). This step sets the origin to the center of the unworn rail profile.
- Step 3. Transform the measured x,y-coordinates into polar coordinates.
- Step 4. Create a polyline connecting the adjacent coordinates using the result of Step 3, which creates the rail profile shape.
- Step 5. Superimpose a set of radial lines originating from the origin and determine a new set of θ, ρ-coordinates by measuring the intersection of the lines and polylines for a consistent set of θ.
- Step 6. Determine the arithmetic mean of the θ, ρ-coordinates for each intersection point.

This thesis adds two more steps to organize the final results in preparation for the temporal trending analysis. Therefore, in Step 7 the θ, ρ-coordinates are transformed back into x,y-coordinates.

The result of each sub-cycle run is organized and stored in a structured array defined by MATLAB, and the final result of the sub-cycle analysis is exported to the *ARP_Final_Result* Excel database. The results database for the ARP is different than the other PIs, since it must store a set of x,y-coordinates that describe the shape of the ARP, rather than just a single mean value.

This thesis adds two more steps to organize the final results in preparation for the temporal trending analysis. In Step 7 the θ, ρ-coordinates are transformed back into x,y-coordinates. Finally, Step 8 'un-normalizes' the coordinate data of the calculated average rail profile, effectively undoing Step 2. This enables the profiles for a segment calculated over multiple years to show actual wear over time with reference to the original vertical datum. Occasional inconsistencies in the vertical datum over time represent a limitation in this final step, since the final positioning of the average rail profile does not always agree with other measured values of rail wear.

3.2.4.2 Analyze Head Loss, Gauge Wear, and Vertical Wear



Inputs:

- List of eligible segments
- Rail profile text files

Outputs:

- Segment-based Head Loss (HL), Gauge Wear (GW), and Vertical Wear (VW) for the eligible segments over the available study period

This section of the algorithm processes the values of HL, GW, and VW determined by Rangecam. Therefore, this part of procedure is only responsible for screening the PI values, organizing the values, distinguishing the east and west rail, and determining the arithmetic mean of the profile-based PI values to produce segment-based values.

The first step of this procedure performs data screening on the profile-based Excel file containing HL, GW, and VW values exported from Rangecam. A customized MATLAB function called *Screen_It* is developed to perform data screening on the Excel input. This function applies some basic controls on the input data. For example, the function ensures that the input values are in a reasonable range based on pre-defined thresholds. It also removes null and negative values from the database. Table 7 provides these thresholds.

Table 7. Thresholds to Apply Data Screening for HL, GW, and VW

Performance Indicator	Minimum	Maximum
Head Loss (%)	0	40
Gauge Wear (mm)	-5	20
Vertical Wear (mm)	0	25

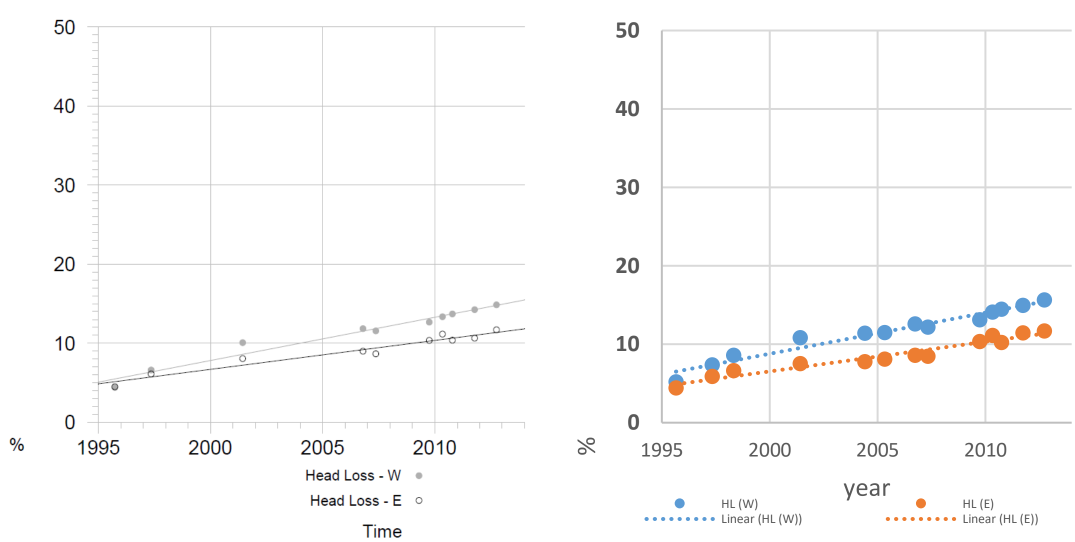
As in the APR analysis, this procedure utilizes a dual-cycle framework. The main cycle, which targets the segments, ensures that all the eligible segments are analyzed. The sub-cycle, which ensures the analysis of HL, GW, and VW over the years that data are available, controls every step of the analysis for these three PIs. Notably, the gauge wear values obtained from Rangecam are calculated based on the default settings, which uses the “floating-point” method (see gauge wear description in section 2.3.3).

After targeting a segment, the main cycle starts by determining the range of mileposts covered by the targeted segment. The Excel files exported from Rangecam contain information about rail segments in a sequential format. Each row of the sheet is allocated to a specific rail segment (e.g., west rail), which is followed by the rail segment on the other side of the same segment (e.g., east rail). This keeps repeating for all the rail segments. Therefore, it is necessary to determine the range of mileposts included in the targeted segment to find its row in the Excel sheet, and then to obtain its PI values for both east and west rail segments.

This objective is achieved by two customised MATLAB functions named *Find_Old_StartingPost* and *Find_New_StartingPost*. The reason to use two functions with the same objective but different targets is because a segment's mileposts may not be consistent over time. For example, in the data analyzed for this thesis, these functions use the database folders for years 1995 and 2007 as the references for old and new mileposts, respectively. The mileposts were the same between 1995 and 2006; however, they were changed in 2007 and remained the same for the following years. Therefore, the mileposts in 1995 and 2007 are the reference for old and new mileposts, respectively. As mentioned in section 3.1.2., the segment folders are named using the codes and mileposts of the segments. The *Find_Old_StartingPost* and *Find_New_StartingPost* functions enable the determination of the old and new mileposts using the segment's names existing in the database folders for 1995 and 2007.

After selecting a new database year, the sub-cycle extracts the PI values of the rail profiles in the targeted segment from the Excel file. A customized MATLAB function named *Locate_By_Milepoint* is developed to locate the profile-based PI values in the database and extract them to a new MATLAB array. This function uses the reference mileposts determined using the *Find_Old_StartingPost* and *Find_New_StartingPost* functions.

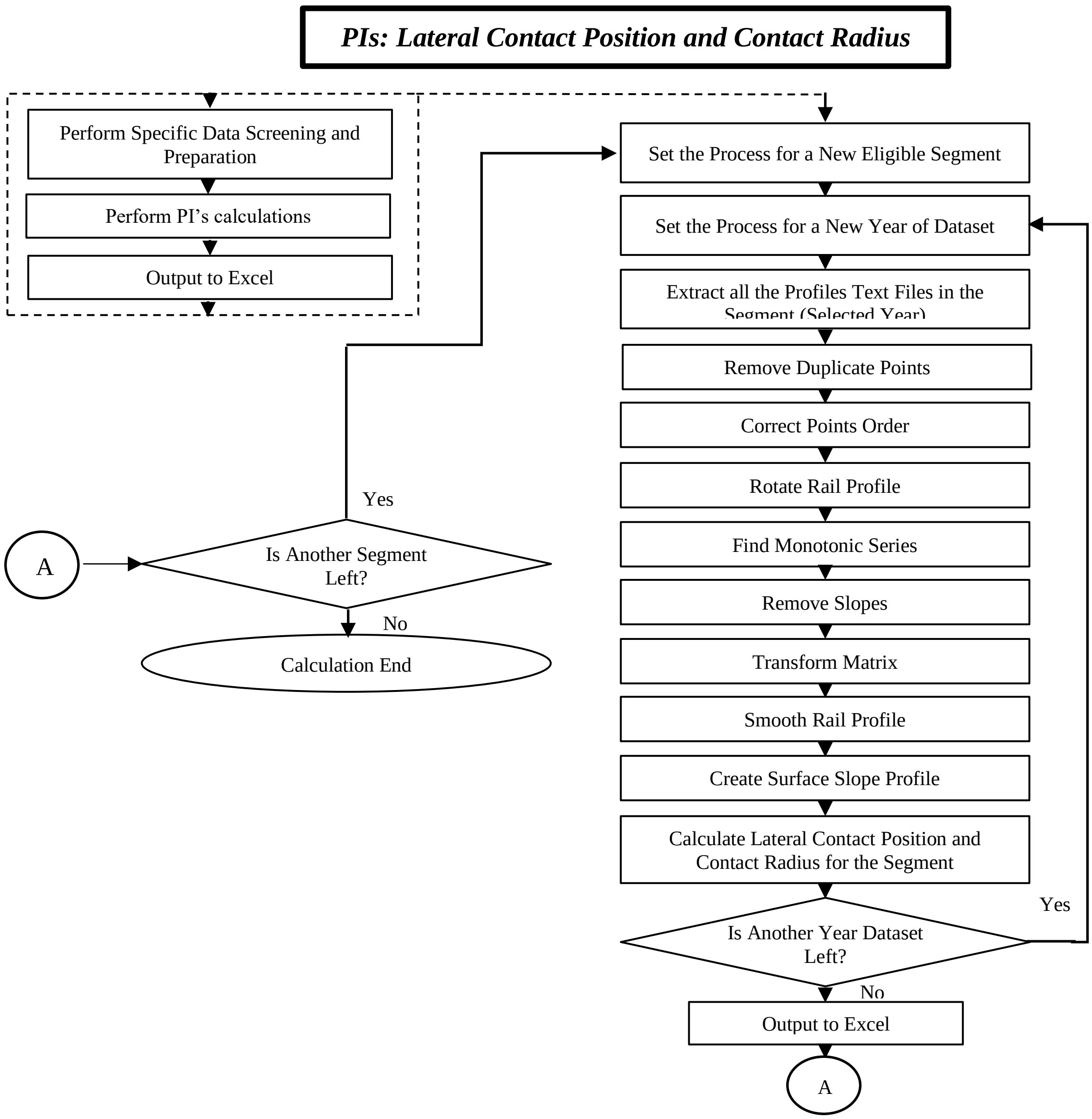
The next step is to organize the data for the targeted segment. In this step, profiles for the east and west rails need to be separated from each other. This objective is achieved by a MATLAB function named *Locate_By_Side*, which is developed to store PI values of the rail profiles for each west and east rail in separate arrays. Next, the sub-cycle calculates the segment-based values of the head loss, gauge wear, and vertical wear. Rangecam calculates the segment-based values of head loss, gauge wear, and vertical wear as the arithmetic mean of the profile-based values. This thesis independently verified these calculations using HL values for a specific segment. As shown in Figure 9, the segment-based HL values produced by Rangecam match the mean HL calculated using values obtained from all profiles in that segment. Therefore, the arithmetic mean MATLAB function is used to determine the PI values for the target segment. Finally, the result of each sub-cycle run is organized and stored in a structured array defined by MATLAB, and the final result of the sub-cycle analysis is exported to the *Final_Result* Excel database.



(a) (b)

Figure 9. (a) HL Graph Provided by Rangecam (b) HL Graph Based on the Arithmetic Mean of Profile-Based HL

3.2.4.3 Analyze Lateral Contact Point and Contact Radius



Inputs:

- List of eligible segments
- Segment database (rail profile text files)

Outputs:

- Lateral contact position (LCP)
- Contact radius (CR)

Vanderwees (2018) developed the original procedure to determine the lateral contact position and contact radius at the point of contact. This section describes how the

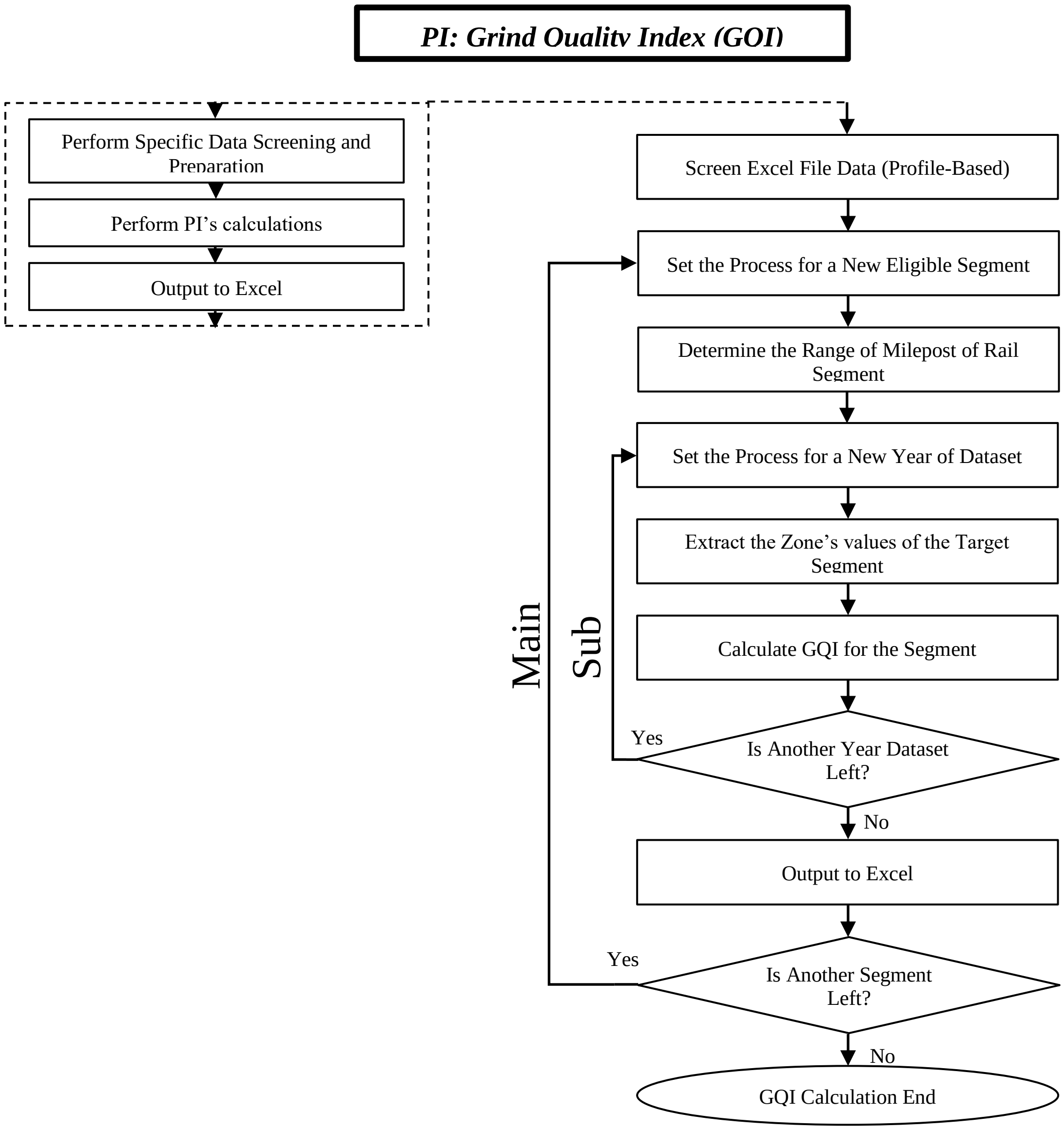
Analyze_Rail_Segments function integrates these procedures into the algorithm's main function.

The original procedure requires user interaction to locate track and rail segments and a start year for the analysis. This is time-consuming when analyzing multiple segments for many years, as is done in this research. Therefore, this thesis developed an automatic procedure to locate and extract the rail profile text files, perform calculation and analysis on the rail profile data, and organize the result in the Excel database. The procedure consists of two algorithm cycles. The main cycle, which targets the segments, ensures that all the eligible segments are analyzed. The sub-cycle, which ensures the analysis of LCP and CR over the years that data are available, controls every step of the LCP and CR analysis. Because of several assumptions built into the original algorithms, this function is only applicable on tangent segments (Vanderwees, 2018). Vanderwees (2018) describes the procedure to determine the lateral contact position and contact radius through the following steps:

- Step 1. Remove similar x,y-coordinates.
- Step 2. Correct x,y coordinate order.
- Step 3. Find the largest monotonically increasing set of x,y-coordinates.
- Step 4. Remove rail profile field and gauge sides.
- Step 5. Transform rail head x,y-matrix.
- Step 6. Smooth rail profile data.
- Step 7. Create surface angle matrix.
- Step 8. Determine lateral contact position and contact radius.

The result of each sub-cycle run is organized and stored in a structured array defined by MATLAB, and the final result of the sub-cycle analysis is exported to the *Final_Result* Excel database.

3.2.4.4 Analyze Grind Quality Index (GQI)



Inputs:

- List of eligible segments
- Grind Quality Control report exported from Rangecam in Excel file

Outputs:

- Grind Quality Index

This section describes how the *Analyze_Rail_Segments* function processes the values of GQI calculated by Rangecam. This part of the function is only responsible for screening the values of the grind quality report, organizing the values, distinguishing the east and west rails, and calculating the GQI using the GQI formula provided in Section 2.3.3.

The first step performs data screening on the grind quality control report containing extreme gauge zone, gauge zone, and centre zone values exported from Rangecam. A customized MATLAB function called *Screen_It* is developed to perform data screening on the Excel input. This function applies some basic controls on the input data. For example, the function ensures that the input values are in a reasonable range and extreme outliers (e.g., 10000) are removed. It also removes null and negative values from the database.

The main cycle, which targets the segments, ensures that all the eligible segments are analyzed. The sub-cycle, which ensures the analysis of GQI over the years that data are available, controls every step of the GQI analysis.

After targeting a segment, the main cycle starts by determining the range of mileposts covered by the targeted segment. This objective is achieved by two customized MATLAB functions named *Find_Old_StartingPost* and *Find_New_StartingPost*. However, the values for the east and west rails are separated from each other in the database.

Next, after selecting a new database year, the sub-cycle extracts the three zone's values (i.e., extreme gauge zone, gauge zone, centre zone) of the rail profiles in the targeted segment from the Excel file. Figure 10 illustrates the four zones of a rail profile.

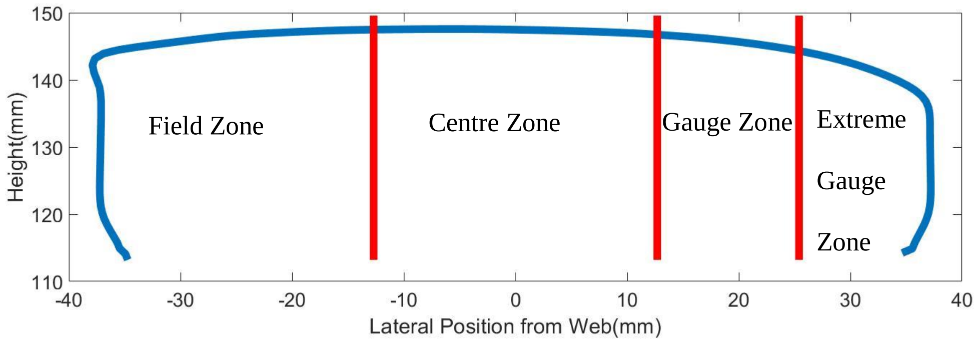


Figure 10. Zones of a Rail Profile

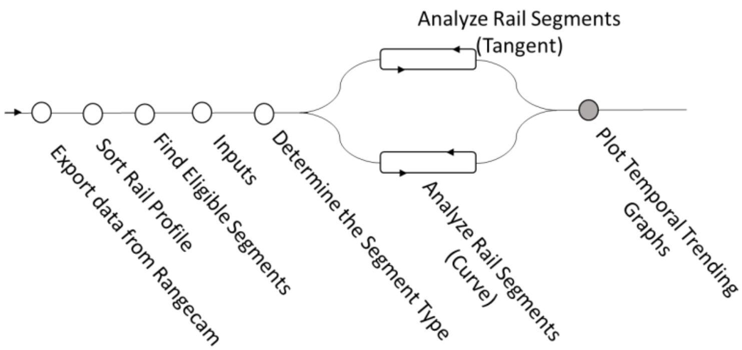
A customized MATLAB function named *Locate_By_Milepoint* is developed to locate the segment zone's values in the database and extract them to a new MATLAB array. This function uses the reference mileposts determined using *Find_Old_StartingPost* and *Find_New_StartingPost*.

The final step calculates the GQI for the target segment as follows:

$$\text{GQI} = (|Extreme\ Gauge\ zone| + |Gauge\ Zone| + |Centre\ Zone|) * 1000$$

The result of each sub-cycle run is organized and stored in a structured array defined by MATLAB, and the final result of the sub-cycle analysis is exported to the *Final_Result* Excel database.

3.2.5 Plot Graphs from Result Excel Database



Inputs:

- The *Final_Result* database
- Date of rail replacement
- Date of rail maintenance

Outputs:

- PI temporal trending graphs

The final function in the algorithm plots temporal trending graphs for the PIs stored in the *Final_Result* database and the dates of rail replacement and rail maintenance. In the case of this thesis, information about rail replacement and maintenance was obtained for the rail property being analyzed; however, the function is generic and applicable to any rail property.

The function starts by extracting the required data from the relevant sources (e.g., *Final_Result* that includes the final results of the PI analysis). Using a customized MATLAB function named *Check_Programs*, the database related to each segment is separated into the periods "before" and "after" the date of rail replacement or maintenance intervention. Obviously, if there has been no rail replacement or maintenance, the database would not be changed.

The next step establishes a structure to organize the trending graphs of the PIs for both the east and west rails.

Figure 11 illustrates an example of the temporal trending graph report developed in this section of algorithm. The report provides the segment's information (e.g., code, mileposts, geometry and rail type) on the top. The components of the rail type information are listed below:

- (Both): This means both the west and east rails have the same type (e.g., Rail Type (Both): 136 RE)
- (BR): This defines the type of rail before replacement (e.g., Rail Type: 132 AREA (BR))
- (AR): This defines the type of rail after replacement (e.g., Rail Type: 136 RE (AR))

The temporal trending graphs for each PI are depicted as a series of time-series plots. Then a linear model is fitted to the PI values between two consecutive rail replacement and/or grinding intervention dates so that the trends can be tested for linearity. If the hypothesis test implies that the trends are linear (p-value is less than 0.05), the graphs are updated with separate linear trend lines for the periods before and after rail maintenance or replacement interventions. The *Plot_Temporal_Trending_Graphs* function uses a linear regression function in MATLAB. Also, the *Plot_Temporal_Trending_Graphs* function calculates the rate of change in the values of the PIs (slopes) for the periods before and after rail maintenance or replacement. This enables the user to perform a comparative evaluation of the situation before and after maintenance or replacement activities.

Finally, the complete set of graphs (for the east and west rails of each segment) is stored as a JPEG file and exported to the graphs database. For tangents, graphs are included for seven PIs, whereas for curves only five graphs are included (i.e., lateral contact position and contact radius are excluded for curves).

The legend for the graphs include the following features:

- PI value: black dot
- Trend line: red solid line
- Yellow condemning limit: yellow medium dash line
- Red condemning limit: red medium dash-dot line
- Rail replacement: magenta medium dash-dot line
- Rail grinding: green dense dot line
- Both replacement and grinding: dark blue medium (dense) dash line
- Extreme gauge zone (for the lateral position graph of tangents only): black medium (light) dash line
- Gauge zone (for the lateral position graph of tangents only): black medium dash-dot line (the centre zone is located between the field and gauge zones and extends 12.7 mm on either side of the longitudinal centre of the railhead)
- Field zone (for the lateral position graph of tangents only): black solid line

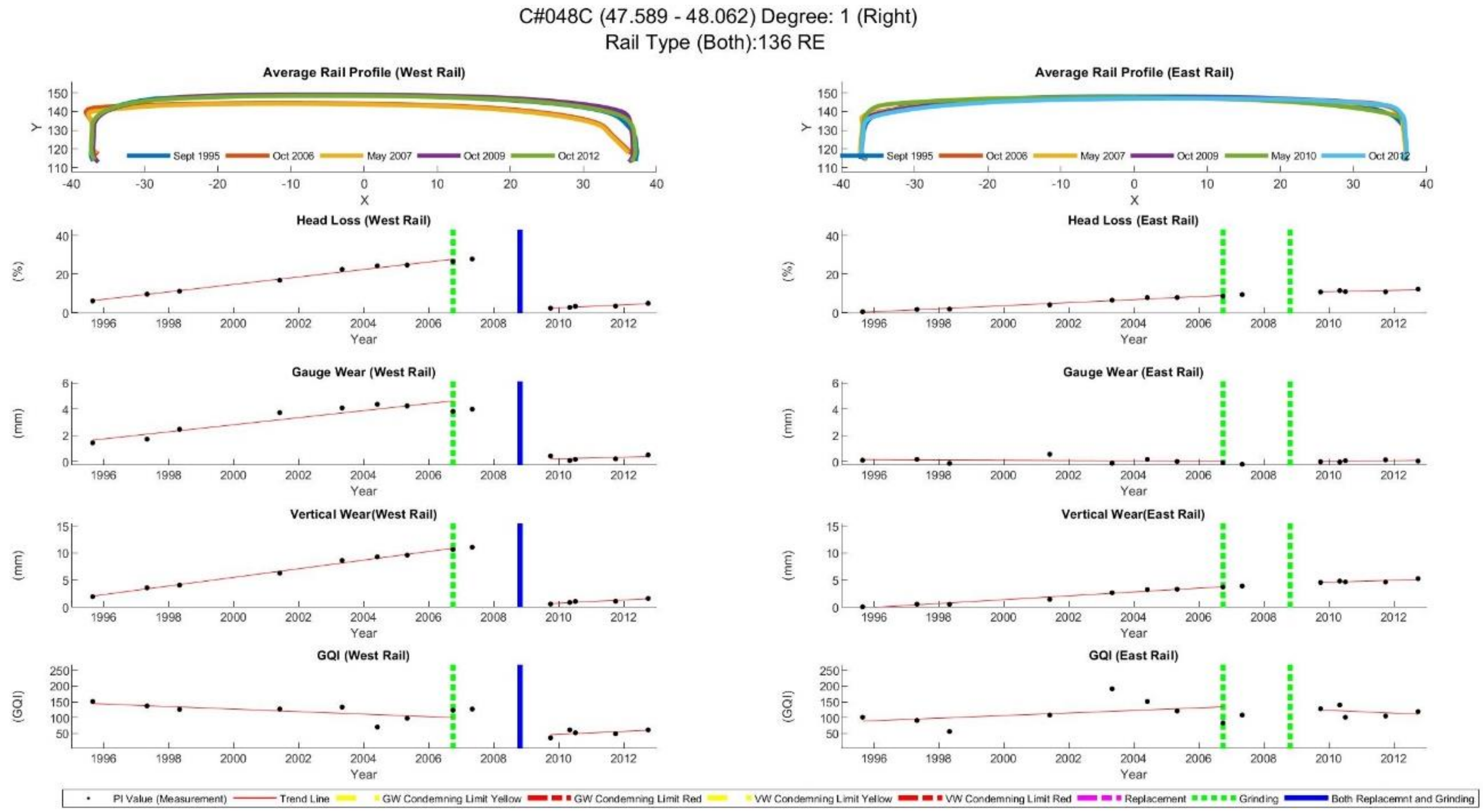


Figure 11. An Example of Temporal Trending Reports for Rail Profile Performance Indicators for Curves

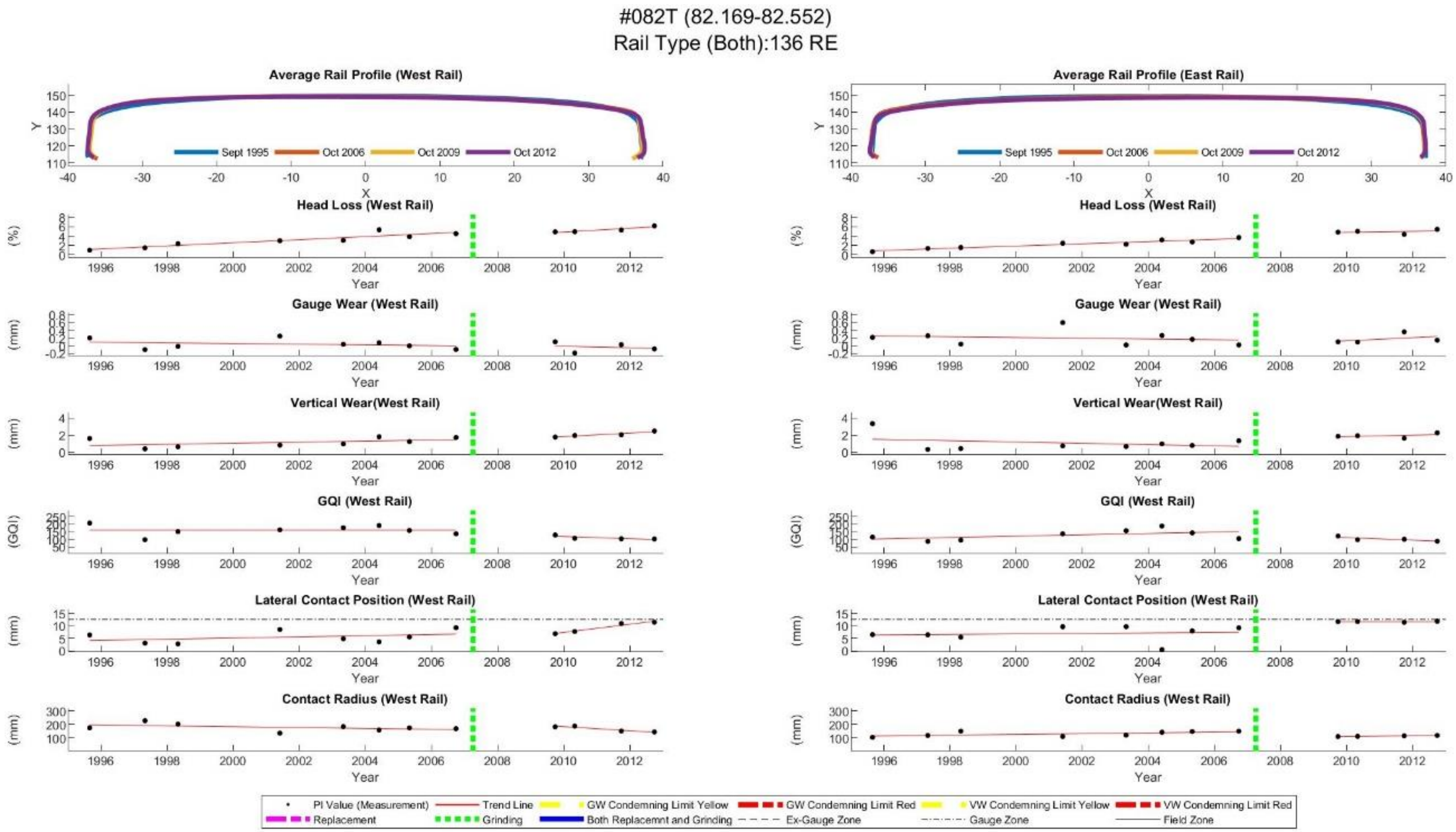


Figure 12. An Example of Temporal Trending Reports for Rail Profile Performance Indicators for Tangents

3.3 Correlation Analysis

This section describes the analytical approach used to address the final objective of this thesis, namely, to investigate the potential relationships between performance indicators through a correlation analysis. To promote consistency in the analysis, only those segments (tangents and curves) with 14, 13, or 12 data points (available years) are considered in the correlation analysis. The analysis produces correlation coefficients for the PIs, for both tangents and curves.

Inputs:

- PI values for tangents with 14, 13 and 12 data points (available years)
- PI values for curves with 14, 13 and 12 data points (available years)

Outputs:

- Correlation coefficients for tangents
- Correlation coefficients for curves

Prior to running the correlation analysis, the assumptions underpinning the two most common correlation techniques (Pearson and Spearman) were considered (Madrigal, 2012). Table 8 summarizes these assumptions and the suitability for use with the PI data. The table indicates that a Spearman correlation analysis is more appropriate for the PI data. Appendix C provides scatter plots for each pair of PIs within curve (sharp and mild, inclusive) and tangent segments.

Table 8. Two Common Correlation Techniques, Their Assumptions and the Suitability for Use with the PI Data

Method	Assumption	Does the PI data satisfy the assumption?
Pearson	The two variables should be measured at the interval or ratio level.	Yes. PI values are interval that are calculated annually with a specific unit (e.g., mm. or in.).
	There is a linear relationship between two variables	No. While some PIs have a linear relationship, most of them are not linearly related, as evidenced by examining the R-squared value obtained from linear regressions.
	No significant outliers should be observed	Yes. This assumption is controlled by the result validation (see section 4.1.1).
	Variables should have a normal distribution	No. None of the PI values are normally distributed. This result was confirmed through (1) application of the one-sample Kolmogorov-Smirnov normality test at the 5% significance level, and (2) visual inspection of histograms generated from the PI data.
Spearman	The two variables should be measured at ordinal, interval or ratio level.	Yes. PI values are interval that are calculated annually with a specific unit (e.g., mm. or in.).
	Variables should have monotonic relationship	Yes. According to the expected results, there is a monotonic relationship between PI values.

To obtain the most reliable results, the input variables (each segment's PIs) for the correlation analysis must meet the following criteria:

1. PIs must show a meaningful trend: Only those segments that do not contain outliers (or for which the identified outliers are otherwise addressed, as in section 4.1.1)

and are compatible with the expected results (see sections 4.1.2) are considered in the correlation analysis.

2. Segments must have a minimum of 12 data points (available years): Only those segments with 14, 13, or 12 data points are considered in the correlation analysis. This ensures that there is a sufficient amount of input data and promotes consistency with the other analyses conducted in this thesis.

As previously stated, the final objective of this thesis is to perform a correlation analysis on all the PIs to support and enhance the findings of the temporal trending analysis. While HL, GW, VW, GQI, CR and LCP are numeric measurements (vectors), the ARP is a set of x,y-coordinates representative of the shape of the railhead. Therefore, it is not possible to include the ARP in the correlation analysis, even though the ARP is included in the temporal trending graphs.

4. RESULTS

Chapter 4 discusses data verification and validation, presents the results of the trending and correlation analyses of the selected rail profile performance indicators, outlines analytical limitations, and discusses the implications of this thesis for managing rail grinding programs. The analyses use a historical time-series dataset for seven performance indicators collected on 100 miles (160 km) of a closed-fleet, heavy-haul short-line railway in Canada.

4.1 Verification of the Input Data and Validation of the Results

As outlined in Section 3.2, the algorithm applies several criteria to screen the input data. These criteria are based on technical considerations (e.g. data collection intervals), consistency requirements (e.g. eligible records for a consistent number of years) and statistical requirements (e.g. having a database with sample size of more than 30). After applying these screening criteria, 111 out of 752 segments are included in the analysis.

Prior to analysis, data for the 111 segments are verified and validated, as follows:

- **Verification of the input data** involves eliminating the outlier data points from the graphs and database that do not imply a meaningful value according to the overall trend.
- **Validation of the temporal trending results** involves comparing the expected and observed results from the temporal trending graphs relative to rail replacement and general trends.

4.1.1 Verification of the Data

According to Aggarwal (2015), an outlier is an observation which is not close to the other observations. Aggarwal (2015) mentions that there are a variety of outlier detection methods that are mainly based on the creation of “a model of normal patterns” to numerically determine a data point as an outlier. These outlier analysis methods include: (1) extreme values, (2) clustering models, (3) distance-based models, (4) density-based models, (5) probabilistic models, and (6) information-theoretic models (Aggarwal, 2015).

Yu et al. (2002) suggests that most of the outlier detection methods are developed based on statistics that have various assumptions (i.e. data distribution). This limits their applicability as their assumption parameters may not be conveniently determined (Yu et al., 2002).

Detecting outliers in time-series datasets—similar to those analyzed in this thesis—is complex because the data may not follow a Gaussian distribution (Cohen, n.d.). Since it may not be evident which outlier detection method is most appropriate, iterative, visual identification of outliers may be applied provided that the dataset is sufficiently small. Cohen suggests that for large datasets, machine learning approaches may be required.

For the trending analysis in this thesis, rail property maintenance and replacement interventions (see section 4.4.4) induce non-normal patterns in the data and precludes a straightforward detection of outliers. Complicating matters is that in some cases such interventions cannot be confirmed and are only suggested by the data. For example, the data plotted in Figure 13 suggests that a rail replacement occurred in 1997, but this replacement could not be validated. Because of these challenges, this thesis investigates the existence of outliers in the input PI data and its trends through visual quality control.

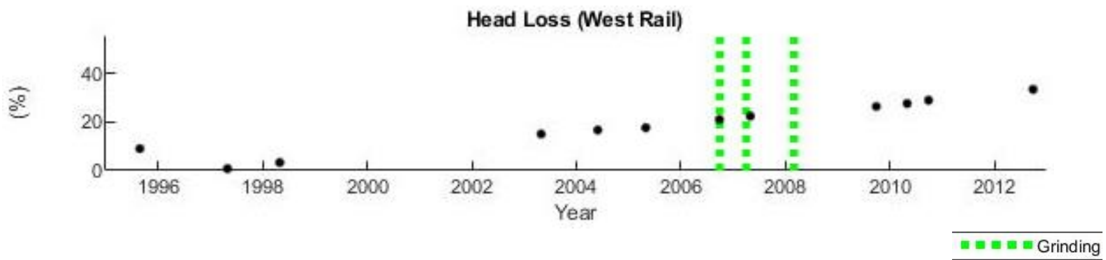


Figure 13. An Example of the Effect of Limited Rail Property Replacement Information on Detecting Outlier

Ghosh & Vogt (2012) suggest three main approaches in treating outliers, including (1) treating the outlier(s) the same as other data points (no change or elimination), (2) adjusting the outlier's value through modifying it to make a closer value to the rest of data points; and (3) deleting the outlier. While various methodologies exist for treating outliers (Ghosh & Vogt, 2012), this thesis treats the outliers by elimination after detection.

The expected results (provided in sections 4.1.2) are the main references to help identify outliers. To sum, this thesis defines a data point as an outlier if it does not follow the same trend as its adjacent data points (years) based on the expected results. When an outlier is observed in a particular year, the next step is to delete the data of that year from the trend. This method also deletes the data of that year from all of the other PI datasets to preserve consistency in the trending and correlation analysis.

To illustrate, consider the temporal trending graph of vertical wear for a particular east rail without any rail replacement through the period of 1995 to 2012, as shown in Figure 14. While Figure 14 illustrates an upward trend on the graph, the data point in 2004 shows an unexpected increase which appears unreasonable relative to its adjacent data points and the overall trend. According to the definitions proposed by this thesis, the data point of 2004 is an outlier, which must be deleted not only from the dataset for vertical wear (east rail) but also from all other PI datasets.

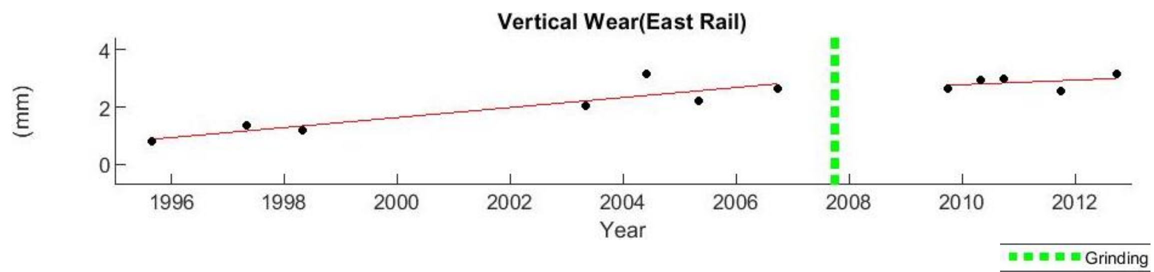


Figure 14. Example of an Outlier Identified in an Upward Trend

The verification process detected outliers in 14 of the 111 segments. After removing outliers from the dataset for the segment, the segment may be considered for further analysis provided it retains a sufficient number of data points (12). However, none of the 14 segments identified as having outliers retained sufficient data.

4.1.2 Validation of the Temporal Trending Results

Validation of the results involves comparing the observed results from the temporal trending graphs with the expected effect of rail replacements and the expected increase in rail wear over time. Generally, a significant improvement in rail condition is expected after rail replacement. If no improvement is observed or the rail wear trend is not compatible with what is expected, the data may be considered invalid. This section discusses two expected results and provides a summary of them.

Expected Result 1:

According to the mechanism of rail deterioration over time, an increasing trend in head loss, gauge wear and vertical wear should be observed between two rail replacement dates. This is followed by a significant drop in their upward trends after the replacement. Figures 15 to 17 illustrate the expected changes in trends as a result of rail replacement (shown by a vertical purple line) for head loss, gauge wear and vertical wear, respectively.

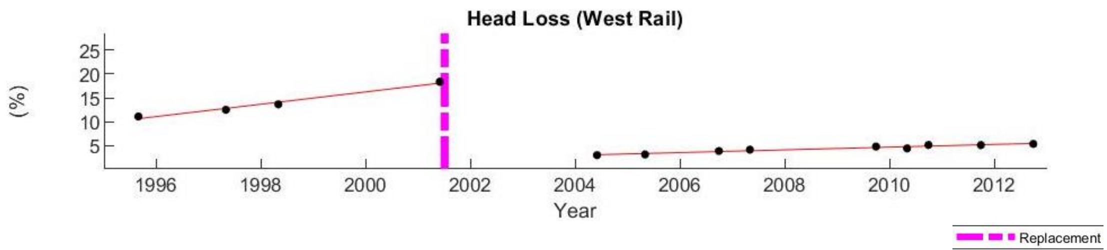


Figure 15. An Example of Expected Changes in Head Loss Trends Before and After Rail Replacement

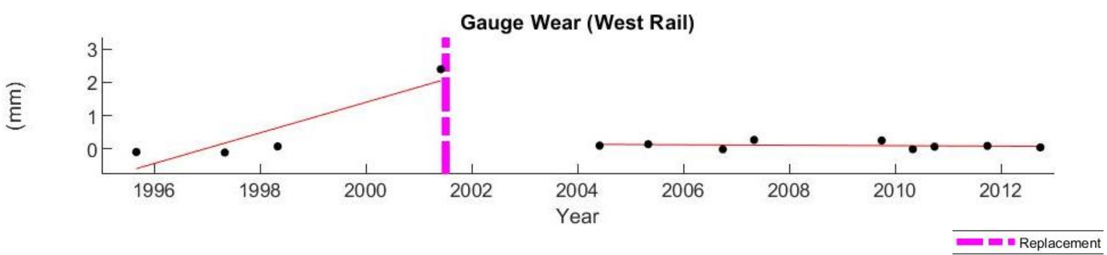


Figure 16. An Example of Expected Changes in Gauge Wear Trends Before and After Rail Replacement

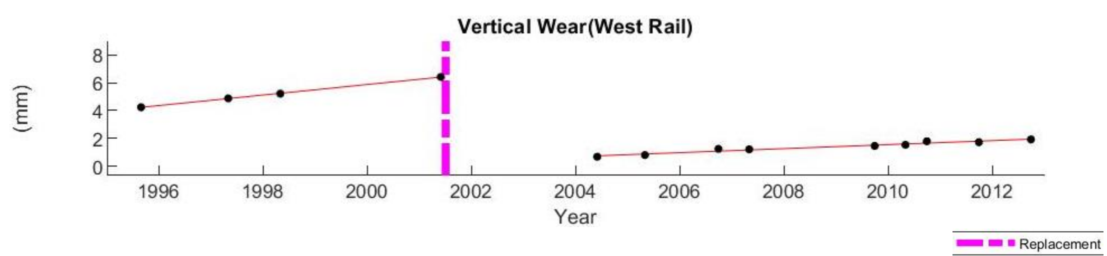


Figure 17. An Example of Expected Changes in Vertical Wear Trends Before and After Rail Replacement

As discussed in section 4.1.1, after eliminating the outliers, 97 of 111 segments are verified and can be included in the temporal trending and correlation analysis. Validation of the temporal trending graphs for these segments identified another 19 segments that were considered invalid for further analysis (i.e. 78 segments remain).

Expected Result 2:

If no rail replacement occurs, it is expected that the shape of the ARP changes over time to reflect the various types of wear (e.g., vertical wear, gauge wear). Figure 18 illustrates six ARPs for the west rail of a sharp-right curve (C#025C) between 1995 and 2012. The ARP in September 1995 illustrates less rail wear particularly on the gauge side compared to the ARP in the following years. As expected, the ARP in 2012 is the most worn profile.

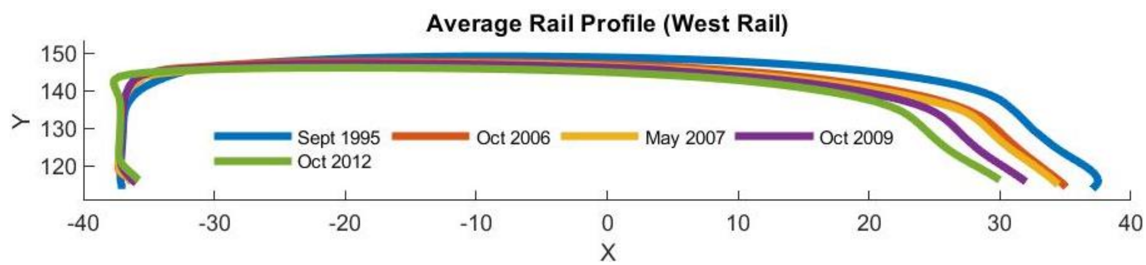


Figure 18. An Example of Changes in the ARP When No Rail Replacement Occurs During the Given Period (1995-2012)

When rail replacement occurs, the transition from a worn rail profile to an unworn (brand-new) rail profile should be obvious from the ARP graph by comparing the profiles before and after rail replacement. Figure 19 illustrates this effect. In this case, the rail was replaced between May and October 2010. The ARP depicts gauge and vertical wear between 1995 and 2010, followed by a return to unworn conditions in 2012 (after replacement). The rail wear between October 2010 and 2012 is negligible. This is why the ARP in October 2010 (yellow polyline) is invisible as it is behind the ARP in October 2012 (purple polyline).

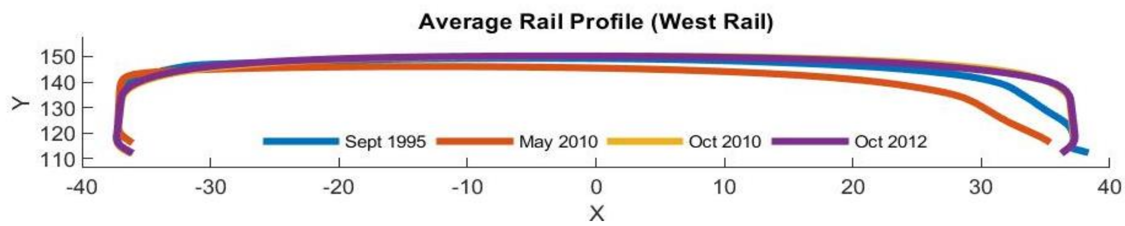


Figure 19. An Example of the Change in ARP Before and After the Rail Replacement

4.1.3 Summary

Unworn rail is expected to illustrate the lowest values for PIs that measure rail wear (e.g. head loss, gauge wear, vertical wear), while it is expected to illustrate the best rail profile shape, as represented by the ARP. These expected results are observed in all the segments with rail replacement. In the case that rail is not replaced, upward trends in HL, GW, and VW are expected, and these trends must be supported by the ARP representing the rail profile as it is worn over the time.

ARP, as a visual tool, is expected (also observed in most of the segments) to illustrate the process of rail wear; however, in some cases this is not observed because of the inconsistency of rail profile data collection in representing the railhead's height (minimum y-coordinate) over time. This limitation is discussed in section 4.4.1.

After applying data verification and validation, a total of 78 segments are retained for temporal trending and correlation analysis.

4.2 Analysis of Results by Segment

The analysis of results relies on segment-by-segment graphs of the time-series of each PI for selected tangent and curve segments. According to several assumptions built into the original algorithms, the contact radius (CR) and lateral contact position (LCP) are only applicable on tangent segments (Vanderwees, 2018). Therefore, the CR and LCP are only discussed in 4.2.1.

As discussed in sections 2.3.3 and 3.2.4, the nature of gauge wear and the GQI calculations may cause year-to-year fluctuations rather than a meaningful trend as is expected for head loss and vertical wear. GW is calculated using the 'floating-point' method, which measures the horizontal wear occurring at a specified vertical distance (5/8 inch in North America) below the top of the worn rail. Therefore, the gauge wear may show a positive value (due to rail wear) or a negative value (due to the relative rate of gauge wear and vertical wear, the nature of the GW calculations, or plastic flow). GQI may also fluctuate over time as it measures the difference between the actual and template rail profiles, which is a function of the desired template, grinding interventions and rail wear.

This thesis aims to support the graph with as much information as is available concerning rail replacement, grinding, and industry-defined rail condemning limits. The graphs of gauge wear and vertical wear include the condemning limits defined by Rangecam. However, in most cases, the rail is replaced before these two PIs reach their condemning limits. Therefore, these limits may not be visible in the graph because the scale of the vertical axis is automatically set based on the range of PI values over time. Table 9 illustrates the available condemning limits for the different rail head sections present in the dataset.

Table 9. Rail Classification Condemning Limits (Adopted from Rangecam©)

Rail	Class	Gauge (mm.)	Field (mm.)	Vertical (mm.)	Combination (mm.)	Head Loss (%)
132AREA	Green	0	NA	0	0	NA
132AREA	Yellow	9.5	NA	13	18	NA
132AREA	Red	12	NA	16	20	NA
136RE	Green	0	NA	0	0	NA
136RE	Yellow	9.5	NA	16	20	NA
136RE	Red	12	NA	18	24	NA

While the available information on rail grinding interventions and replacement is limited, personal communications with railway experts involved with the railway property being examined produced instructive information about the rail maintenance practices for that property. In particular, there was poor or almost no grinding activity around 2000 while regular grinding interventions activated after 2002 using new grinding machines (G. Bachinsky, personal communications, 2019).

In total, the dataset contains 78 segments eligible for analysis that have more than 12 data points (years). This includes 32 tangents, 33 mild curves (curvature less than or equal to three degrees), and 13 sharp curves (curvature greater than three degrees). These segments are verified and validated, as described in Section 4.1. However, not all segments provide data that are instructive for detailed analysis of trends. To scope the analysis, the data were categorized based on the type of information that could be gained from an examination of the trends in each segment. As summarized in Table 10, the segments fall into one of the following two categories:

- Category 1: The first category includes segments with meaningful trends and sufficient information about grinding and rail replacement. Specifically, the HL trend was used to assess the meaningfulness of the data, since it provides reliable and easily-understood data and is frequently used by industry. The category includes two sub-categories: (a) segments which have not had rail replacement but which have at least one grinding intervention record; and (b) segments with both grinding intervention and rail replacement records. A total of 20 segments fall into this category.
- Category 2: The second category includes segments with meaningful trends (based on HL) but which lack some information about either or both the date of rail replacement and/or the dates of rail grinding. Specifically, the category includes three sub-categories: (a) segments with at least one grinding intervention record but no information available to support a rail replacement revealed by the trending data; (b) segments with information about rail replacement, but which do not have a record of rail grinding; and (c) segments which have meaningful trends but for which there is no information available for rail grinding or rail replacement. Segments in this category may be moved into Category 1 if additional information about rail replacement becomes available. A total of 58 segments fall into this category.

Table 10. Summary segment-by-segment information about the dataset used for the trending analysis

Segment → / Attribute ↓	Tangents	Mild Curves		Sharp Curves		Notes
		Left Curvature	Right Curvature	Left Curvature	Right Curvature	
Category 1	12	1	7	0	0	Meaningful trend and sufficient information on grinding intervention and rail replacement is available
Category 2	20	10	15	7	6	Meaningful trend, but requires more information on either (or both) the rail replacement date and/or the date(s) of rail grinding
Total number **of valid segments (Category 1 and 2)**	32	11	22	7	6	

To constrain the scope of the analysis but still provide representative results, sections 4.2.1 to 4.2.3 provide observations about the trends for tangents, mild curves, and sharp curves selected from Categories 1 and 2. Specifically, the selections were made so that at least one segment from each of the sub-categories mentioned above, if available, could be discussed. Appendix D provides all graphs for tangents, mild curves and sharp curves based on their mileposts in ascending order.

4.2.1 Tangent Tracks

This section discusses the findings of the temporal trending graphs for five tangent segments. The east and west rail segments in tangent tracks are expected to have similar trends. Table 11 provides the information on the five tangent segments selected for detailed analysis (e.g. mileposts, rail replacement and grinding interventions). While no information is available on rail replacement for tangent tracks, there are only a few observations (see Figure 21) that suggest a rail replacement took place (Category 2) during the analysis period (1995-2012).

Table 11. Information on the tangent segments discussed in section 4.2.1

Segment Code	Mileposts	Date(s) (M/Y) of Replacement(s)	Date(s) (M/Y) of Grinding(s)	Reason to be included in detailed discussion
#016CT (Fig. 20)	17 – 17.236	NA	2005	Meaningful trend, at least one grinding intervention record is available and track segment is not replaced (Category 1a).
#022BT (Fig. 21)	22.558 –22.855	NA	10/2007	Meaningful trend, at least one grinding intervention record is available and rail replacement is observed that requires replacement information (Category 2a).
#044BT (Fig. 22)	44.795 – 44.931	NA	10/2007	Meaningful trend, at least one grinding intervention record is available and track segment is not replaced (Category 1a).
#088T (Fig. 23)	88.033 – 88.386	NA	NA	Meaningful trend, no rail grinding or rail replacement information is available (Category 2c)

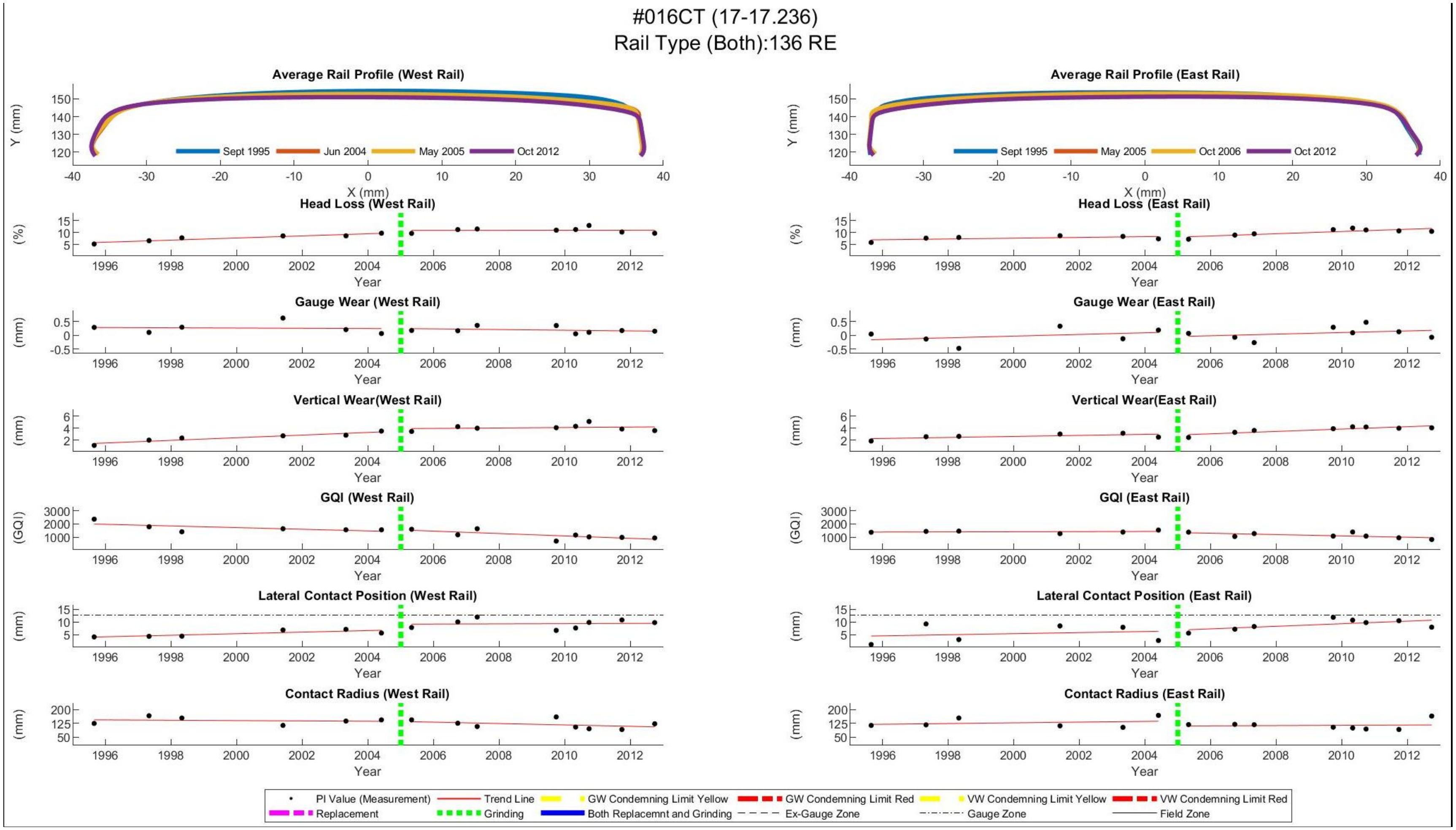


Figure 20. Tangent #016CT – Temporal Trending Graphs

Figure 20 shows the temporal trending graphs for Tangent #016CT. The rail type is 136 RE for both the west and east rail. This segment falls into Category 1a. The figure reveals the following findings:

- The rails on this segment were not replaced in the period from 1995 to 2012. Available information indicates that the rails were ground in 2005. However, the HL, VW and GQI data suggest possible dates for grinding in 2000 and 2009.
- There appears to be strong agreement between the HL and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends. The data points for GW and GQI exhibit less consistency over time, possibly due to the ways these PIs are measured. Notably, the scale of the GW graph accentuates the measurement errors.
- The LCP graph reveals an increasing trend over time on both rails. The overall trend is below the gauge zone's boundary, suggesting that the lateral contact is positioned in the centre zone, moving towards the gauge zone. There appears to be a slower change in LCP as a result of the grinding intervention.
- The CR graph illustrates a downward trend over time. In contrast to the LCP, CR appears to decrease at a higher rate after the grinding intervention.
- Comparing HL (W) and VW (W) before and after the rail grinding in 2005, the wear rate decreased after the intervention with an almost steady trend between May 2005 and October 2012. However, the wear rate in HL (E) and VW (E) first increased between 2006 and 2008, then became almost steady after 2009.
- GW (W) has an almost steady trend over time before and after grinding, while showing fluctuations potentially because of the measurement technique. In

contrast, the east rail shows a different wear rate on HL, GW and VW. It appears that the wear rate on these graphs increased after rail grinding in 2005. However, a close examination of the period from May 2005 to October 2012 reveals that rail grinding was potentially performed around 2009, resulting in a steady trend between 2010 and 2012. The descending trend in the GQI graph supports this possibility. Overall, for both east and west rails, the decreasing GQI trends suggest that rail grinding had a generally positive outcome.

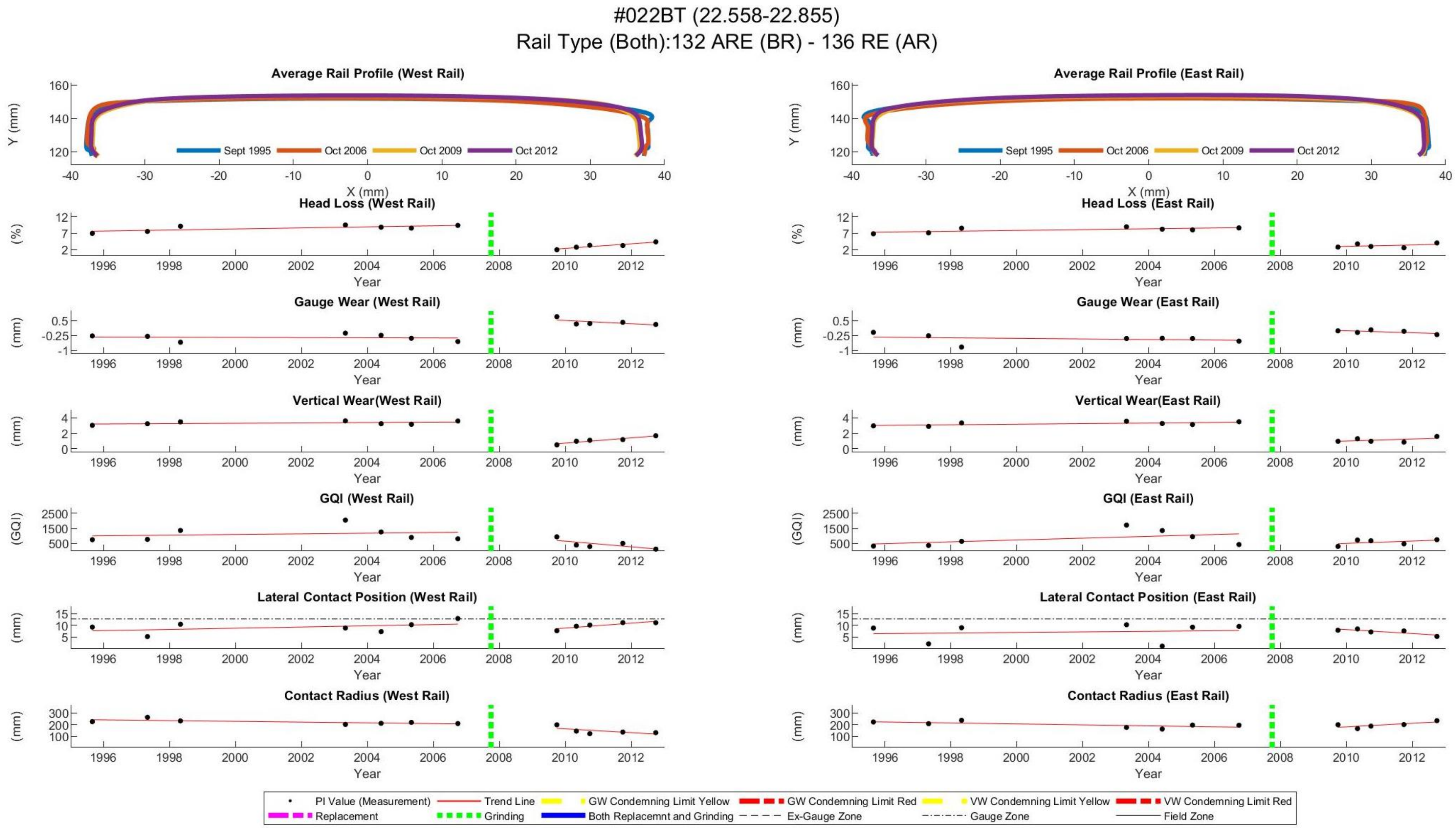


Figure 21. Tangent #022BT – Temporal Trending Graphs

Figure 21 includes temporal trending graphs for Tangent #022BT. The rail type is 132 AREA for both the west and east side before replacement and 136 RE after replacement. This segment falls into Category 2a. The figure reveals the following findings:

- While the figure suggests that the rails on this segment were not replaced in the period from 1995 to 2012, the observations from PI the graphs and the information on the changed rail types suggest a rail replacement between 2007 and 2009. Available information indicates that the rails were ground in October 2007.
- There appears to be strong agreement between the HL and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends. The ARP, HL and VW trends reveal a significant change in the rail condition between 2007 and 2009, as would be expected from a rail replacement.
- Both GW (W) and GW (E) reveal a steady overall trend between 1995 and 2012, although there are fluctuations in the data during this period.
- GQI reveals fluctuations over time. The downward trend on both east and west rails between 2002 and 2007 suggests a possibility of annual rail grinding.
- Generally, the LCP graph reveals an increasing trend over time on both rails. The overall trend is below the gauge zone's boundary, suggesting that the lateral contact is positioned in the centre zone, moving towards the gauge zone. The LCP for the east rail after grinding appears to trend downward, indicating movement away from the gauge zone.
- The CR graph illustrates an overall steady trend over time while showing an opposite trend compared to LCP after the rail grinding in 2007. This suggests that

the contact radius decreases as the lateral contact position moves towards the gauge zone from the center zone (increases).

- Comparing HL and VW before and after the possible rail replacement between 2007 and 2009, it appears that the wear rate increased following replacement. A possible reason for this change could be the change in rail type. However, operational and environmental information such as tonnage is required to derive a solid conclusion on the effectiveness of the 136 RE rail type.

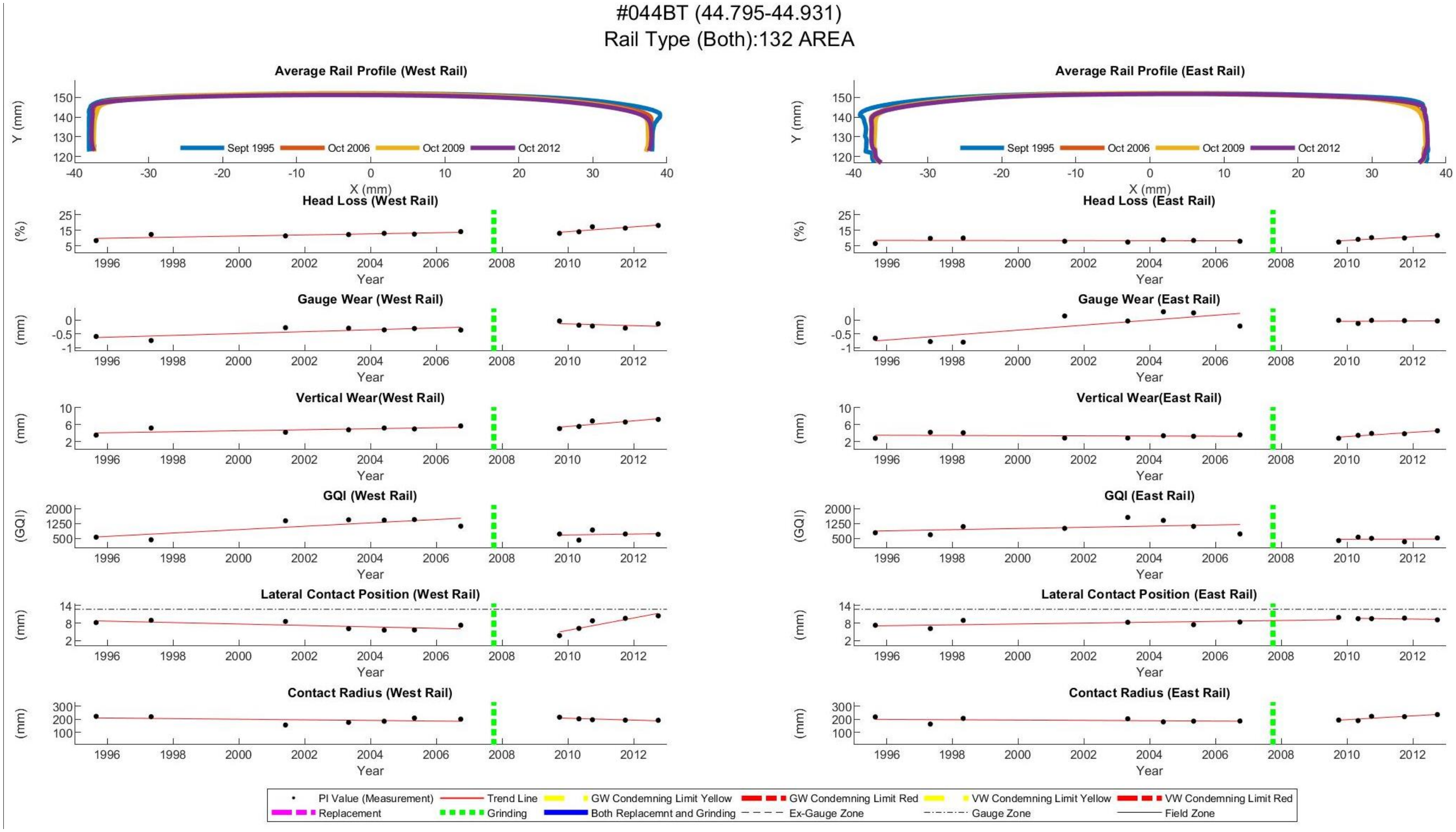


Figure 22. Tangent #044BT – Temporal Trending Graphs

Figure 22 includes temporal trending graphs for Tangent #044BT. The rail type on both the west and east side is 132 AREA. This segment falls into Category 1a. In contrast to Figure 20 (#016CT), the rail wear after grinding appears to increase. The figure reveals the following findings:

- The rails on this segment were not replaced in the period from 1995 to 2012. Available information indicates that the rails were ground in October 2007.
- There are appears to be strong agreement between the HL and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends. The data points for GW (E) and GQI (E) exhibit less consistency between 2002 and 2007, possibly due to the grinding interventions in this period.
- Comparing HL and VW before and after the rail grinding in October 2007, the wear rate increased after grinding, an observation counter to expected results. While such outcomes are impacted by the efficiency of the grinding program, operational and environmental information such as tonnage is required to derive a solid conclusion on the effectiveness of the program.
- Generally, LCP indicates that the wheel-rail contact takes place in the centre zone and CR reveals that the radius remained at approximately 200 mm over the period of 1995 to 2012. While overall LCP and CR tends are steady over time, there appears to be a monotonic relationship between GQI and each of LCP and CR.
- GQI data illustrate an approximately steady trend over the period between October 2009 and 2012. This may support the effectiveness of the grinding programs in managing rail profile.

- In contrast to Figure 21, GQI (E) in Figure 22 illustrates a decreasing trend with smaller changes in values, suggesting that the grinding on #044BT (E) was less aggressive (deep) than on #022BT (Figure 20) between 2002 and 2007.

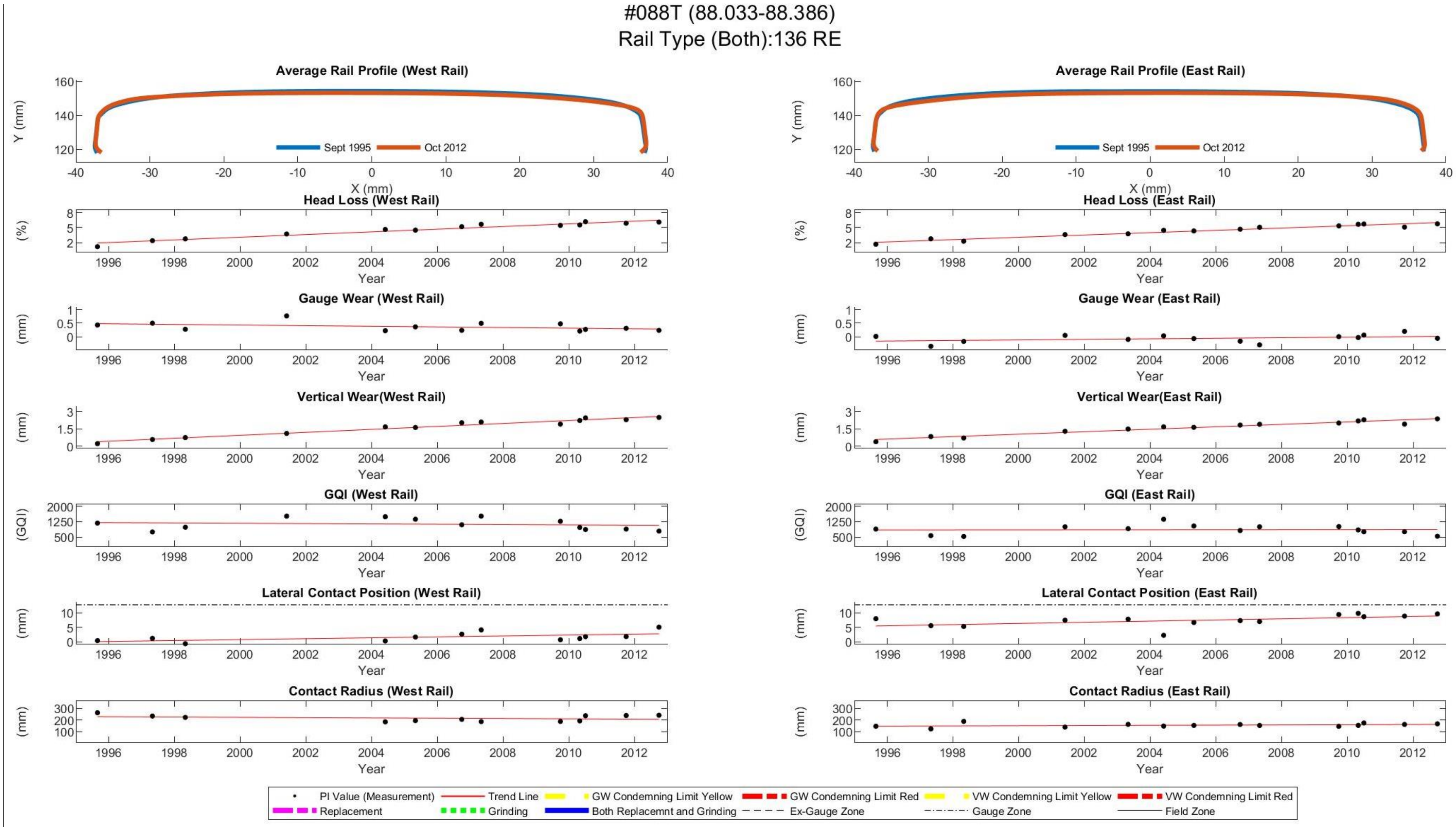


Figure 23. Tangent #088T – Temporal Trending Graphs

Figure 23 includes temporal trending graphs of Tangent #088T. The rail type on both the west and east side is 136 RE. This segment falls into Category 2c. The figure reveals the following findings:

- The rails on this segment were not replaced in the period from 1995 to 2012. The ARP, HL and VW support this statement. Although no information is available on grinding interventions, the overall steady trend for GQI suggests regular grinding interventions with light cuts.
- There are appears to be strong agreement between the HL and VW trends for both west and east rails. They suggest that both rails were replaced in the mid-90s as the values of head loss and vertical wear were almost zero in 1995. The shapes of the ARPs generally confirm these trends. The data points for GW and GQI exhibit less consistency over time, possibly due to the ways these PIs are measured. Notably, the scale of the GW graph accentuates measurement changes and errors.
- The GW graphs show an almost steady trend around 0.5 mm on the west rail and 0 mm on the east rail over the 14-year period between 1995 and 2012. While showing an almost stable trend, the GQI graphs have some fluctuations that suggest the possibility of rail grinding between 1995 and 2012.
- Overall, LCP and CR reveal an almost steady trend over time. However CR (W) indicates a decreasing trend over the period of 1995 to 2012. This observation shows a monotonic relationship with GQI (W) as both have a downward trend during the period.

4.2.2 Mild Curve Tracks

This section discusses the findings of the temporal trending graphs for mild curve tracks. Traditionally, North American railways define mild curves as those with a degree of curvature of less than 3° (G. Bachinsky, personal communication, 2018). In curve tracks, the outside rail is known as the high rail and the inside rail is called the low rail. Table 12 provides information for the four mild curve tracks selected for detailed analysis (e.g. mileposts, rail replacement and grinding interventions and the reason to be included in detailed discussions).

Table 12. Information on the mild curves discussed in section 4.2.2

Segment code	Mileposts	Date(s) (M/Y) of Replacement(s)	Date(s) (M/Y) of Grinding(s)	Reason to be included in detailed discussion
C#018C (Fig. 24)	18.197 – 18.525	NA	NA	Meaningful trend, no rail grinding or rail replacement information is available (Category 2c)
C#048BC (Fig. 25)	48.525-49.045	07/2010 (West rail only)	10/2006, 07/2010	Meaningful trend, sufficient information is available on both rail grinding and replacement (Category 1b).
C#057AC (Fig. 26)	57.106 – 57.280	NA	10/2006, 04/2007, 10/2007, 04/2008	Meaningful trend, sufficient information is available on rail grinding, and track segment is not replaced (Category 1a)
C#099C (Fig. 27)	99.075 – 99.720	07/2001	NA	Meaningful trend, information is available on observed track segment replacement, but rail grinding information is required (Category 2b)

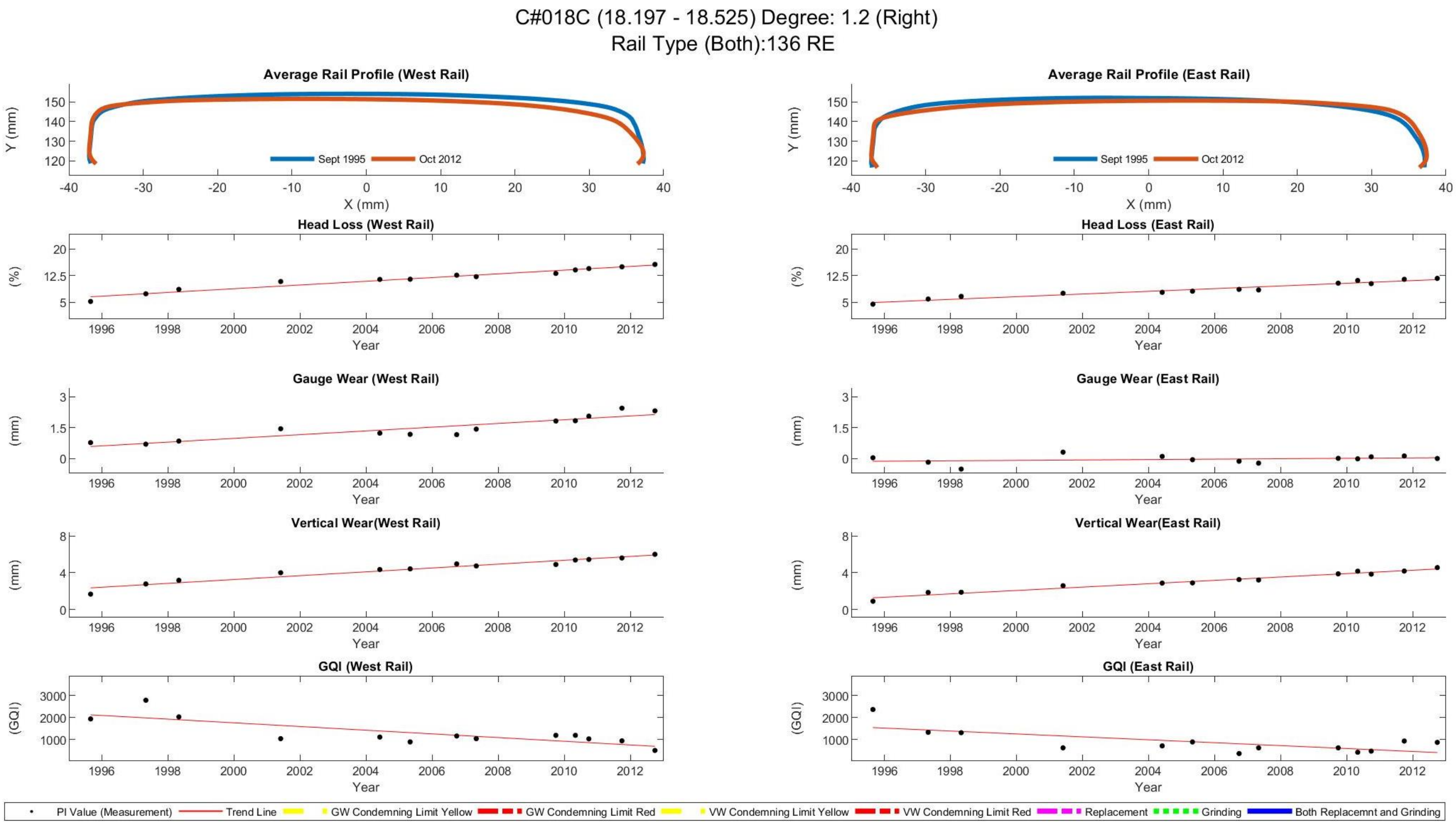


Figure 24. Curve C#018C (1.2° Right) – Temporal Trending Graphs (West = High Rail, East = Low Rail)

Figure 24 includes temporal trending graphs for Curve C#018C. The rail type on both the west and east side is 136 RE. This segment falls into Category 2c. The figure reveals the following findings:

- The rails on this segment were not replaced in the period from 1995 to 2012. The ARP, HL and VW support this statement. Although no information is available on grinding interventions, the overall increasing trend of GQI suggest regular grinding interventions with heavy cuts between 1995 and 2002 and light cuts for the rest of the period.
- There appears to be strong agreement between the HL, GW and VW trends for both the west and east rails—each with an upward trend. The shapes of the ARPs generally confirm these trends. However, changes in the vertical datum used to reference the y-coordinate value may prevent the ARP from clearly revealing rail wear.
- Comparing the west (high) and east (low) rails, the wear rate is more intense on the west rail than east rail, with the west rail exhibiting significant GW.

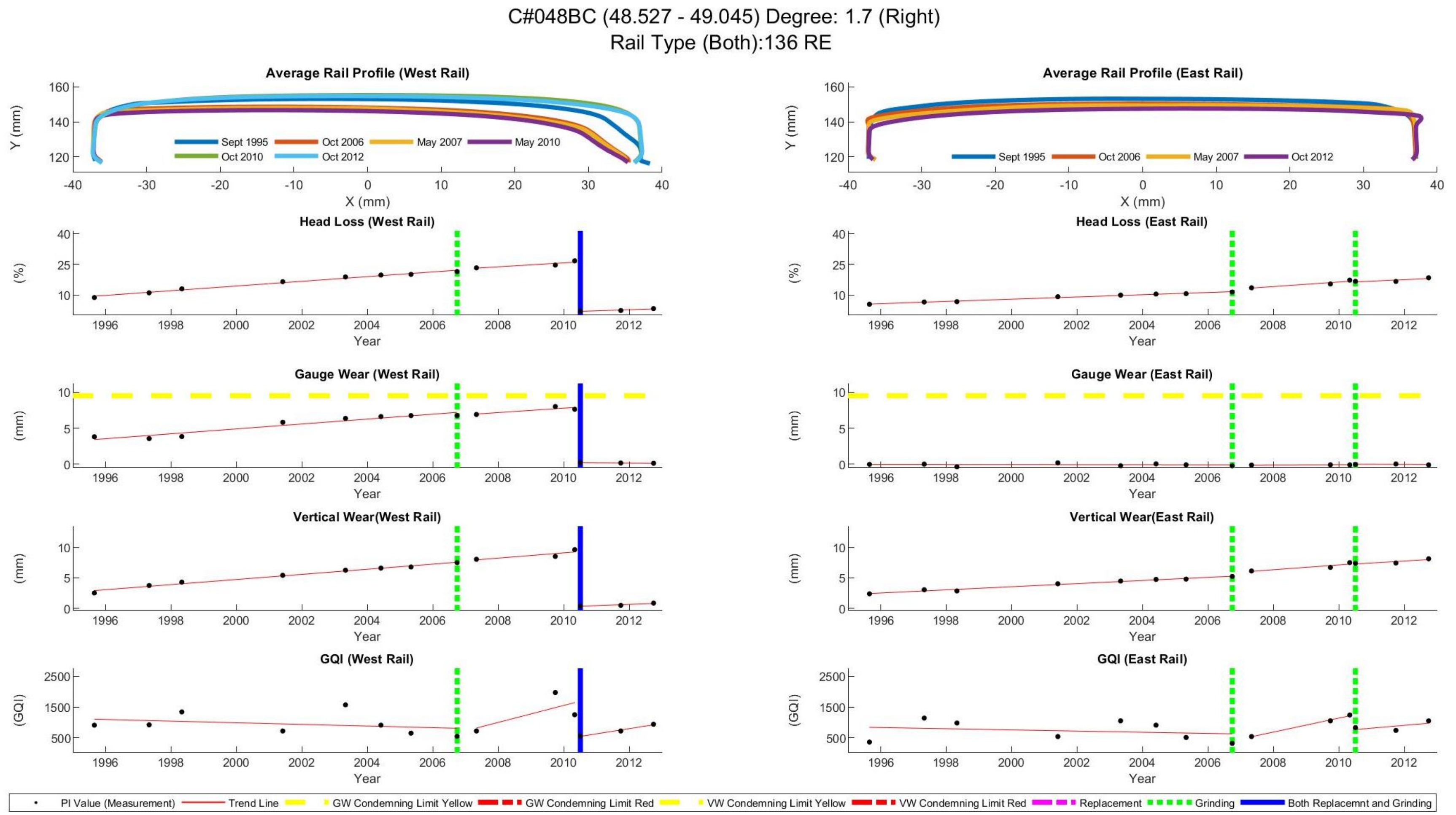


Figure 25. Curve C#048BC (1.7° Right) – Temporal Trending Graphs (West = High Rail, East = Low Rail)

Figure 25 includes temporal trending graphs for Curve C#048BC. The rail type on both the west and east side is 136 RE. This segment falls into Category 1b. It should be noted that the west rail was replaced and ground in 2010, with no data collection between these interventions. This situation is represented by a dark blue vertical line. The figure reveals the following findings:

- Only the west rail on this segment was replaced in July 2010. The ARP, HL, GW, and VW trends confirm the rail replacement on the west rail, and suggest that no such replacement occurred for the east rail. Available information indicates that the rails were ground in October 2006 and July 2010.
- There appears to be strong agreement between the HL, GW and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends. For example, ARP (W) highlights the difference between the worn (May 2010) and unworn (October 2010, 2012) average rail profiles before and after the replacement on July 2010. These ARPs support the significant drop in HL (W), GW (W) and VW (W) after the replacement.
- Comparing the west (high) and east (low) rails, the wear rate is more intense on the west rail rather than the east rail. This observation supports the expectation that the high rail experiences more intense pressure from the wheel compared to the low rail. The intense wear rates necessitated the rail replacement observed in 2010.
- On the west (high) rail, the rail grinding that occurred in 2006 appears to have made a nominal (but slightly positive) impact on the rail wear rates.
- The fluctuations observed in the GQI trend suggests the possibility of regular rail grinding interventions.

- While GW (E) shows an almost steady trend around zero, the GW (W) illustrates an intense wear rate over the time. The ARP (W) clearly illustrates the changes in the rail shape due to GW. The west rail was replaced just prior to reaching its yellow condemning limit (9.5 mm.). This observation illustrates how trending information can be used to better plan rail maintenance interventions.

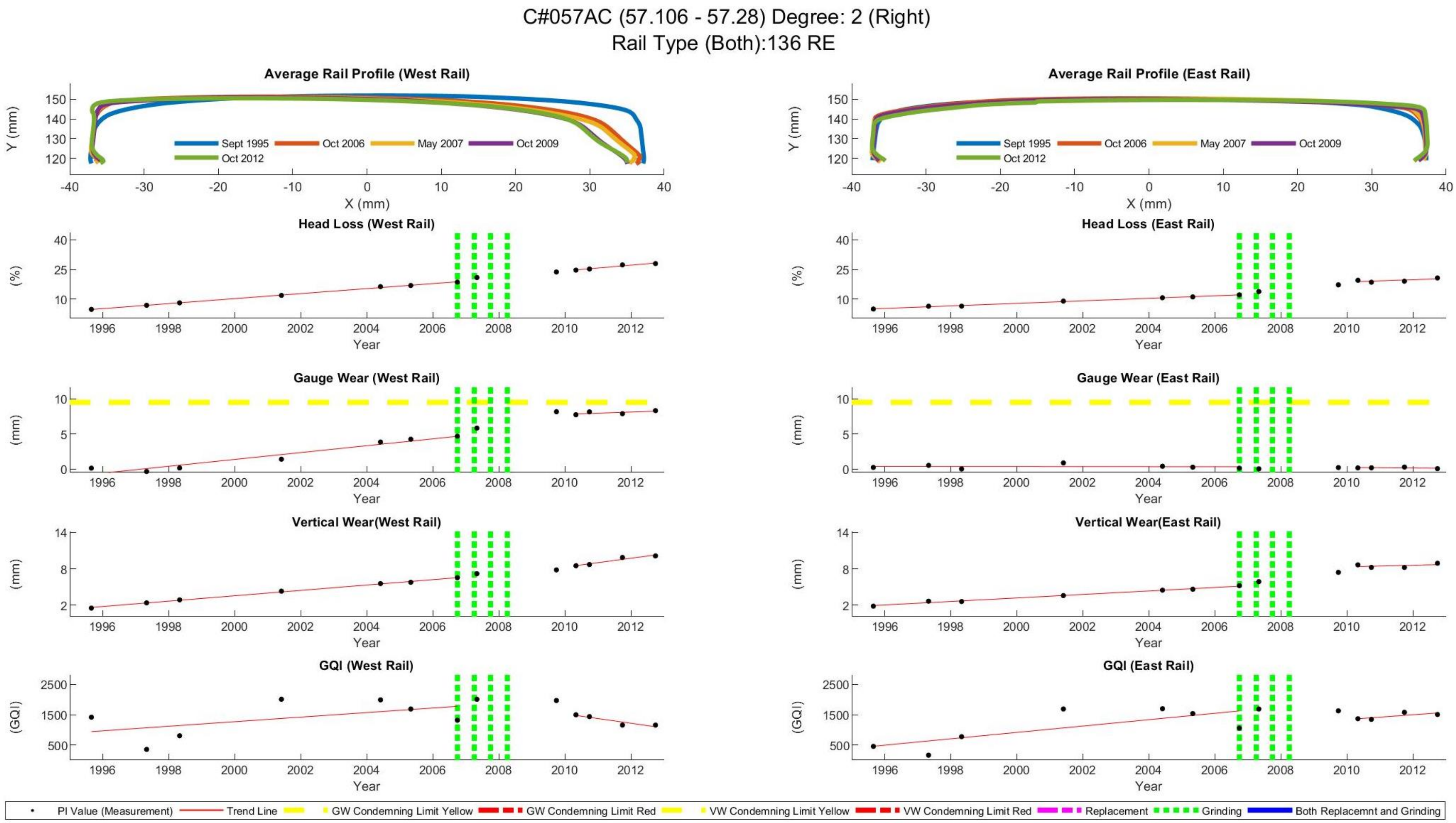


Figure 26. Curve C#057AC (2° Right) – Temporal Trending Graphs (West = High Rail, East = Low Rail)

Figure 26 includes temporal trending graphs for Curve C#057AC. The rail type on both the west and east side is 136 RE. This segment falls into Category 1a. The figure reveals the following findings:

- The rails on this segment were not replaced in the period from 1995 to 2012. Available information indicates that the rails were ground four times between 2006 and 2008.
- There appears to be strong agreement between the HL, GW and VW trends for both the west and east rails. The shapes of the ARPs generally confirm these trends. ARP (W) provides a more illustrative perspective of rail wear over time.
- Comparing the west (high) and east (low) rails, the wear rate is more intense on the west rail than east rail. This observation supports the expectation that the high rail experiences more intense pressure from the wheel compared to the low rail.
- The rate of GW (W) appears to have declined following the four sequential grinding interventions.
- The fluctuations observed in the GQI trends suggest the possibility of regular rail grinding interventions.
- While GW (E) shows an almost steady trend around zero, the GW (W) illustrates an intense wear rate over time. An interesting trend is observed from GW (W) in 2009-2012, which shows an almost steady trend below the condemning limit (9.5 mm). This suggests the effectiveness of the rail grinding interventions in controlling rail profile performance.

- Notwithstanding the limited availability of grinding interventions throughout the period, the overall GQI trends after the grinding interventions suggest improvements matching the actual and desired rail profiles.

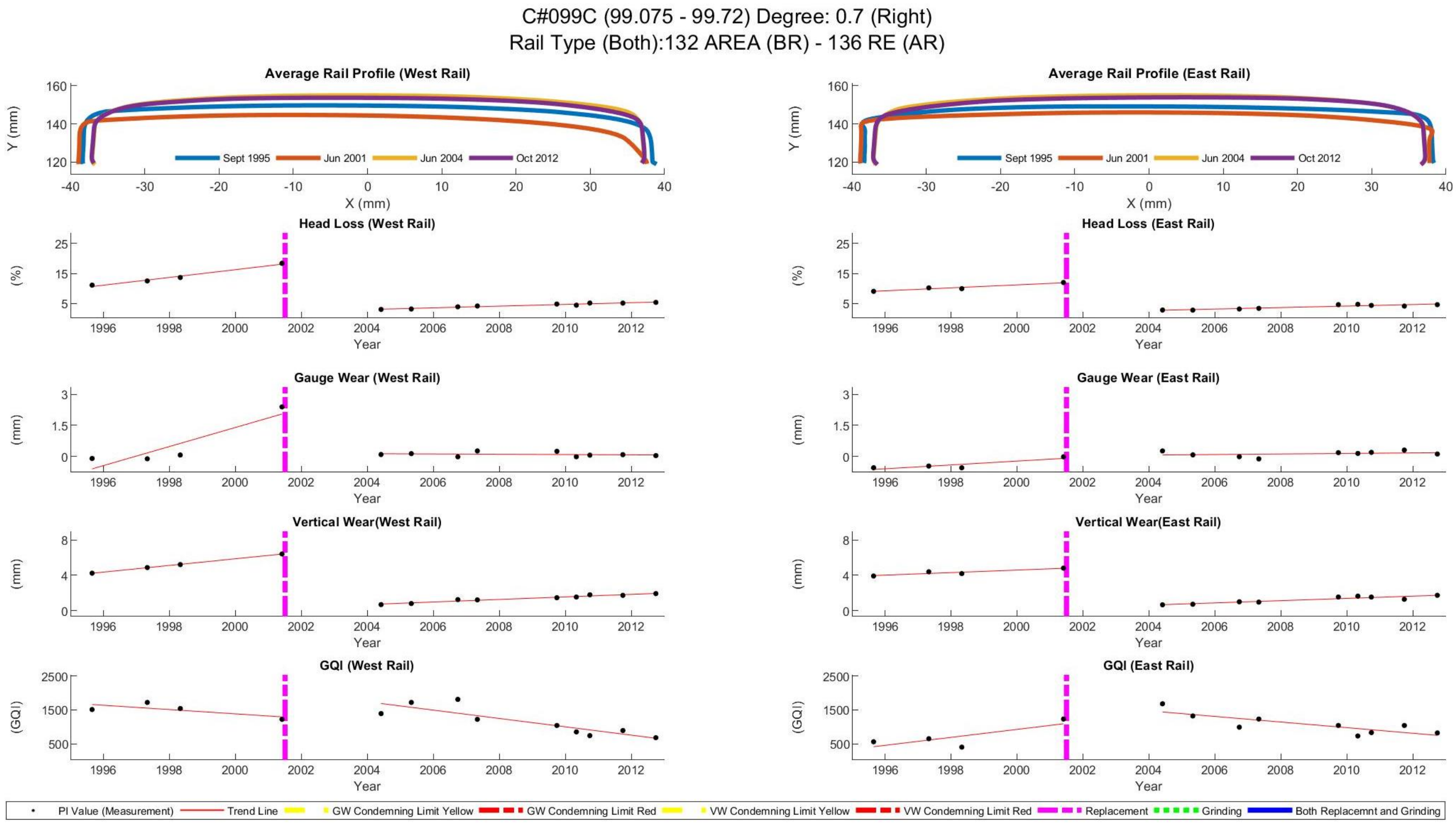


Figure 27. Curve C#099C (0.7° Right) – Temporal Trending Graphs (West = High Rail, East = Low Rail)

Figure 27 includes temporal trending graphs for Curve C#099C. In 2001, the 132 AREA rail was replaced with 136 RE. This segment falls into Category 2b. The figure reveals the following findings:

- The rails on this segment were replaced on July 2001. However, no information is available on rail grinding.
- There appears to be strong agreement between the HL, GW and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends.
- Comparing the wear rates in HL, GW and VW for both rail segments, a higher wear rate in the west (high) rail is observed, particularly prior to rail replacement.
- Generally, the graphs show a reduction in the wear rate after the rail replacement. Considering that the freight tonnage on this closed-fleet, heavy-haul short-line railway was almost steady over the given period (1995-2012) (G. Bachinsky, personal communications, 2019), the observed reduction in the wear rate may indicate that the 136 RE rail type is better suited for the expected traffic than the 132 AREA rail type. The improved performance may also be influenced by changes in the rail maintenance program (though no grinding information is available).
- The fluctuations observed in the GQI trend suggests the possibility of regular rail grinding interventions. The GQI graph reveals relatively high GQI values on both the east and west rails after the rail replacement. This suggests that the grinding template may have been redesigned and the recently replaced rail (unworn rail) does not completely match the desired rail shape (M. Reimer, personal communication, 2008).

4.2.3 Sharp Curve Tracks

This section provides detailed observations from the temporal trending analysis of sharp curve tracks. While limited information on rail grinding interventions is available for the sharp curve track segments, no rail replacement information is available (even though there are cases where rail replacement appears to have occurred). As such, the two segments selected for detailed fall into Category 2a. Table 13 provides details about these two segments.

Table 13. Information on the sharp curves discussed in section 4.2.2

Segment code	Mileposts	Date(s) (M/Y) of Replacement(s)	Date(s) (M/Y) of Grinding(s)	Reason to be included in detailed discussion
C#025C (Fig. 28)	24.924 – 25.201	NA	10/2006, 04/2007, 03/2008	Meaningful trend, sufficient information available on rail grinding, track segment replacement is observed but cannot be confirmed (Category 2a)
C#047AC (Fig. 29)	47.079 – 47.389	NA	2005, 10/2006, 04/2007, 04/2008	Meaningful trend, sufficient information available on rail grinding, more than one track replacement is observed but cannot be confirmed (Category 2a)

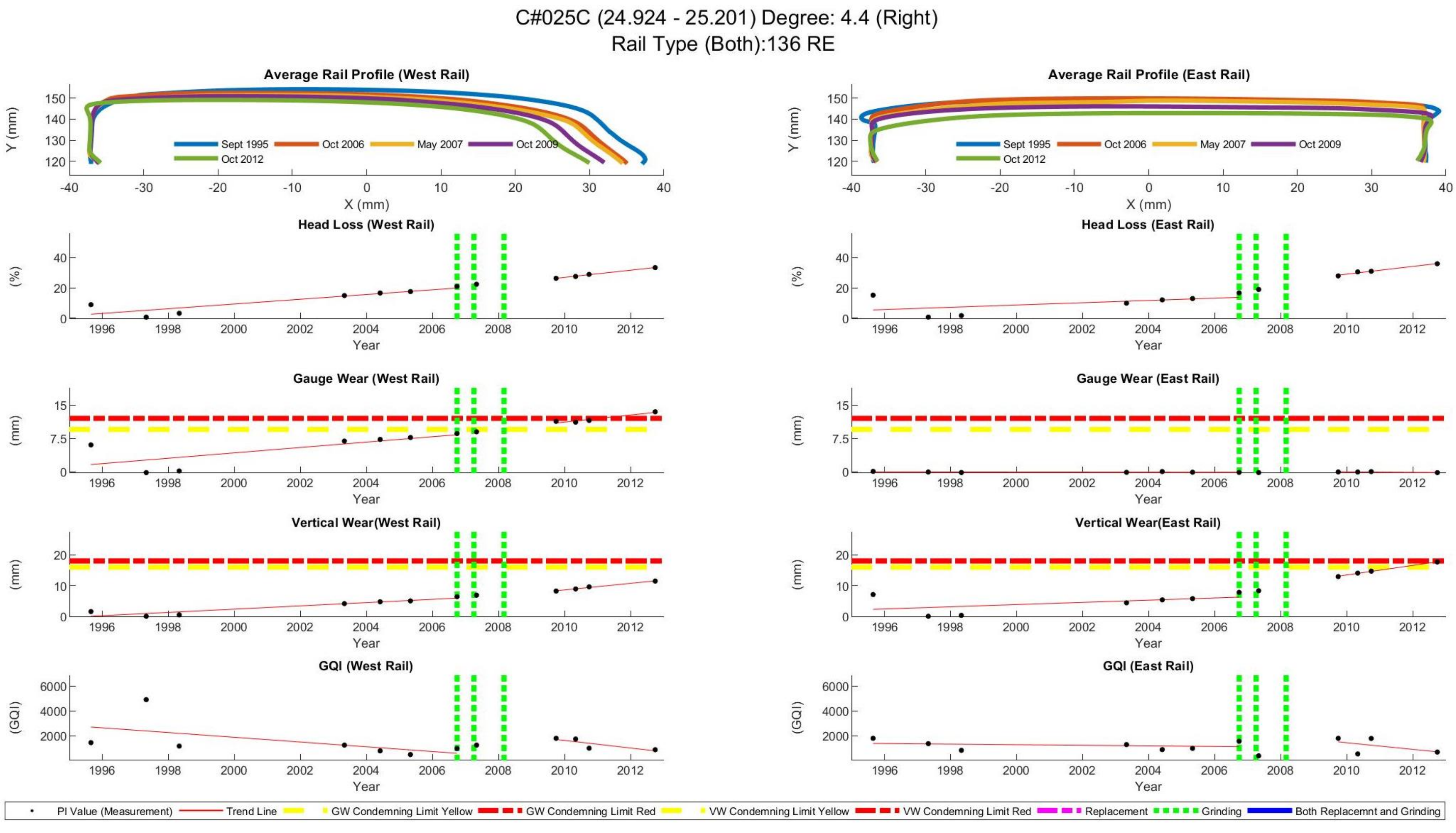


Figure 28. Curve C#025C (4.4° Right) – Temporal Trending Graphs (West = High Rail, East = Low Rail)

Figure 28 includes temporal trending graphs for Curve C#025C. The rail type is 136 RE. This segment falls into Category 2a. The figure reveals the following findings:

- The rails on this segment do not appear to have been replaced in the period from 1997 to 2012. However, the HL, VW and GQI data suggest a possible date for replacement in 1997. Available information indicates that the rails were ground in 2006, 2007 and 2008.
- There are appears to be strong agreement between the HL, GW and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends.
- Comparing the west (high) rail and east (low) rail, an intense wear rate is observed both in GW and VW on the west rail while the low rail reveals a high rate of VW.
- The rail grinding interventions do not appear to have reduced the wear rate. Both rails reached condemning limits during the period. In 2012, the west rail reached its GW condemning limit and the east rail reached its VW condemning limit.
- The GQI data reveal overall downward trends, suggesting that the grinding program generally made a positive contribution to rail profile performance. In particular, the GQI (E) data point for 2007 provides an example of improved rail profile conditions seemingly caused by rail grinding.

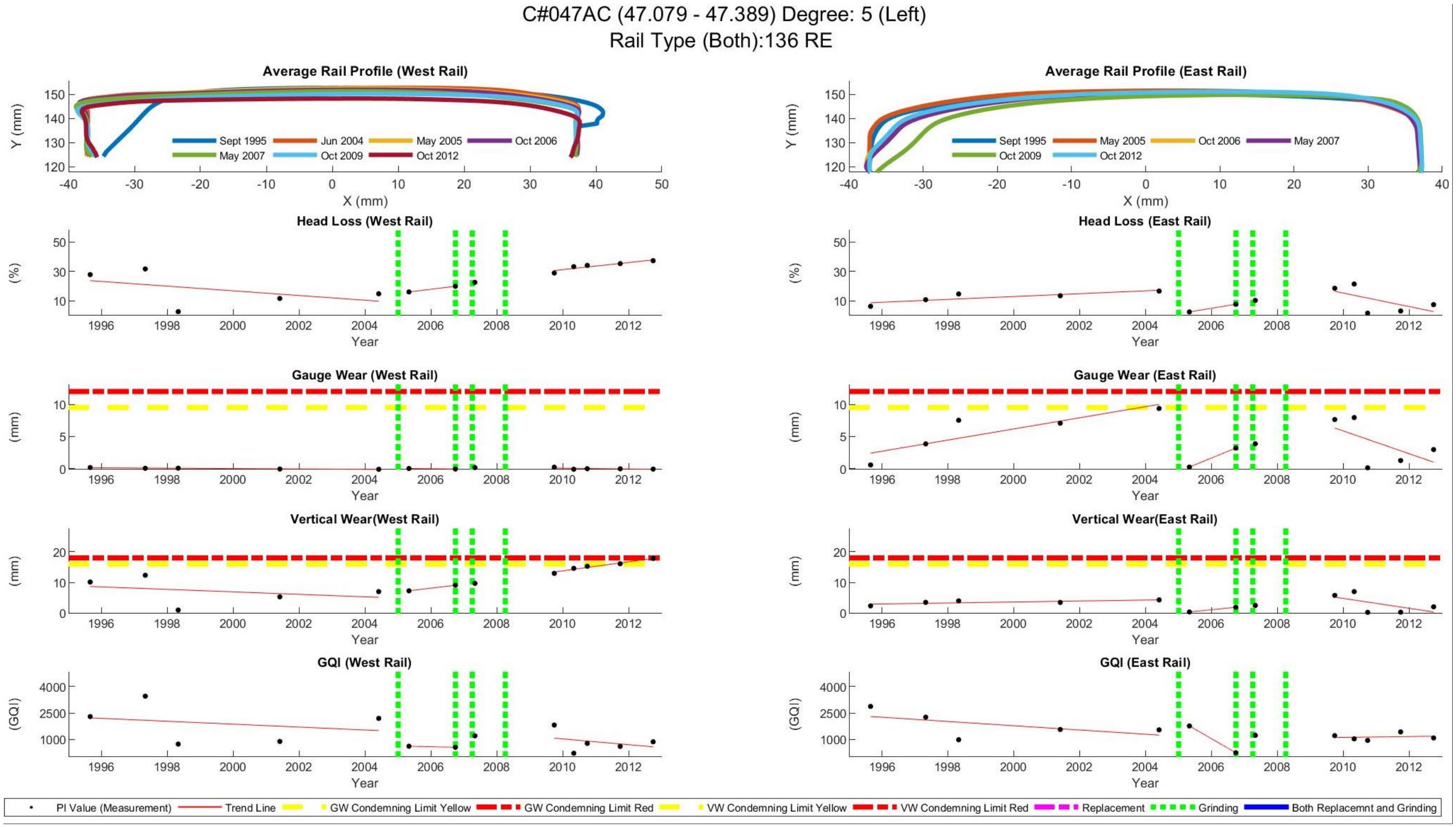


Figure 29. Curve C#047AC (5° Left) – Temporal Trending Graphs (West = Low Rail, East = High Rail)

Figure 29 includes temporal trending graphs for Curve C#047AC. The rail type is 136 RE. This segment falls into Category 2a. The figure reveals the following findings:

- No information about rail replacement is available for this segment. However, the HL, VW and GQI data suggest a possible date for replacement in 1998 for west rail and in 2005 and 2010 for the east rail. Available information indicates that the rails were ground in 2005, 2006, 2007 and 2008. However, the GQI graphs suggest regular grinding interventions.
- There appears to be strong agreement between the HL, GW and VW trends for both the west and east rails. The shapes of the ARPs generally confirm these trends.
- Comparing the west (low) rail and east (high) rails, an intense GW rate is observed for the east (high) rail while the east (low) rail reveals a more intense VW rate.
- In 1995, the ARP (W) appears to be mirrored about the longitudinal centre of the rail head (relative to the ARPs for later years). This may be indicative of a relatively common rail maintenance practice in which low and high rails are switched to take advantage of the lack of wear on the field side of the rail head.
- The rail grinding interventions do not appear to have been able to reduce the wear rates. For the east rail, the GW reached the yellow condemning limit (9.5 mm) at least two times over the period of 1995-2012 (suggesting two rail replacements)For the west rail, the VW reached the red condemning limit (18 mm) in 2012.
- The steady trend of GQI for west rail between 2005 and 2006 (between two grinding interventions) suggests that the grinding program was effective enough to stabilize the condition of the west rail. The GQI values for the west rail in October

2009 and May 2010 show an example of pre- and post-grinding GQI values, suggesting that there was a rail grinding in early 2010.

- GQI (E) shows a relatively high value on May 2005 when a potential rail replacement is observed. This is an example of when the grinding template is redesigned and a recently replaced rail (unworn rail) does not completely match its shape, resulting in a relatively high GQI value (M. Reimer, personal communication, 2008). However, after grinding to the new template the GQI value is expected to decrease. The GQI (E) in May 2005 and October 2006 supports this statement by revealing a significant drop in the GQI value from more than 200 to less than 50.

4.2.4 Summary

- Generally, curved segments exhibit more intense wear than tangent segments.
- For curves, the high rail is more likely to be more intensely worn compared to the low rail. There appears to be a more intense rail wear rate on sharp curves than on mild curves.
- Provided that adequate performance can be assured, it may be most effective to replace the rail just before it reaches applicable condemning limits (e.g., Figure 21 - #022BT). There is evidence that some replacements occurred well in advance of this condition, while other replacements were not completed until after the rail exceeded the condemning limit (e.g., Figure 28 - C#025C).
- There appears to be strong agreement between the HL, GW and VW trends for both west and east rails. The shapes of the ARPs generally confirm these trends.

- The LCP and the CR are only applicable for tangents. There appears to be an almost steady contact radius for tangents over time. The LCP suggests the wheel-rail contact position is mainly in the centre zone, while it tends to move to the gauge zone over time. However, the changes in LCP are observed to be dependant on the relative rate of gauge wear and vertical wear.
- Generally, it is expected that the GQI graph follows an upward trend between two grinding interventions, followed by a decrease after each grinding intervention. However, because GQI depends on several factors, interpreting the GQI graphs poses challenges. Notably, the availability of information about the timing and nature of grinding interventions specifies which trend might be observed. Considering these issues, a fluctuating trend (see Figure 21), a steady trend (see Figure 29 - East Rail (1995-2007)), a decreasing trend (see Figure 24), and an increasing trend (see Figure 27 – East Rail (1995-2001) could be observed.
- Generally, the graphs illustrate the value of rail grinding (specifically after 2002 with new grinding machines) and rail replacement (using 136 RE instead of 132 AREA). While the influence of grinding is not always conclusive, the PIs, when considered together, generally indicate positive outcomes. Comparatively, rail replacement is immediately evident from the PI graphs.

4.3 Findings of the Correlation Analysis

This section discusses the findings of the correlation analysis. First a brief description of expected results is provided, which is then compared to the observed results of the correlation analysis. The purpose of the correlation analysis is to statistically support the findings of the temporal trending analysis and to investigate the application of this set of PIs as a holistic rail grinding monitoring tool.

As discussed earlier in sections 3.3 and 4.2, the segments must meet various criteria to be considered as input variables into the correlation analysis. To preserve consistency, the selection of correlation analysis inputs focuses on only the segments that have:

- A minimum of 12 data points (years),
- No outliers (or, if present, addressed as per the verification in section 4.1.1), and
- A meaningful trend (as per the validation in section 4.1.2).

While various guidelines exist on interpreting the strength of correlation coefficient (Hinkle et al., 2003; Hemphill, 2003; Cohen, 1988; Rumsey, n.d.), this research has the following definitions on interpreting the Spearman's correlation coefficients:

- No Correlation: 0
- Weak Correlation: 0.1 to 0.29 (- 0.1 to – 0.29)
- Moderate Correlation: 0.3 to 0.59 (- 0.3 to – 0.59)
- Strong Correlation: 0.6 to 0.99 (- 0.6 to – 0.99)
- Perfect Correlation: 1 (-1)

The selection follows the same approach as for the trending analysis (section 4.2), so that only those segments in Category 1 and 2 are included. Table 14 provides the number of eligible segments included in the correlation analysis.

Table 14. Number of eligible segments for correlation analysis

	Tangents	**Curves**			
	32	Mild		Sharp	
		Left Curvature	Right Curvature	Left Curvature	Right Curvature
		11	22	7	6
Total	32	33		13	

4.3.1 Tangent Tracks

Table 15 provides the results of the Spearman correlation analysis for tangent tracks.

Table 15. Results of correlation analysis between PIs – Tangent Tracks

Spearman Correlation Coefficients													
	West Rail							East Rail					
	HL	GW	VW	CR	LCP	GQI		HL	GW	VW	CR	LCP	GQI
HL		-0.44	**0.98**	0.07	0.15	-0.08	HL		-0.30	**0.98**	0.09	0.15	-0.01
GW			-0.51	-0.03	-0.47	0.19	GW			-0.32	0.13	-0.31	0.26
VW				0.08	0.22	-0.14	VW				0.08	0.19	-0.06
CR					-0.33	-0.10	CR					-0.23	0.00
LCP						-0.30	LCP						-0.37
GQI							GQI						
Sample Size: Based on Data from 32 Segments													

Strong Positive Correlation	Moderate Positive Correlation	Strong Negative Correlation	Moderate Negative Correlation

Table 15 reveals the following findings:

- There is a strong positive correlation between the HL and VW.
- Moderate negative correlations are observed between GW and VW and GW and HL in both the west and east rails. Potential reasons for why vertical wear increases while the gauge wear decreases are the GW calculation method that is based on the "floating-point" (See section 2.3.3) and the possibility of more intense vertical wear than gauge wear.
- Moderate negative correlations are observed between gauge wear and lateral contact position on both west and east rails. This suggests that the gauge side of the rail is more exposed to the wheel flange (GW increases) as the lateral contact position decreases (moves towards the field zone).
- There is a moderate negative relationship between contact radius and lateral contact position, suggesting that the contact radius increases as the contact point moves to the central and field zones from gauge zone.
- Based on the results of the correlation analysis between LCP and GQI on both east and west rails, there is a moderate negative correlation between these two PIs. This may indicate that the efforts in rail grinding reduce the GQI value to facilitate the wheel-rail contact while moving the LCP towards the gauge zone.
- Except for LCP, there appears to be no significant correlation between CR and the other PIs. This is also true for GQI. This suggests that CR and GQI are two unique PIs that measure different aspects of rail performance.

4.3.2 Mild Curve Tracks

Table 16 provides the results of the Spearman correlation analysis on mild curves.

Table 16. Results of correlation analysis between PIs – Mild Curve Tracks

Spearman Correlation Coefficients									
	Low Rail				High Rail				
	HL	GW	VW	GQI		HL	GW	VW	GQI
HL		0.16	**0.99**	0.08	HL		-0.12	**0.99**	0.02
GW			0.10	-0.06	GW			-0.19	0.04
VW				0.05	VW				0.00
GQI					GQI				
Sample Size**:** Based on Data from **33** Segments									

	Strong Positive Correlation		Moderate Positive Correlation		Strong Negative Correlation		Moderate Negative Correlation

Table 16 reveals the following findings:

- There is a significant positive correlation between HL and VW.
- Except for HL and VW, there is a poor or almost no correlation between all other PIs.
- GQI is not correlated with other PIs. This suggests that the GQI provides a unique perspective on rail profile performance, which should be considered collectively along with other PIs.

4.3.3 Sharp Curve Tracks

Table 17 provides the results of the Spearman correlation analysis on sharp curves.

Table 17. Results of correlation analysis between PIs – Sharp Curve Tracks

Spearman Correlation Coefficients									
Low Rail					High Rail				
	HL	GW	VW	GQI		HL	GW	VW	GQI
HL		-0.04	**0.97**	0.03	HL		**0.79**	**0.98**	-0.09
GW			-0.07	0.08	GW			**0.65**	-0.16
VW				-0.03	VW				-0.02
GQI					GQI				
Sample Size: Based on Data from 13 Segments									

Strong Positive Correlation	Moderate Positive Correlation	Strong Negative Correlation	Moderate Negative Correlation

Table 17 reveals the following findings:

- HL and VW are significantly correlated on both low and high rails.
- There are appears to be strong positive correlation between GW and HL and GW and VW on high rails. This suggests that rail wear on high rails of sharp curve tracks involves wear on both the gauge side and the top of rail, respectively.
- GQI has no significant correlation with other PIs. Similar to mild curve tracks, this suggests that the GQI is a unique PI for rail profile monitoring.

4.3.4 Summary

This section summarizes findings from the correlation analysis on tangents, mild curves and sharp curves.

- There is a strong positive correlation between the HL and VW regardless of the type of segment. A potential reason for this strong correlation is the similarity of how HL and VW measure rail wear (HL as a percentage and VW as an absolute value).

- Moderate negative correlations are observed between GW and HL and GW and VW for tangent tracks. Potential reasons for such relationships are the GW calculation method that is based on the "floating-point" (See section 2.3.3) and the possibility of more intense vertical wear than gauge wear.
- Except for LCP, there appears to be no correlation between CR and the other PIs. This suggests that the CR truly measures a unique aspect of rail profile performance and should be considered alongside other PIs. In practice, it is important to keep contact radius at a moderate level because a low CR increases the chance of intense rolling contact fatigue on the rail and a high CR causes steering difficulties.
- Moderate negative correlations between GW and LCP on both west and east rails of tangent tracks may suggest that the gauge side of the rail is more exposed to the wheel flange (GW increases) as the lateral contact position decreases (moves towards the field zone).
- Generally, the GQI has no significant correlation with other PIs. GQI appears to measure a unique aspect of rail profile performance (i.e., the level of agreement between the actual and desired rail profiles). This supports the idea of considering this PI along with other PIs for monitoring rail profile performance.
- Except for a strong positive correlation observed between GW and HL and VW in high rails of sharp curve tracks, GW reveals no significant correlation with other PIs in curve tracks. This suggests that the high rails of sharp curve tracks are worn approximately evenly on both the top (vertical wear) and gauge side (gauge wear).

4.4 Limitations of the Analysis

This section describes the analysis limitations identified through the development, validation, and application of the algorithm for analyzing trends and correlations. The limitations include:

- inconsistency in the railhead x,y-coordinate records;
- the application of the average rail profile in only qualitative analysis and not the quantitative (correlation) analysis;
- inclusion of only segments illustrating meaningful trends in the trending and correlation analyses;
- the limited information about rail property maintenance and replacement interventions; and
- future implementation of the algorithm.

4.4.1 Inconsistent Railhead x,y-Coordinate Records

The x,y-coordinate records used to describe the shape of the railhead may be inconsistent in terms of: (1) the number of data points used to describe the railhead; and (2) the vertical datum (y-coordinate). The number of data points measured varies by profile based on several types of imaging obstructions, including rail head shape/size, vegetation, ballast, guard rail, ambient light contamination, and embedded track (S. Kweens, personal communications, 2018).

Changes in the vertical datum used to reference the y-coordinate value cause issues when attempting to superimpose profiles collected throughout a segment or for multiple data collection runs. The originally-developed average rail profile procedure overcomes this limitation by normalizing rail profiles within a segment at the top-of-rail, ensuring that the average shape of the railhead is accurately calculated. However, to observe rail profile wear over time, it is necessary to "un-normalize" the calculated average rail profiles for a segment over multiple years. Occasionally, this results in trends that are inconsistent with observations for other PIs (e.g., HL, VW). While some attempts have been made to address this issue, there are some cases (segments) that are not resolved.

4.4.2 Application of the ARP in only qualitative analysis

The average rail profile procedure results in a table consisting of the average rail profile's x,y-coordinates. This table illustrates the shape of the average rail profile, which is used by thesis in the temporal trending graphs. In this way, the ARP provides an easy-to-understand representation of the rail profile over time and supporting the interpretation of the trends for the other PIs. However, since it cannot be described quantitatively by a single value, the average rail profile could not be used in the correlation analysis.

4.4.3 Inclusion of Only Segments Illustrating Meaningful Trends in Conclusion and Correlation Analysis

This thesis applies different criteria and filters on the input data. These are based on technical considerations (e.g. collection intervals), consistency requirements (e.g. valid and eligible records for a consistent number of years) and statistical requirements (e.g. having a database with sample size of more than 30). As a result of these filters, 111 out of 752 segments are included in the analysis as the final valid input data.

After verification and validation, 78 segments are included in the trending and correlation analyses. These segments illustrate meaningful trends over time and are qualitatively valid for these analyses. A lack of rail maintenance information and technical errors in collecting, measuring or storing the data are possible reasons for the presence of non-meaningful trends.

4.4.4 Limited Rail Property Maintenance and Replacement Interventions Information

This thesis uses the limited available data on rail replacement and grinding interventions to support the temporal trending analysis. Although the observations from the temporal trending graphs suggest potential dates of rail replacement and grinding interventions, the collection of this type of information is critical to provide a better understanding of the trends for the user.

4.4.5 Future Implementation of the Algorithm

While the main concepts developed in this research are applicable to all types of rail properties having information on the condition and performance of the rail profiles, this thesis develops the algorithm around the rail profile text files and the measured PI data exported from Rangecam©. These are processed in a MATLAB environment, which may not be readily-available for implementation to all users.

4.5 Implications for Managing Rail Grinding Programs

The results of the analyses in this thesis have implications for rail maintenance and management programs, as discussed below.

- **The algorithm:**

  The algorithm developed in this thesis provides an automatic tool for screening, analysing, storing and illustrating rail profile and PI data without depending too much on user interaction. One of the main contributions of the algorithm is in big data analysis and management. While the algorithm is developed to perform analysis on a specific type of data, conceptually, it has universal application for other rail properties with different data formats. However, the use of the algorithm on other rail properties may necessitate revisions to accommodate different data formats.

- **The graphs:**

  The temporal trending graphs are developed using the rail data collected on a closed-fleet, heavy-haul short-line railway in Canada. The graphs enable the Canadian railway and its maintenance contractors to evaluate the performance of the rail grinding by conducting a comparative investigation on rail wear rates before and after grinding interventions. The graphs support this investigation by providing a meaningful illustration of the rail condition/performance over time for different performance indicators, including several newly developed indicators.

  In addition, the graphs include the best-fit trend line between any two replacement/maintenance interventions (if they exist). In addition to enabling the railway and contractor to investigate the changes in the rates at which the PIs change over time, when extrapolated, the best fit trends enable predictions of when a PI might reach its condemning limit.

- **The results of the validation, trending, and correlation analyses:**

  The analysis reveals three opportunities to improve data collection and management. First, through the validation it was revealed that certain data collection runs (years) contain errors and inconsistencies. Efforts to validate results immediately following data collection may improve the overall data quality. Second, the trending analysis revealed the importance of including and maintaining information about maintenance interventions (e.g., grinding, rail replacement) in the database. This information is critical for interpreting trends and drawing meaningful conclusions. Third, the results of the correlation analysis statistically proved the feasibility and applicability of analysing different PIs relative to each other. The implication of this is that decision-makers can become confident in interpreting trends amongst a group of related PIs. Moreover, should a data point on one of the PIs be absent, such a data point might be inferred based on the measurement of the corresponding data point for a strongly correlated PI.

5 CONCLUSION

This chapter provides the conclusion of the thesis. This chapter includes (1) the main contributions, (2) a summary of key findings and (3) recommendations for future research.

5.1 Contributions

The thesis makes three principal contributions:

1. The algorithm developed in the thesis automates the compilation of data for multiple PIs over multiple years, and transparently applies criteria to ensure consistency in the underlying rail profile data. The algorithm enables user flexibility in the definition of temporal periods to evaluate performance before and after maintenance interventions. Moreover, it improves analytical efficiency and enables customization of analysis steps and results.

2. The trending and correlation analyses integrate industry-standard PIs (head loss, gauge wear, vertical wear, GQI) with newly developed PIs (APR, LPC, CR). These analyses reinforce expected inter-relationships between several well-understood PIs and introduce potentially new ways to monitor rail profiles within a rail maintenance program.

3. The analysis provides an understanding of (1) the trends PIs exhibit over time and (2) the relationships between PIs. Specifically, the findings provide some evidence of the value of maintenance interventions—quantified in terms of the generally lower GQIs over time. Also, the trends for certain PIs reveal the pending need for

replacement when the PIs approach relevant condemning limits. This information supports more proactive and effective rail maintenance intervention decisions.

In terms of relationships between PIs, with the exception of a consistently strong positive correlation between head loss and gauge wear, the set of PIs investigated in this thesis provide unique perspectives on rail profile wear.

5.2 Summary of Key Findings

This research develops and validates an algorithm to automatically perform temporal trending analysis on rail infrastructure using seven different performance indicators. One of the main characteristics of the algorithm is the ability to call and analyze a significant amount of data and store the results in a database without requiring user interface. The algorithm processes nearly two million rail profile records for roughly 100 miles (160 km) of a closed-fleet, heavy-haul short-line railway in Canada during 14 data collection runs. Seven PIs are investigated, namely: average rail profile (ARP), head loss (HL), gauge wear (GW), vertical wear (VW), lateral contact position (LCP), contact radius (CR), and grind quality index (GQI).

The following sections present the key findings of the trending and correlation analyses.

5.2.1 Temporal Trending Graphs

The temporal trending graphs discussed in section 4.2 provide different cases observed in the temporal trending analysis. This section outlines key findings from this analysis.

- It is evident that tangents are less frequently replaced than curves because the wear rate is less intense. Moreover, the trends reveal more intense wear—and consequently more frequent rail replacement—on sharp curves than mild curves and on high rails than low rails.
- ARP, HL, VW and in most of cases GW suggest the following sorting of different rails based on their rail wear intensity, in descending order.

1. High rail – sharp curve tracks
2. Low rail – sharp curve tracks
3. High rail – mild curve tracks
4. Low rail – mild curve tracks
5. Tangent tracks

- ARP, HL, VW and GW all measure an aspect of the process of rail wear. The graphs of HL, VW and GW numerically represent this process while the ARP provides a visual representation.
- For the first time, the trending analysis includes LCP and CR alongside the more traditional measures of rail profile wear. While specific observations suggest the value of these PIs, it is difficult to develop general conclusions about the expected performance of these values. More research is needed to better understand the trends evident for these PIs.

- The GQI reveals the rail condition from a different perspective compared to the PIs mentioned above. The GQI shows how well the rail profile matches the desired template. Significant changes in the GQI trend are observed after rail grinding while for other PIs they are observed after rail replacement. Therefore, a strong monotonic relationship is not be observed between GQI and the other PIs.
- For practical applications concerning rail performance, particularly changes after rail replacement, there appears to be complementary information provided by the ARP, either HL or VW, and GW. In contrast, the GQI provides more useful information about the effectiveness of rail grinding than the ARP, HL, or GW.
- As the wear rate on tangent tracks is lower than on curves, the magnitude of changes in the PIs shown on the graphs for is smaller. For example, over 14 years the HL on the west rail of one segment (#088T) had a slight upward trends (from 2% to almost 6%), while the HL rates increased from 5% to 15% on the high rail of one mild Curve (C#018C).
- In some cases the grinding template is redesigned after performing rail replacement. So, the recently replaced rail (unworn rail) does not completely match the new template, resulting in a relatively high GQI value. However, after grinding to the new template the GQI value is expected to reduce. The GQI (E) data points for C#036C in May 2005 and October 2006 support this statement by revealing a significant drop in the GQI value from just above 200 to less than 50.
- In some cases it is observed that the wear rate increased after a number of sequential grinding interventions. There are three possible reasons for this: (1) undesirable condition of the rail profile and intense wear; (2) heavy and deep cut grinding, and

(3) a combination of (1) and (2). However, a detailed review of the GQI graphs (e.g., for C#025C – East Rail – 2007) indicates that such changes in wear may be caused by heavy and deep cut grinding.

- Two major types of rail replacement are evident from the temporal trending graphs: (1) replacing with a new rail; and (2) replacing a rail (east or west) with an existing rail from the opposite side (west or east). The second form of rail replacement consists of two subcategories: (1) replacing the rail segment with the rail on the opposite side of the exact same segment; or (2) replacing the rail segment with a rail on the opposite side of another segment.
- It is evident that the rail wear rate decreases after replacing 132 AREA with 136 RE rails. This finding assumes that the tonnage is almost steady over time on the rail property analyzed in this thesis.
- Based on the available data, it appears that HL, GW, and VW vary linearly with time. This relationship has the potential to be used to predict when the rails will reach condemning limits (or some other pre-determined performance limit). In most cases, rails were replaced before their GW and/or VW reached the condemning limits.

5.2.2 Correlations

The correlation analysis discussed in section 4.3 reveals the following key findings:

- HL and VW are significantly correlated on all the segments (tangents and curves). This suggests that these could be used interchangeably in the industry. Or, if data were missing for one PI, it could be reliably estimated using the other.

- Moderate negative correlations are observed between GW and HL and GW and VW for tangent tracks. Potential reasons for such relationships are the GW calculation method that is based on the “floating-point” (See section 2.3.3) and the possibility of more intense vertical wear than gauge wear.
- For the high rail of sharp curve tracks, HL has a strong positive correlation with VW and GW. This suggests that the rail wear mechanism affects both the top of rail and gauge side of the high rail in sharp curve tracks.
- Except for LCP, there appears to be no correlation between CR and the other PIs. This suggests that the CR truly measures a unique aspect of rail profile performance and should be considered alongside other PIs. Similarly, the GQI has no significant correlation with other PIs. GQI appears to measure a unique aspect of rail profile performance (i.e., the level of agreement between the actual and desired rail profiles).
- Moderate negative correlations between GW and LCP on both west and east rails of tangents may suggest that the gauge side of the rail is more exposed to the wheel flange (GW increases) as the lateral contact position decreases (moves towards the field zone).

5.3 Recommendations for Future Research

This thesis identifies the following recommendations for future research:

- There is a need to upgrade the algorithm with an automatic procedure for detecting and treating outliers. While the algorithm developed in this thesis is capable of automatically performing most of the analysis, the process of verification by removing outliers depends on user judgement. This degrades the potential efficiency of the algorithm when analysing large amounts of data.

- As discussed in 4.4.1, there is a need to address inconsistencies in the rail profile vertical datum within a segment and over time. This will provide a more consistent and sensible visualisation of the average rail profile over time, specifically for those segments that are observed with these limitations.
- It is observed that in most cases rail segments were replaced before reaching condemning limits for gauge and vertical wear. This implies that additional life may be available, provided adequate performance can be assured. Moreover, based on the observation that head loss, gauge wear and vertical wear trend linearly, it would be instructive to conduct regression analyses using these PIs to predict appropriate times for future rail maintenance interventions. Such a prediction would assume that the historical conditions affecting the rail life cycle (e.g. climate, tonnage and train speed) persist into the future.
- It is important to preserve a stable position for wheel-rail contact over time (G. Bachinsky, personal communications, 2019). The average rail profile can facilitate the understanding of the wheel-rail contact position, but the LCP and CR offer an opportunity to provide complementary quantitative values for understanding the nature of wheel-rail contact. Further research is needed to better understand how LCP and CR relate to the other PIs under varying operating conditions.
- The GQI (and its trends) depend on various factors, such as the rail profile condition (GQI) before grinding, the desired template, how many interventions and how much grinding was conducted, and how successful the grinding was (GQI after

grinding). Interpreting such a PI requires more frequently collected rail profile data (i.e. ideally more than two collection intervals between each grinding intervention and data just prior to and just after grinding) and more detailed information about the nature of the grinding effort (e.g, date, extent of effort, depth of cut). Consideration may be given to the establishment of field test sites at which such information can be more closely monitored.

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APPENDIX A:

COLLECTION INTERVALS

Year	Curve (ft.)	Tangent (ft.)	Accepted Deviation
October, 2012	6	6	1 ft.
October, 2011	5	5-15	
October, 2010	5	5-15	
May, 2010	5	5-25	
October, 2009	5	5-25	
May, 2007	5	5-25	
October, 2006	5	5-25	
May, 2005	5	5-25	
June, 2004	5	5-25	
May, 2003	5	5-25	
June, 2001	5	5-25	
May, 1998	15	5-15	
May, 1997	15	5-15	
September, 1995	15	5-15	

APPENDIX B:

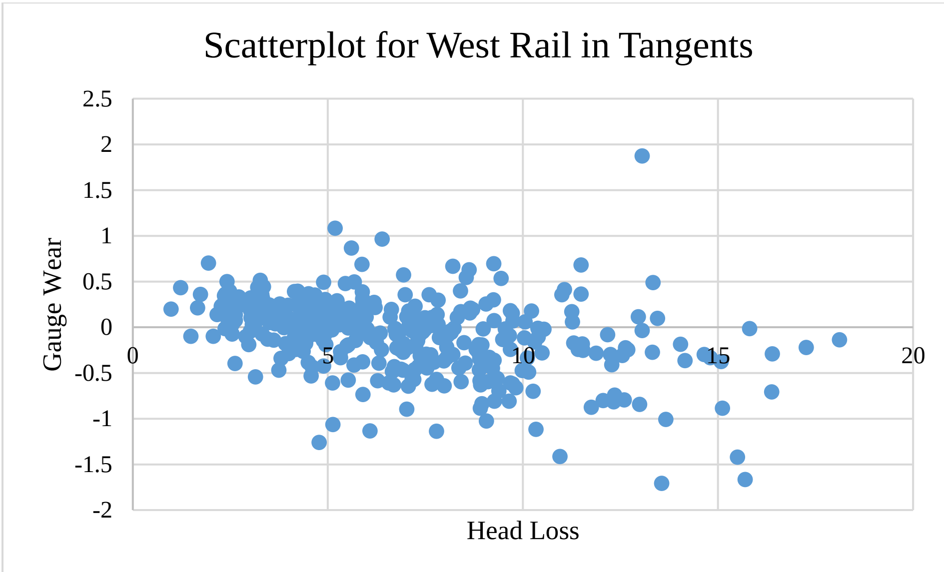
LIST OF ELIGIBLE SEGMENTS (MINIMUM DATA POINTS: 12)

Segment Code	Number of Available Years	Years
'C#025AC'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#038AC'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#048BC'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#048C'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#018C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#041C'	13	'1995 1997 1998 2001 2003 2005 2006 2007 2009 20101 20102 2011 2012'
'C#042BC'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#043C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#046BC'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2007 20101 20102 2011 2012'
'C#047AC'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#055BC'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2012'
'C#057AC'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#062C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#069C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#076C'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#093C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#099C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#108C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#109C'	13	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#017AC'	12	'1995 1997 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#023BC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#024C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#025C'	12	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2012'
'C#029AC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#029C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#036C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#038C'	12	'1995 1997 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#039BC'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#042CC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#052C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#055C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#077BC'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#082AC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#084C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#085CC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#090C'	12	'1995 1997 1998 2001 2004 2005 2006 2009 20101 20102 2011 2012'
'C#094BC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#096C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 20101 20102 2011 2012'
'C#097C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#098C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2012'
'C#101C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#102AC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#102C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#103C'	12	'1995 1997 1998 2001 2004 2005 2006 2007 2009 20101 2011 2012'
'C#104AC'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#104C'	12	'1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#105C'	12	'1995 1997 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'
C#108AC'	12	1995 1997 1998 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'C#045AC'	12	'1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2012'
'C#057BC'	12	'1997 1998 2001 2004 2005 2006 2007 2009 20101 20102 2011 2012'

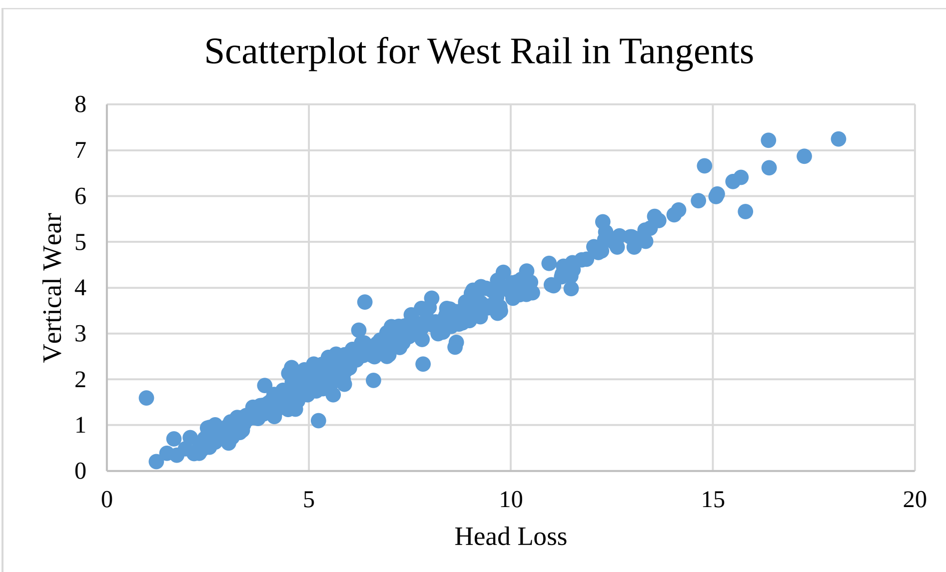
Segment Code	Number of Available Years	Years
'Tangent 15.702-15.878'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 17-17.236'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 19.315-19.475'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 24.627-24.939'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 32.77-32.958'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 88.033-88.386'	14	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 102.824-103.029'	13	'1995 1997 1998 2001 2003 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 107.236-107.693'	13	'1995 1997 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 108.617-108.756'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 16.666-16.858'	13	'1995 1997 1998 2001 2003 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 18.678-18.804'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 22.558-22.855'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 27.142-27.689'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 44.795-44.931'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 46.205-46.492'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 60.283-60.45'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 61.64-62.024'	13	'1995 1997 1998 2001 2003 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 67.99-68.186'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2007 2009 20101 20102 2011'
'Tangent 70.353-70.568'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 75.543-75.801'	13	'1995 1997 1998 2001 2003 2004 2006 2007 2009 20101 20102 2011 2012'
'Tangent 77.261-77.569'	13	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 20102 2011 2012'
'Tangent 83.496-83.959'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 84.181-84.843'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 96.559-96.992'	13	'1995 1997 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 101.364-101.816'	12	'1995 1997 1998 2001 2003 2004 2005 2009 20101 20102 2011 2012'
'Tangent 104.3-104.54'	12	'1995 1998 2001 2003 2004 2005 2007 2009 20101 20102 2011 2012'
'Tangent 13.17-13.276'	12	'1995 1997 1998 2001 2003 2004 2005 2009 20101 20102 2011 2012'
'Tangent 22.982-23.178'	12	'1995 1997 1998 2001 2003 2004 2005 2009 20101 20102 2011 2012'
'Tangent 27.828-28.241'	12	'1995 1997 1998 2001 2003 2004 2007 2009 20101 20102 2011 2012'
'Tangent 38.054-38.437'	12	'1995 1997 1998 2003 2004 2006 2007 2009 20101 20102 2011 2012'
'Tangent 38.691-38.99'	12	'1995 1998 2003 2004 2005 2006 2007 2009 20101 20102 2011 2012'
'Tangent 42.908-43.247'	12	'1995 1997 1998 2001 2003 2004 2005 2009 20101 20102 2011 2012'
'Tangent 49.041-49.172'	12	'1995 1997 1998 2001 2003 2006 2007 2009 20101 20102 2011 2012'
'Tangent 57.48-57.982'	12	'1995 1997 1998 2001 2003 2004 2006 2009 20101 20102 2011 2012'
'Tangent 82.169-82.552'	12	'1995 1997 1998 2001 2003 2004 2005 2006 2009 20101 2011 2012'
'Tangent 94.3-94.628'	12	'1995 1997 1998 2001 2003 2004 2006 2007 2009 20101 2011 2012'

APPENDIX C:

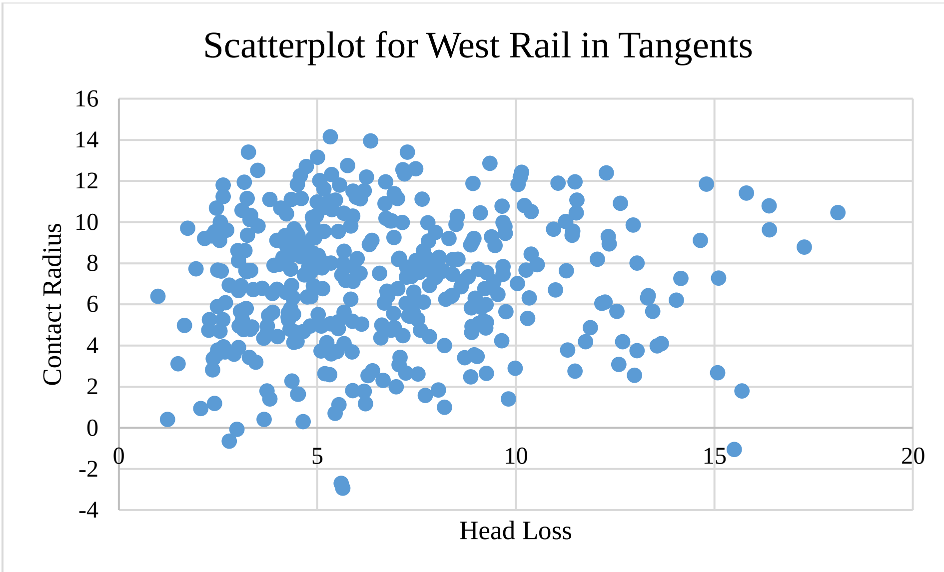
SCATTERPLOTS FOR PERFROMANCE INDICATORS (TANGENTS - MILD CURVES – SHARP CURVES)

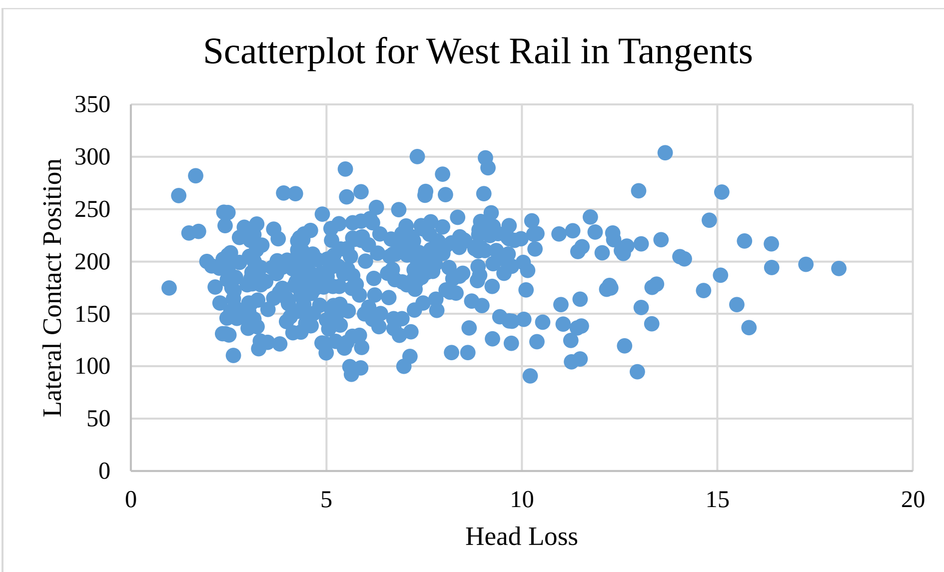


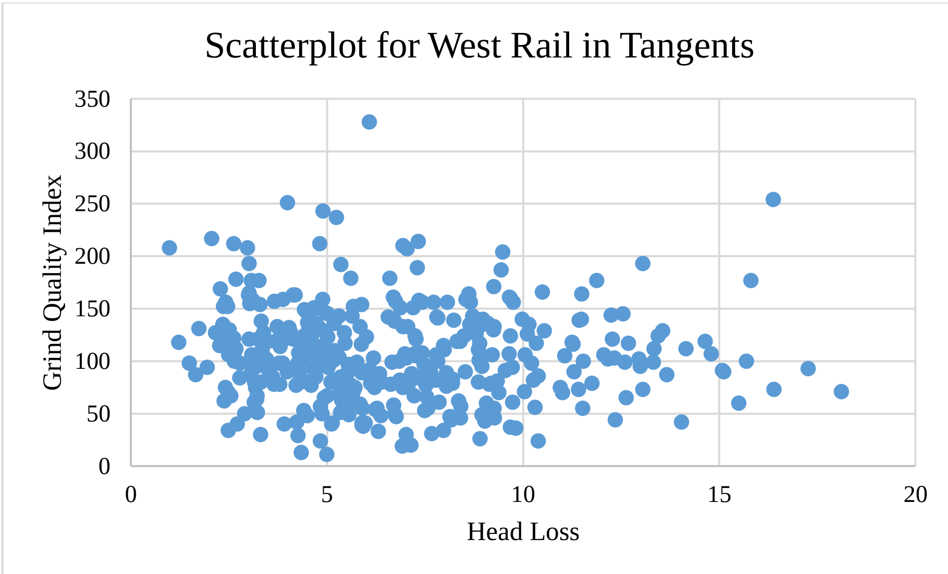
Scatterplot for West Rail in Tangents
Gauge Wear
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
5
10
15
20
Head Loss



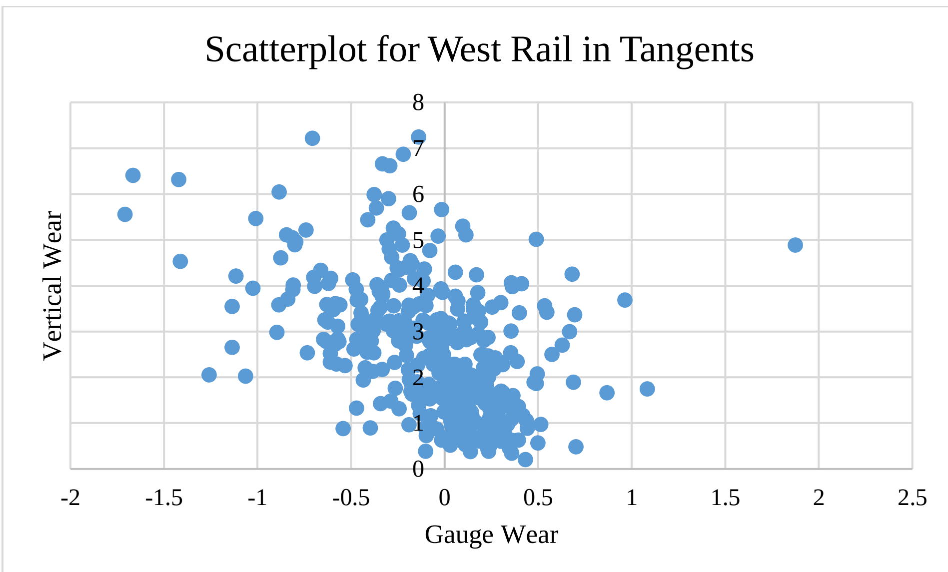
Scatterplot for West Rail in Tangents
Vertical Wear
8
7
6
5
4
3
2
1
0
0
5
10
15
20
Head Loss


Scatterplot for West Rail in Tangents
Contact Radius
Head Loss
16
14
12
10
8
6
4
2
0
-2
-4
0
5
10
15
20

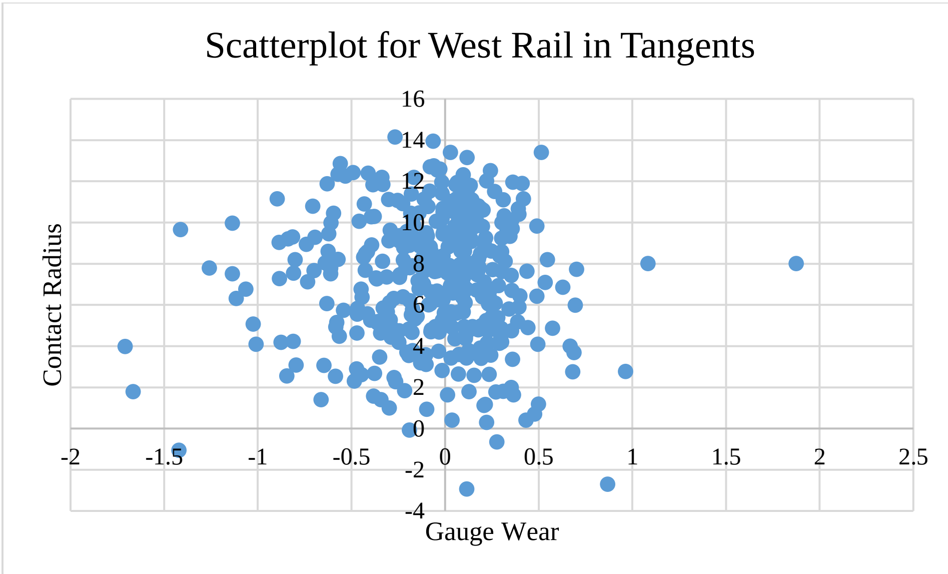

Scatterplot for West Rail in Tangents
Lateral Contact Position
Head Loss
350
300
250
200
150
100
50
0
0
5
10
15
20



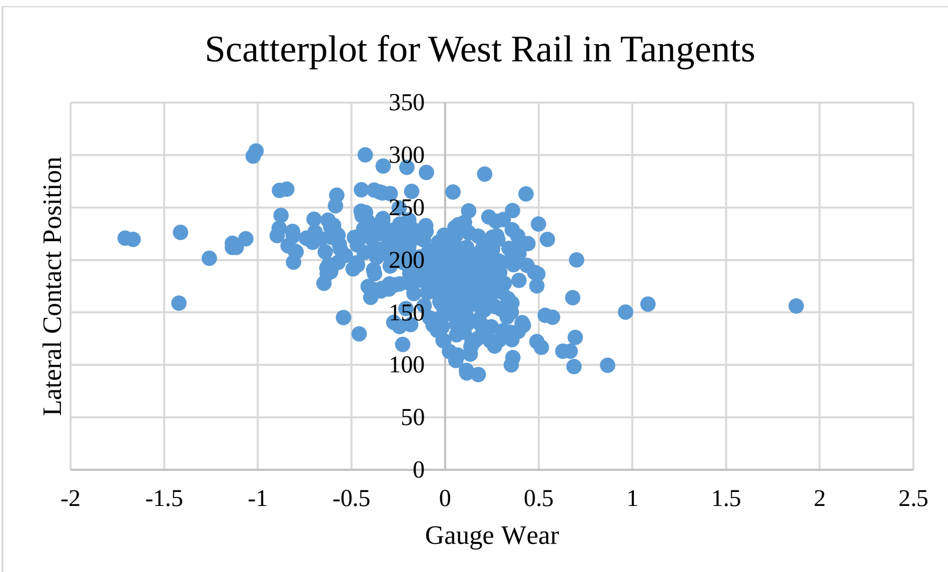
Scatterplot for West Rail in Tangents
Grind Quality Index
350
300
250
200
150
100
50
0
0
5
10
15
20
Head Loss



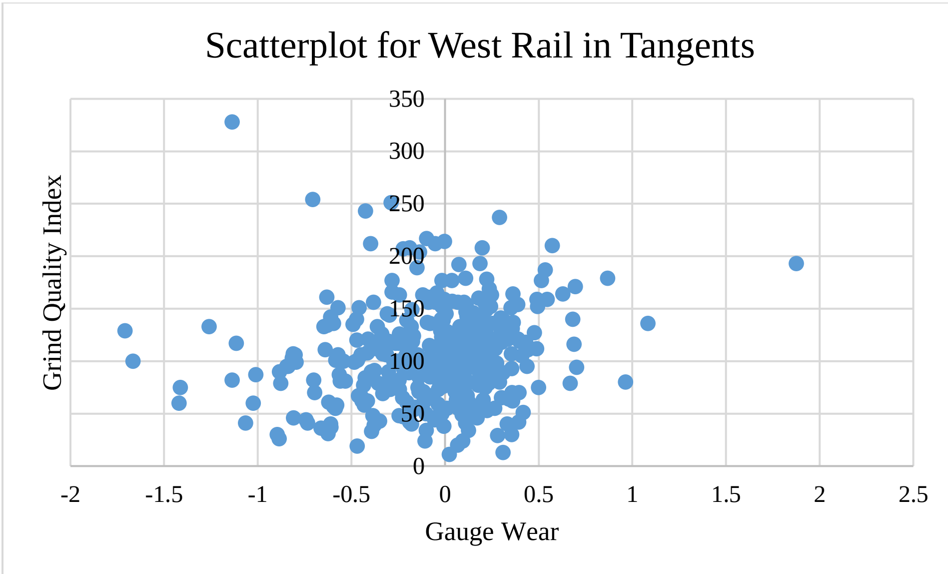
Scatterplot for West Rail in Tangents
Vertical Wear
8
7
6
5
4
3
2
1
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Gauge Wear

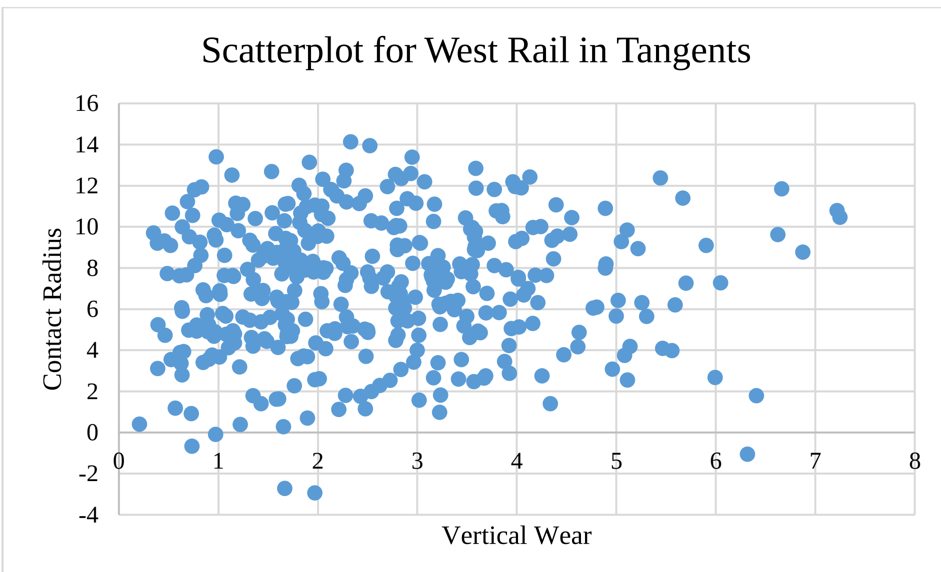


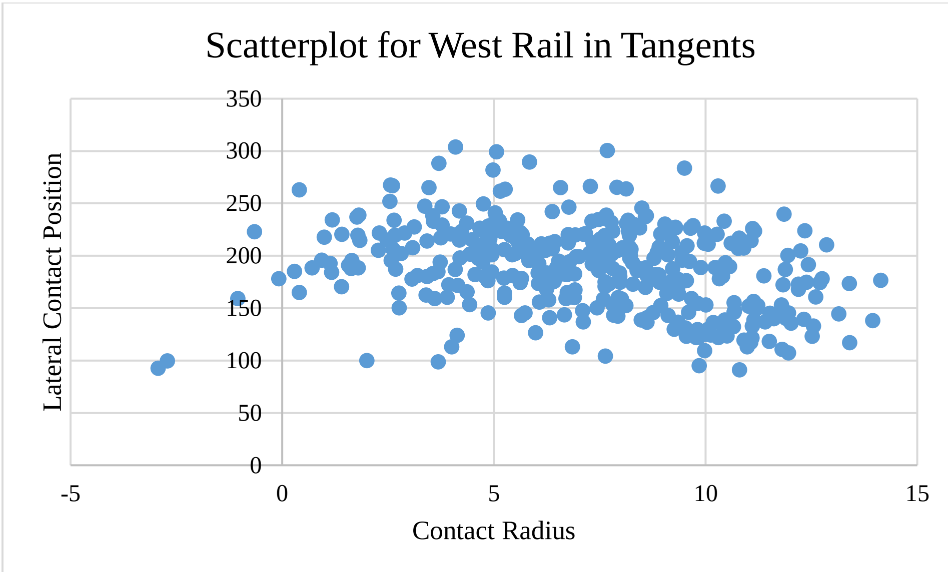
Scatterplot for West Rail in Tangents
Contact Radius
Gauge Wear
16
14
12
10
8
6
4
2
0
-2
-4
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

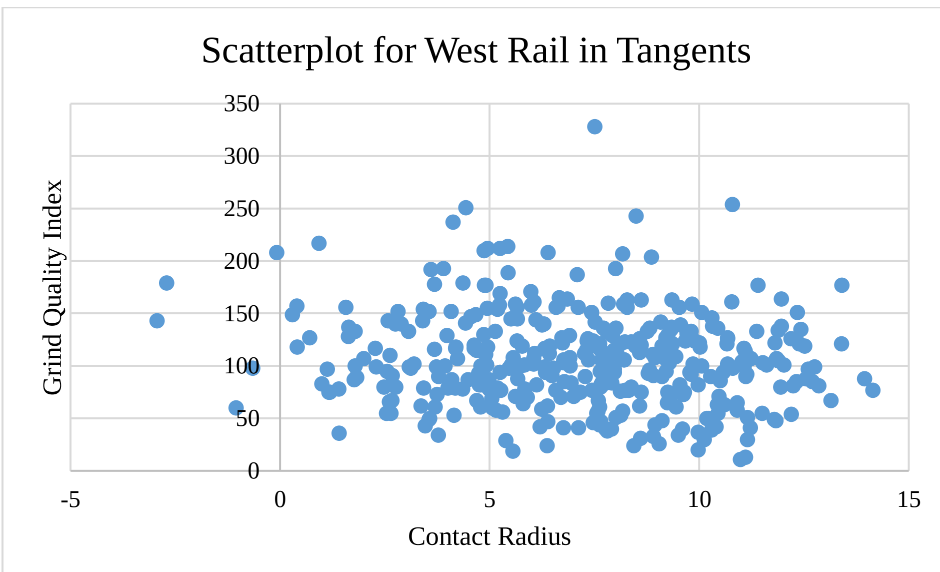


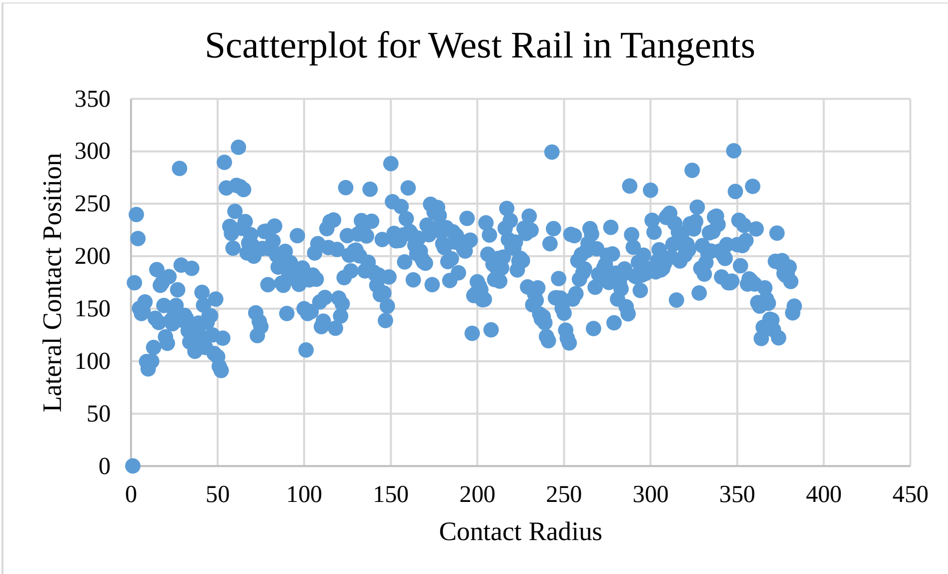
Scatterplot for West Rail in Tangents
Lateral Contact Position
Gauge Wear
350
300
250
200
150
100
50
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

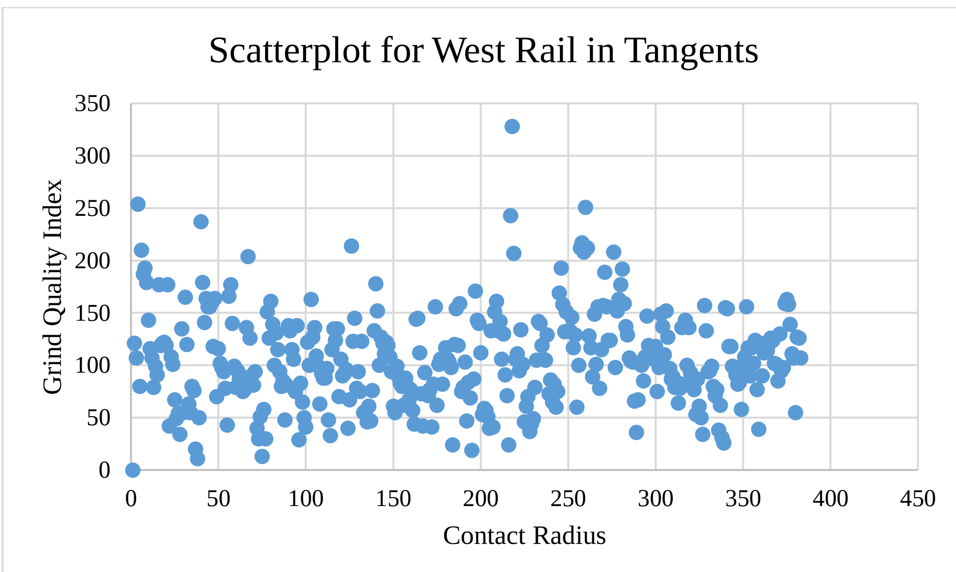

Scatterplot for West Rail in Tangents
Grind Quality Index
Gauge Wear
350
300
250
200
150
100
50
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

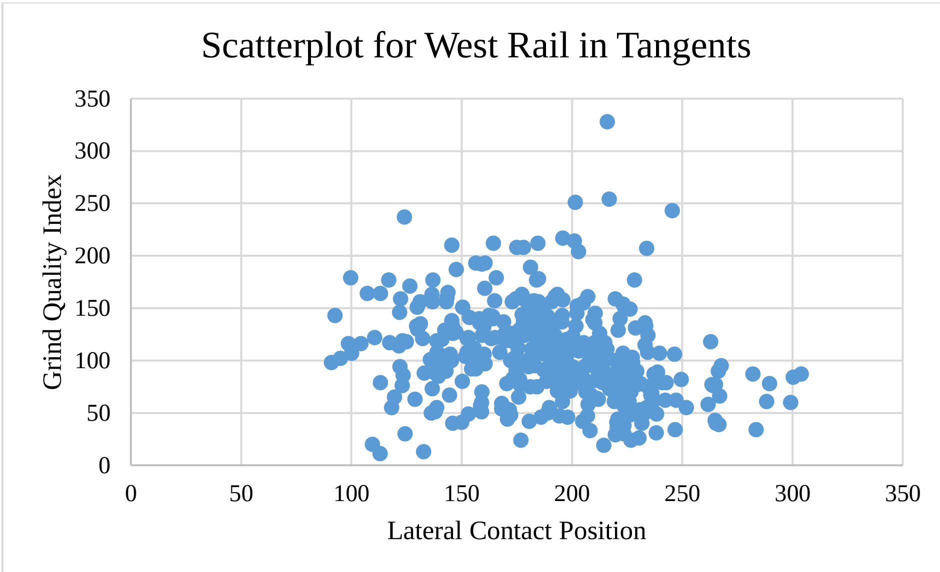

Scatterplot for West Rail in Tangents
Contact Radius
Vertical Wear
16
14
12
10
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
8

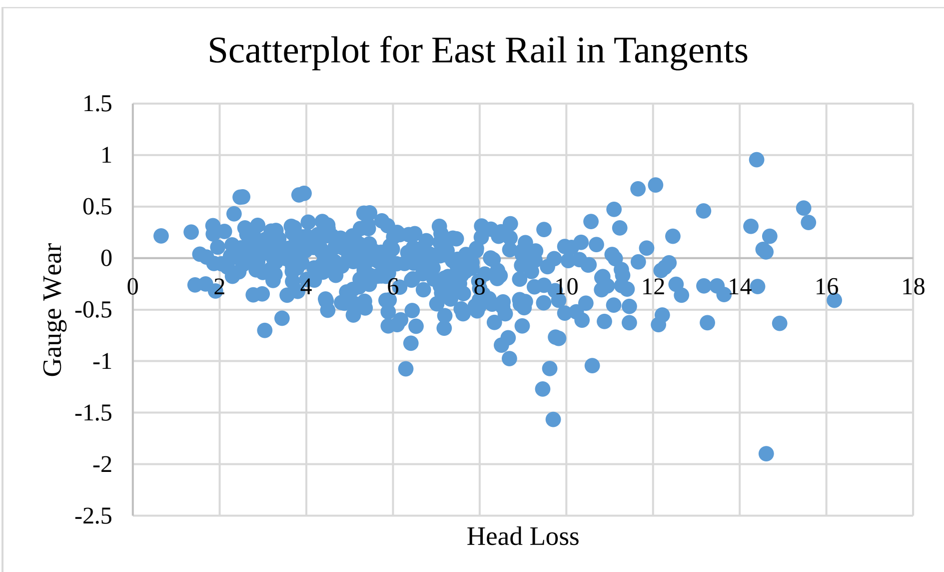

Scatterplot for West Rail in Tangents
Lateral Contact Position
350
300
250
200
150
100
50
0
-5
0
5
10
15
Contact Radius

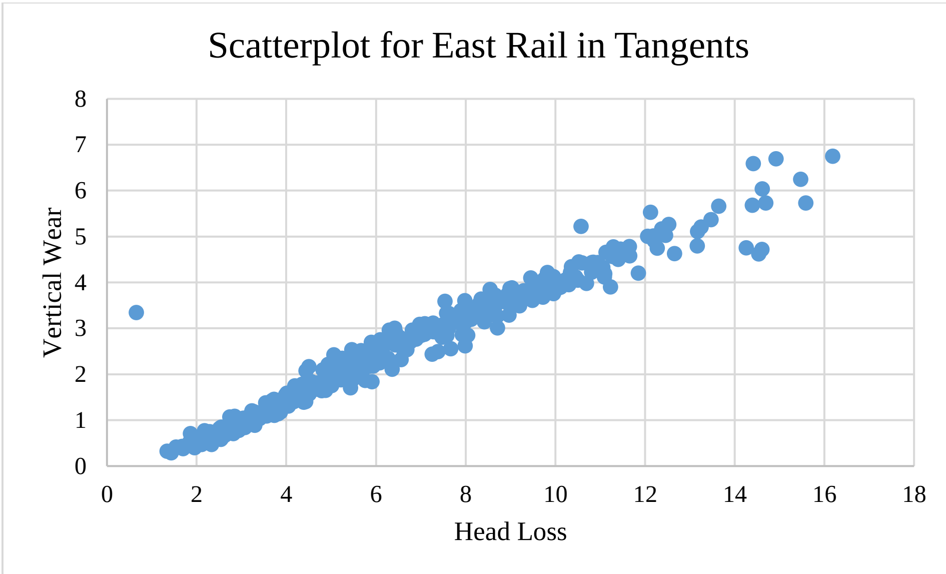

Scatterplot for West Rail in Tangents
Grind Quality Index
350
300
250
200
150
100
50
0
-5
0
5
10
15
Contact Radius

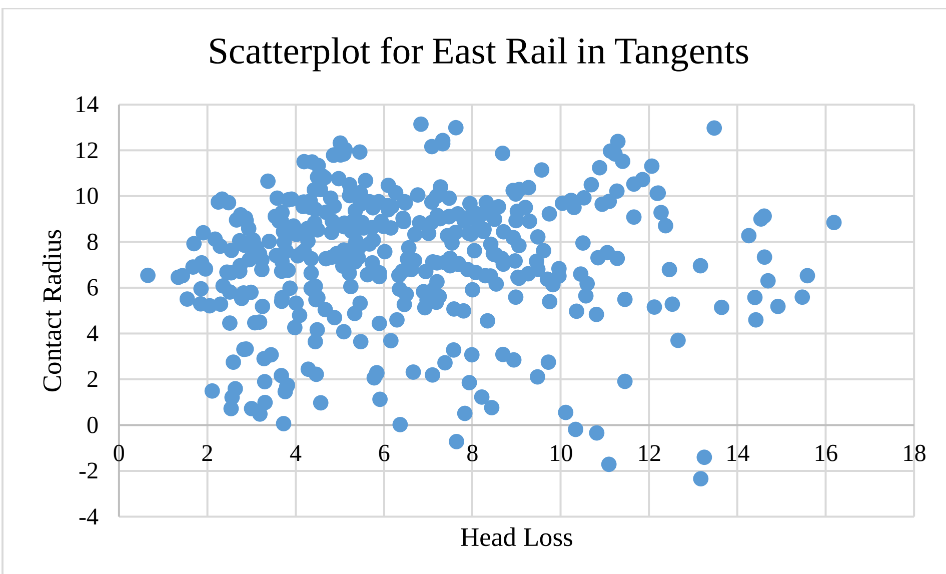

Scatterplot for West Rail in Tangents
Lateral Contact Position
Contact Radius
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450

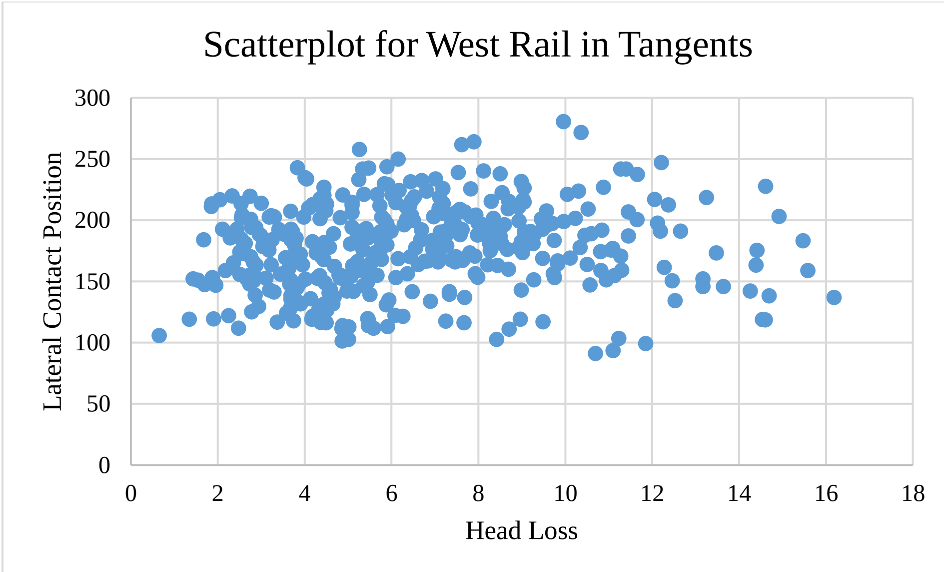

Scatterplot for West Rail in Tangents
Grind Quality Index
Contact Radius
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450


Scatterplot for West Rail in Tangents
Grind Quality Index
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
Lateral Contact Position

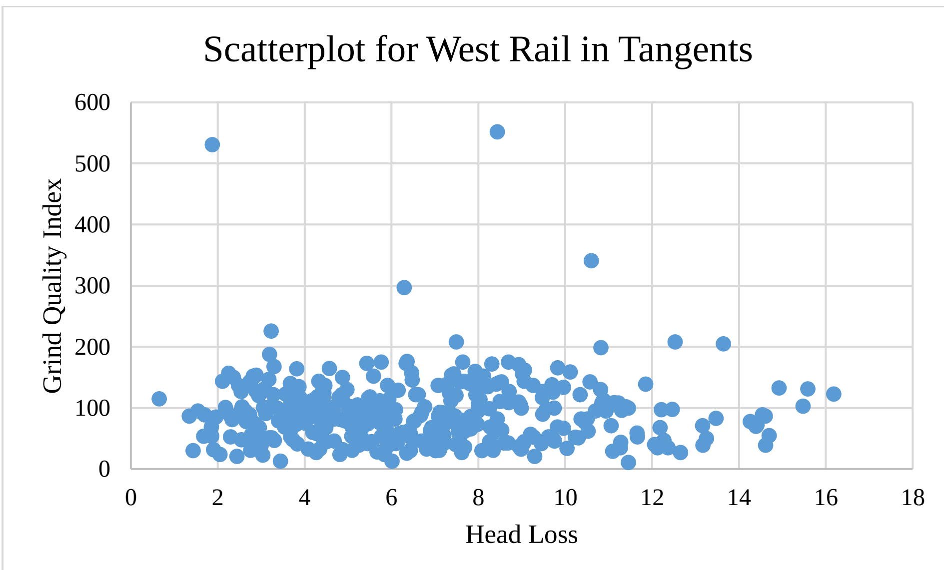

Scatterplot for East Rail in Tangents
Gauge Wear
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
2
4
6
8
10
12
14
16
18
Head Loss


Scatterplot for East Rail in Tangents
Vertical Wear
Head Loss
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18

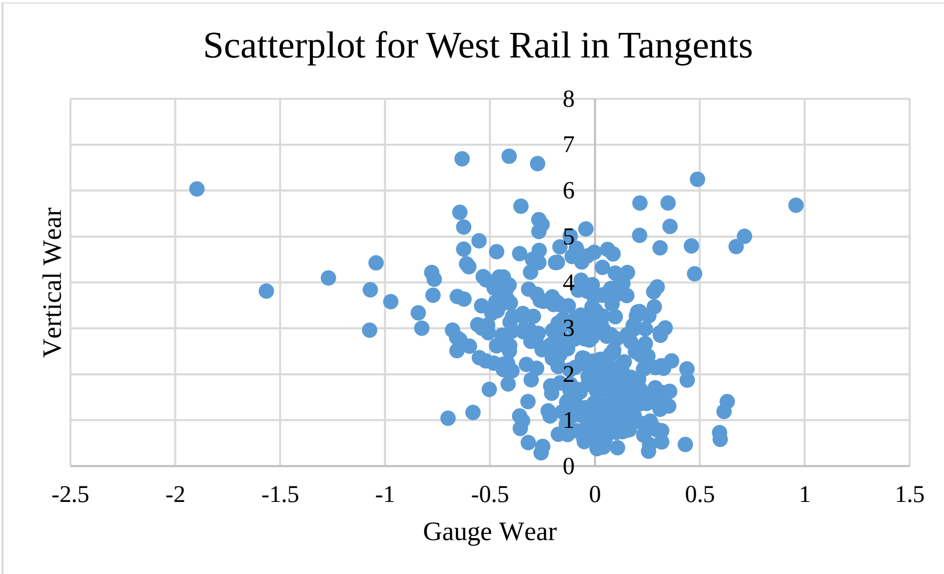

Scatterplot for East Rail in Tangents
Contact Radius
Head Loss
-4
-2
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
14
16
18



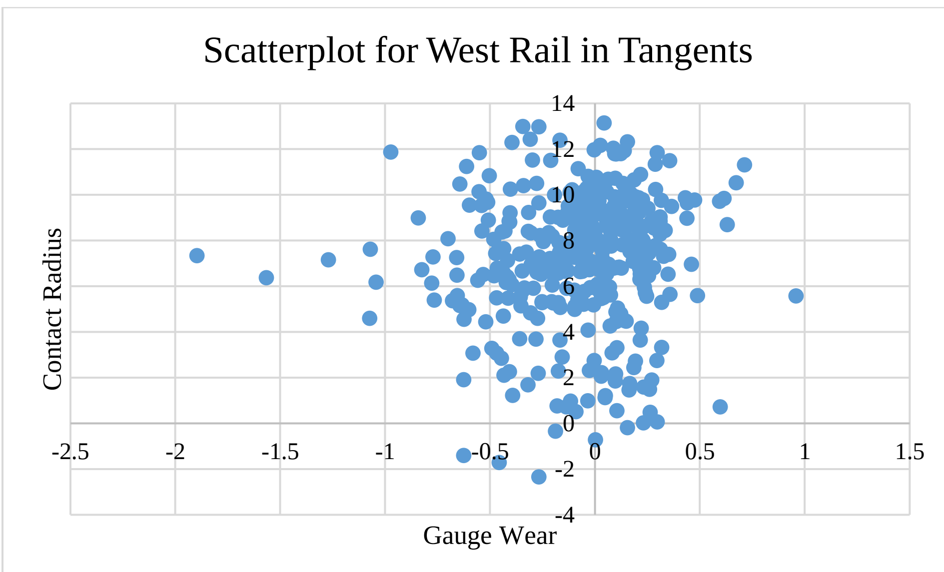
Scatterplot for West Rail in Tangents
Lateral Contact Position
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
Head Loss



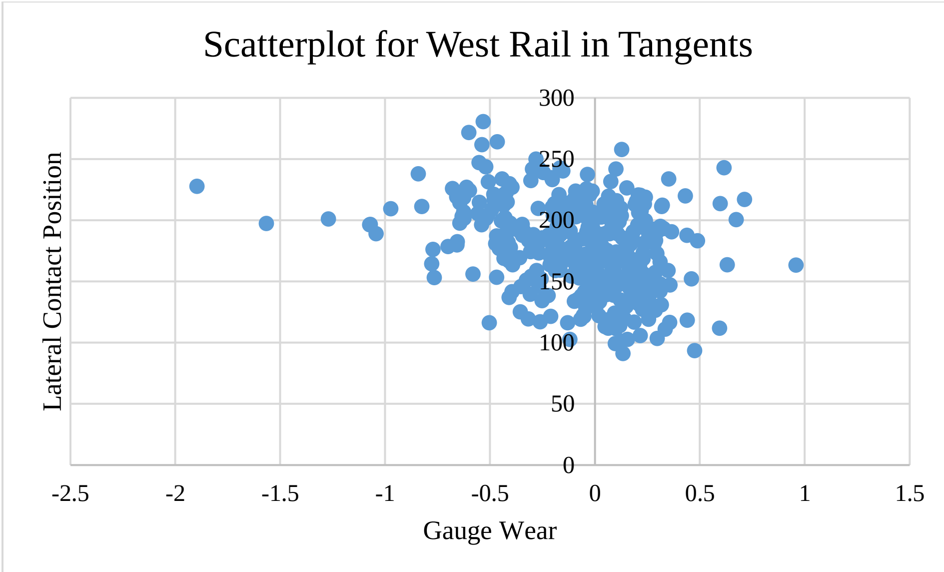
Scatterplot for West Rail in Tangents
Grind Quality Index
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
Head Loss



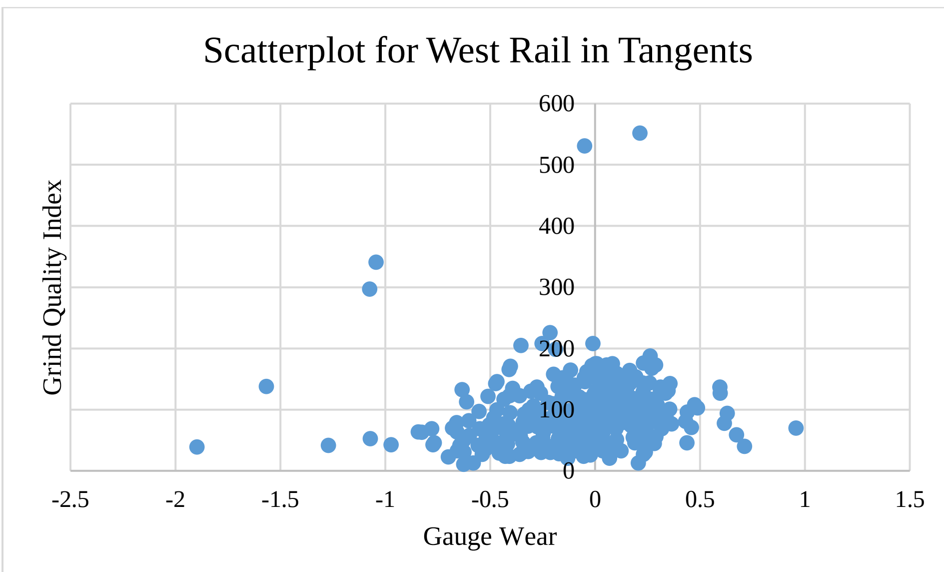
Scatterplot for West Rail in Tangents
Vertical Wear
Gauge Wear
8
7
6
5
4
3
2
1
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5



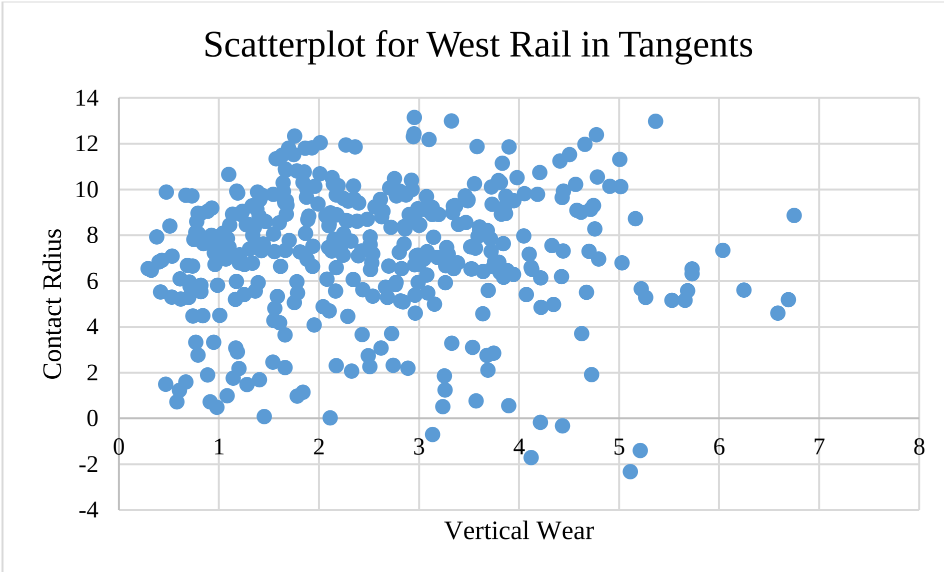
Scatterplot for West Rail in Tangents
Contact Radius
Gauge Wear
14
12
10
8
6
4
2
0
-2
-4
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5

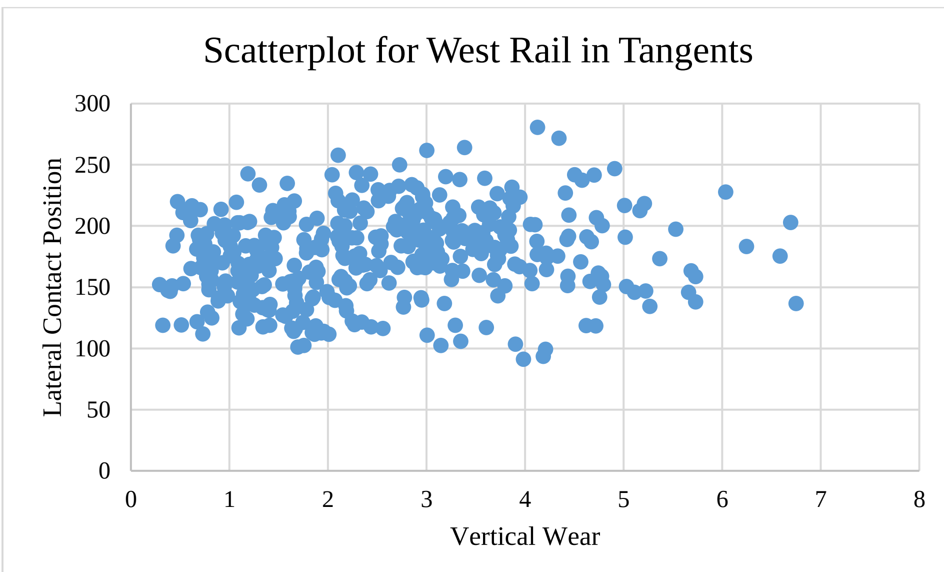


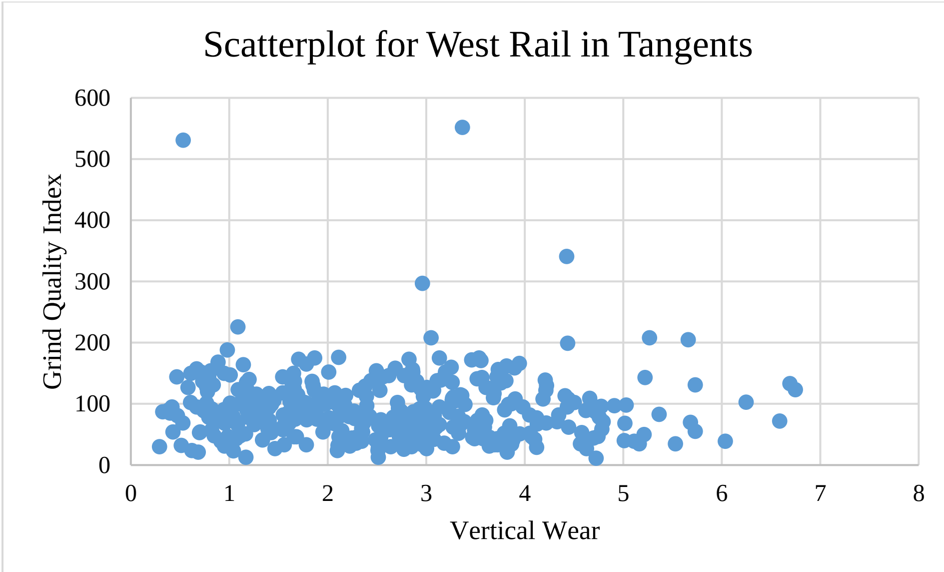
Scatterplot for West Rail in Tangents
Lateral Contact Position
300
250
200
150
100
50
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
Gauge Wear

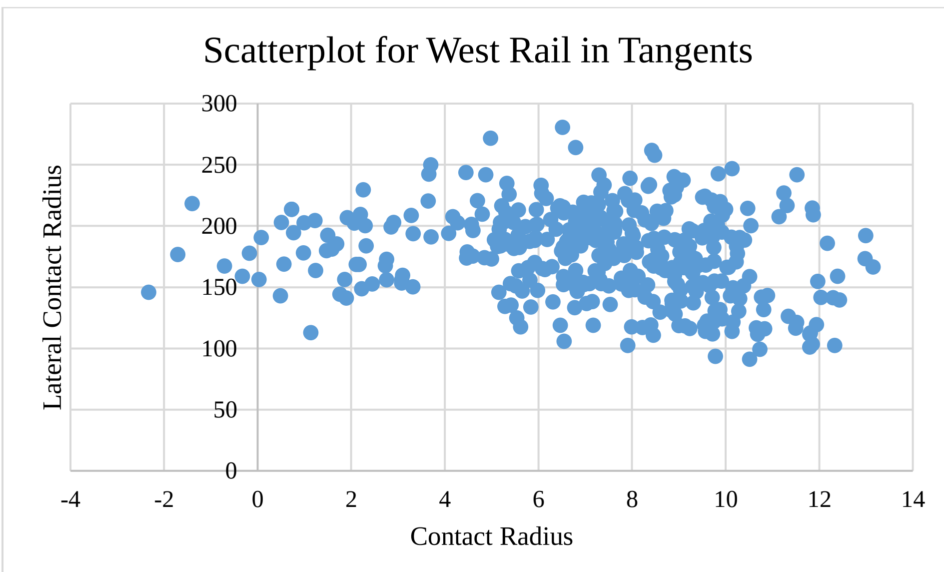


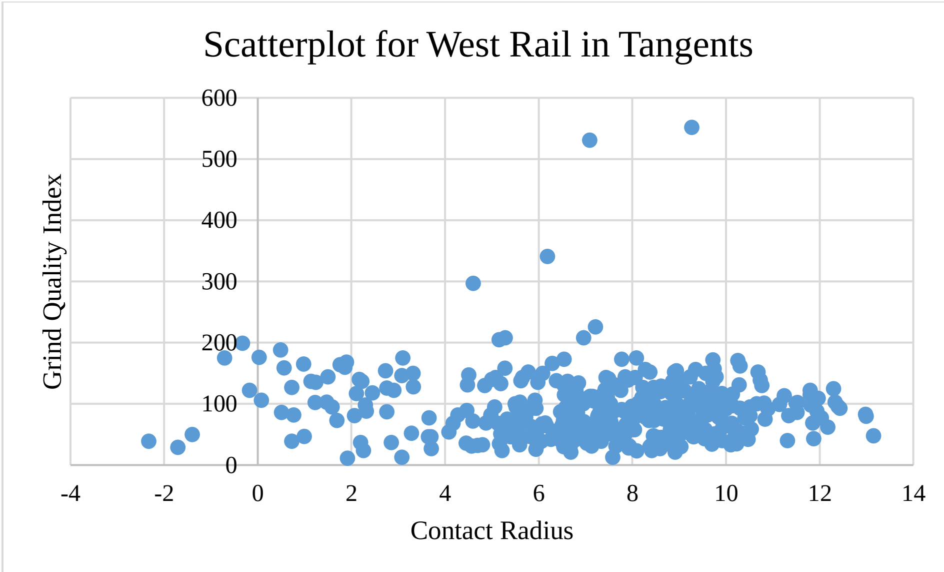
Scatterplot for West Rail in Tangents
Grind Quality Index
600
500
400
300
200
100
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
Gauge Wear

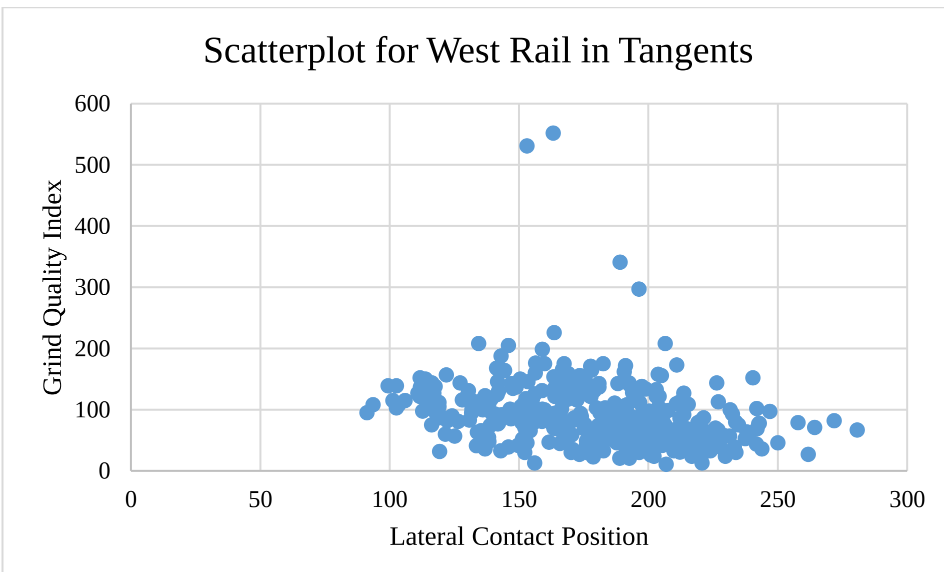

Scatterplot for West Rail in Tangents
Contact Rdius
14
12
10
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
8
Vertical Wear

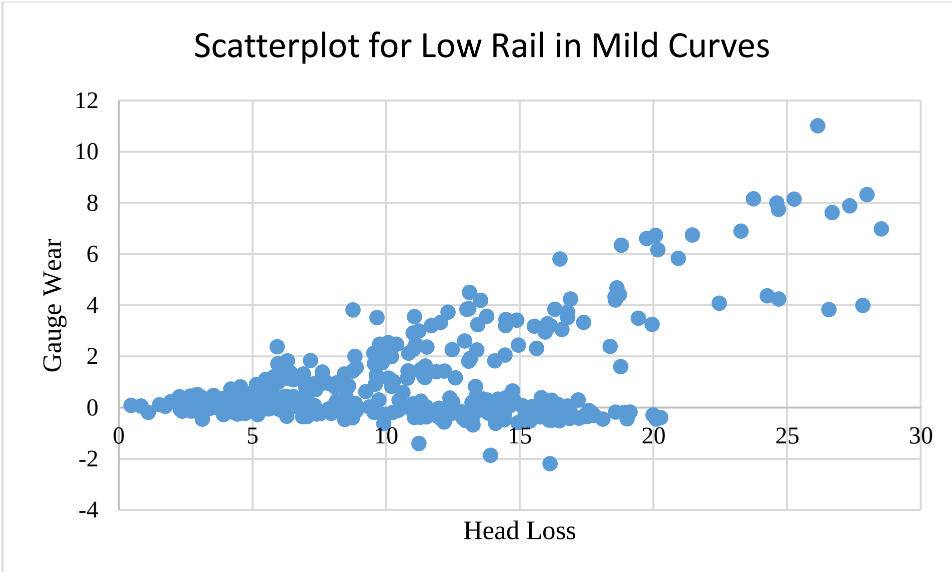

Scatterplot for West Rail in Tangents
Lateral Contact Position
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
Vertical Wear

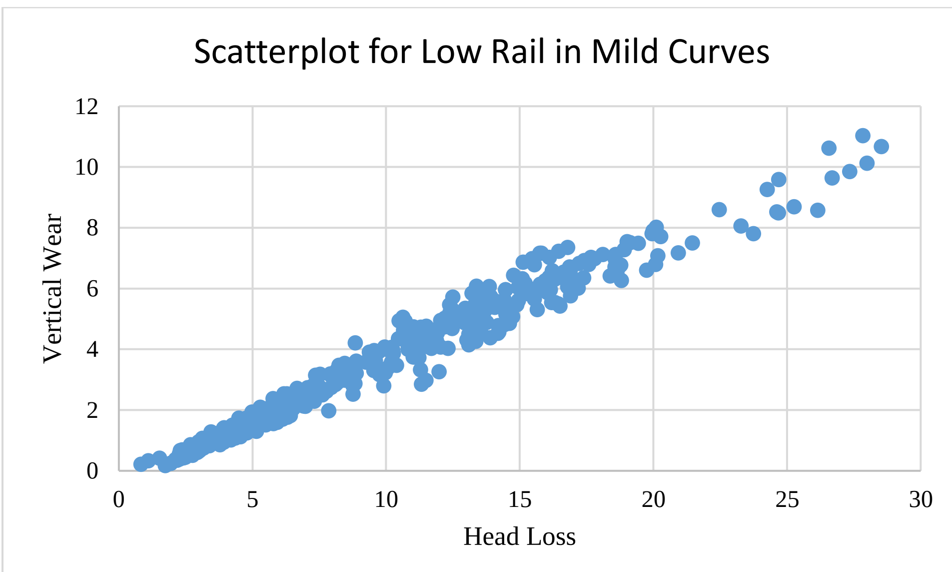

Scatterplot for West Rail in Tangents
Grind Quality Index
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
Vertical Wear

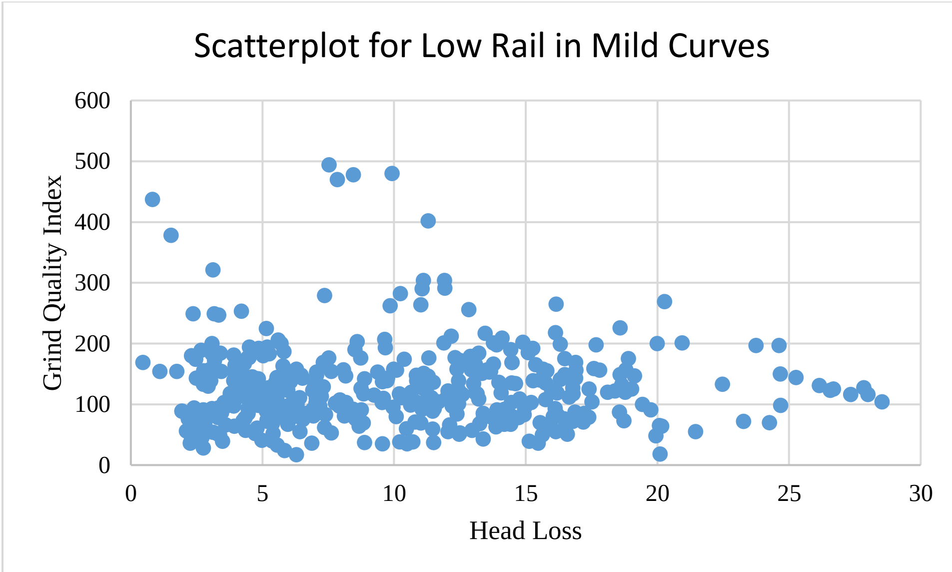

Scatterplot for West Rail in Tangents
Lateral Contact Radius
300
250
200
150
100
50
0
-4
-2
0
2
4
6
8
10
12
14
Contact Radius

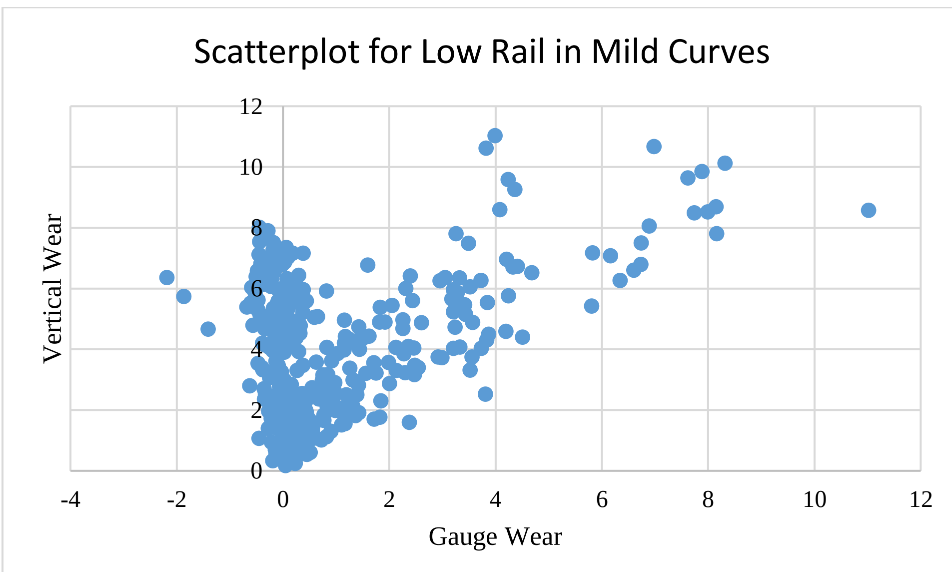

Scatterplot for West Rail in Tangents
Grind Quality Index
600
500
400
300
200
100
0
-4
-2
0
2
4
6
8
10
12
14
Contact Radius

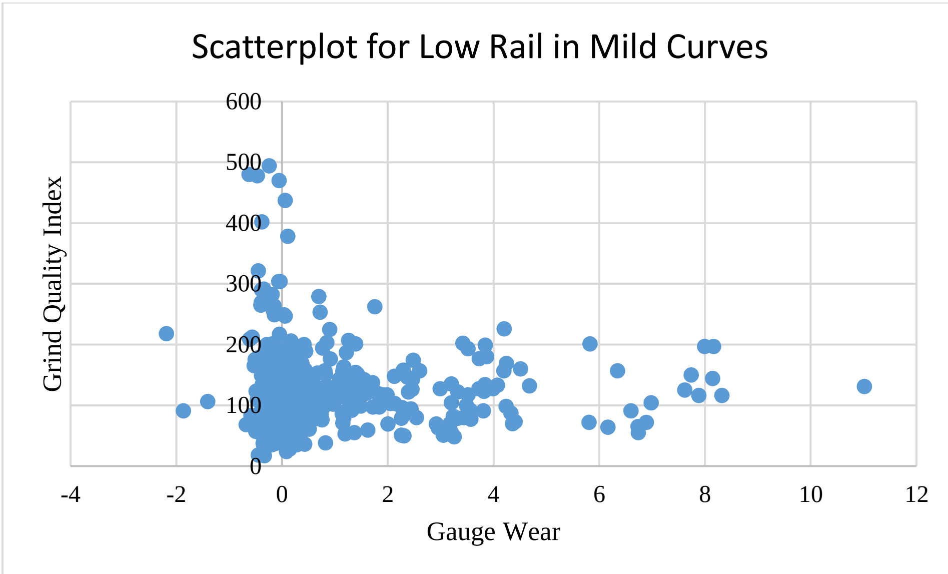

Scatterplot for West Rail in Tangents
Grind Quality Index
600
500
400
300
200
100
0
0
50
100
150
200
250
300
Lateral Contact Position

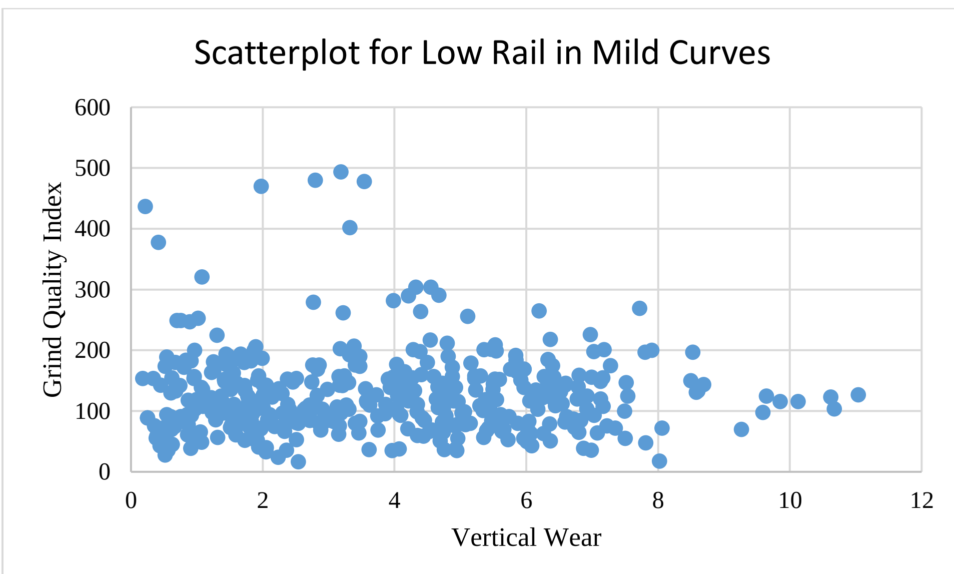

Scatterplot for Low Rail in Mild Curves
Gauge Wear
12
10
8
6
4
2
0
-2
-4
0
5
10
15
20
25
30
Head Loss

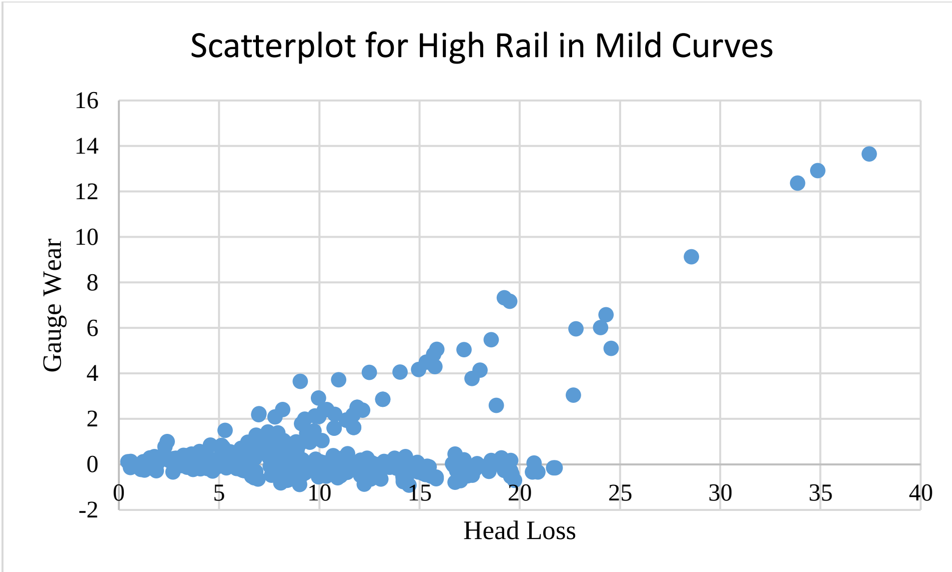

Scatterplot for Low Rail in Mild Curves
Vertical Wear
12
10
8
6
4
2
0
0
5
10
15
20
25
30
Head Loss


Scatterplot for Low Rail in Mild Curves
Grind Quality Index
600
500
400
300
200
100
0
0
5
10
15
20
25
30
Head Loss

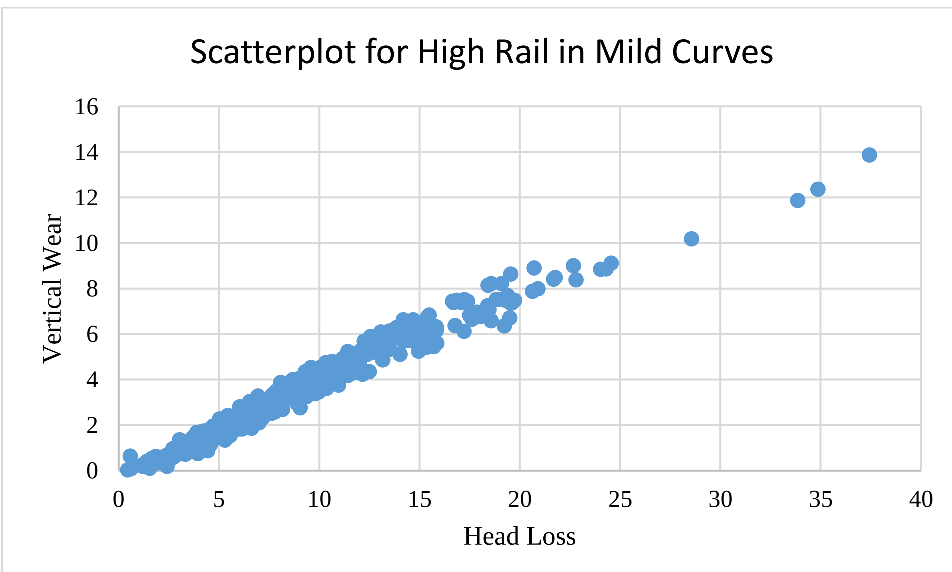

Scatterplot for Low Rail in Mild Curves
Vertical Wear
12
10
8
6
4
2
0
-4
-2
0
2
4
6
8
10
12
Gauge Wear


Scatterplot for Low Rail in Mild Curves
Grind Quality Index
600
500
400
300
200
100
0
-4
-2
0
2
4
6
8
10
12
Gauge Wear

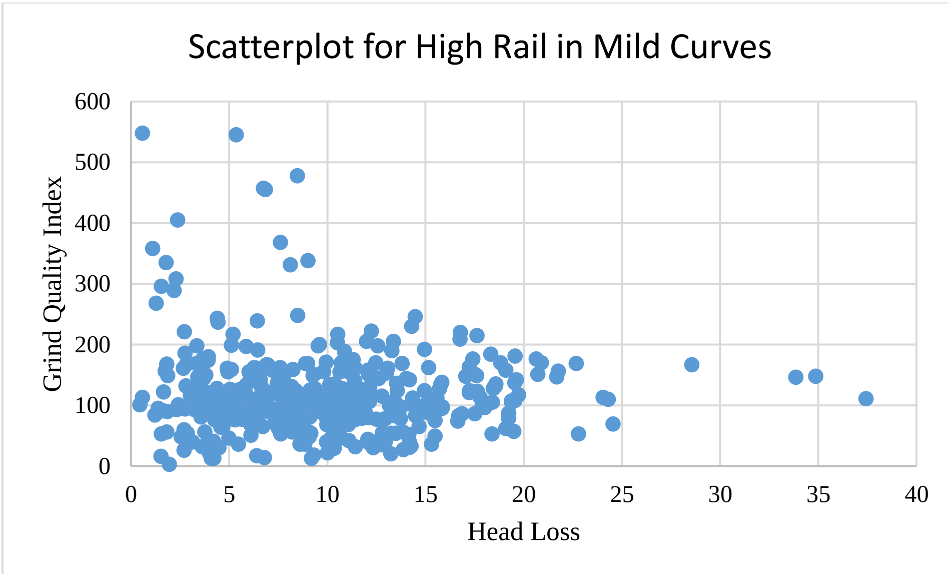

Scatterplot for Low Rail in Mild Curves
Grind Quality Index
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Vertical Wear

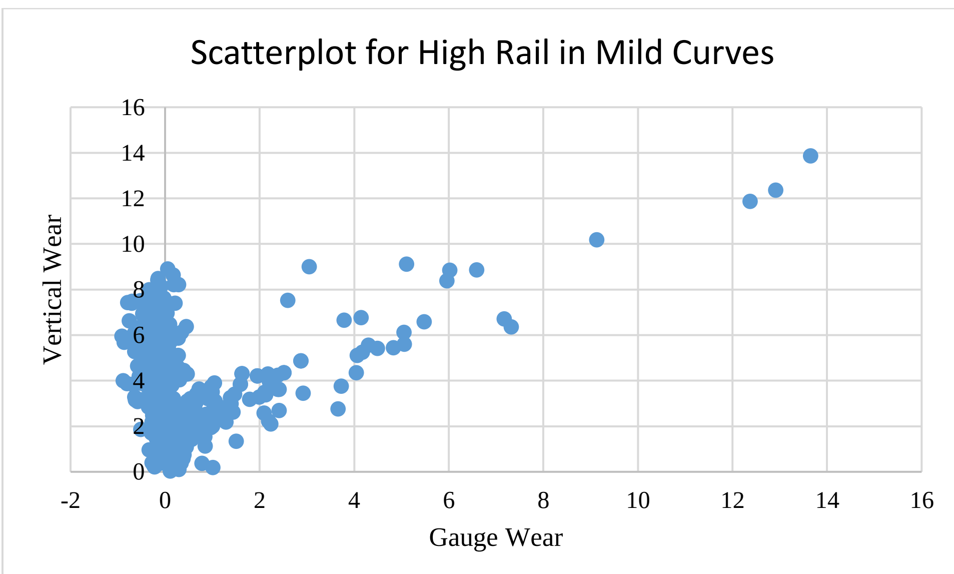


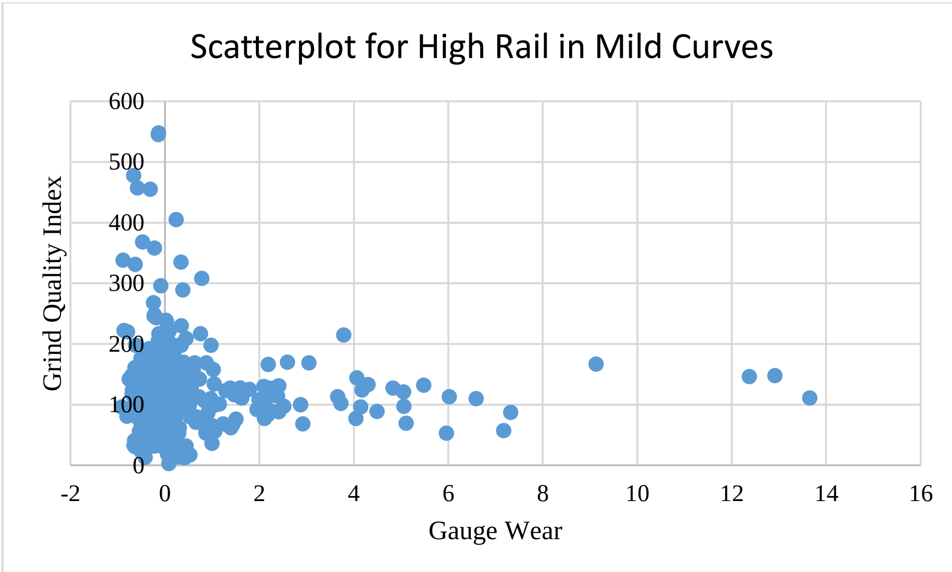
Scatterplot for High Rail in Mild Curves
Gauge Wear
Head Loss
16
14
12
10
8
6
4
2
0
-2
0
5
10
15
20
25
30
35
40

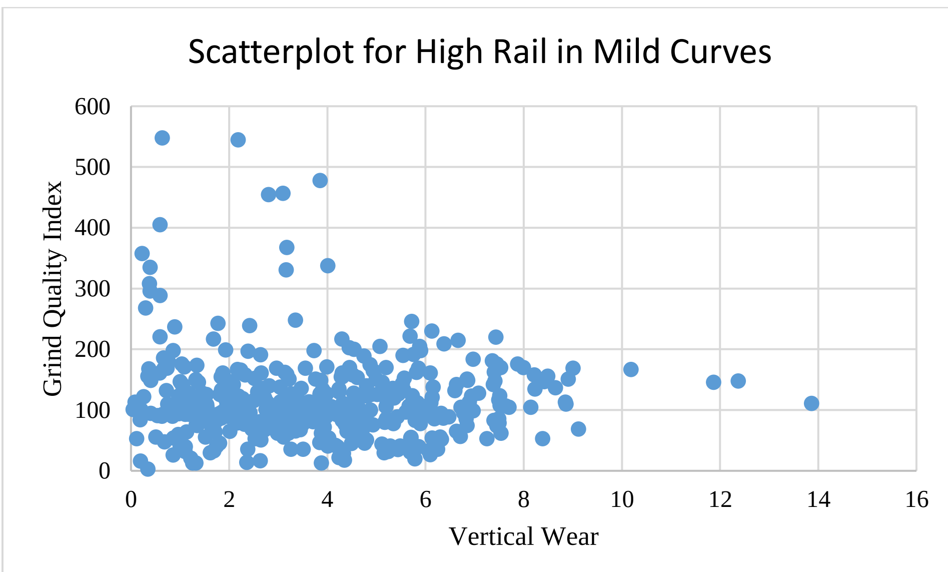


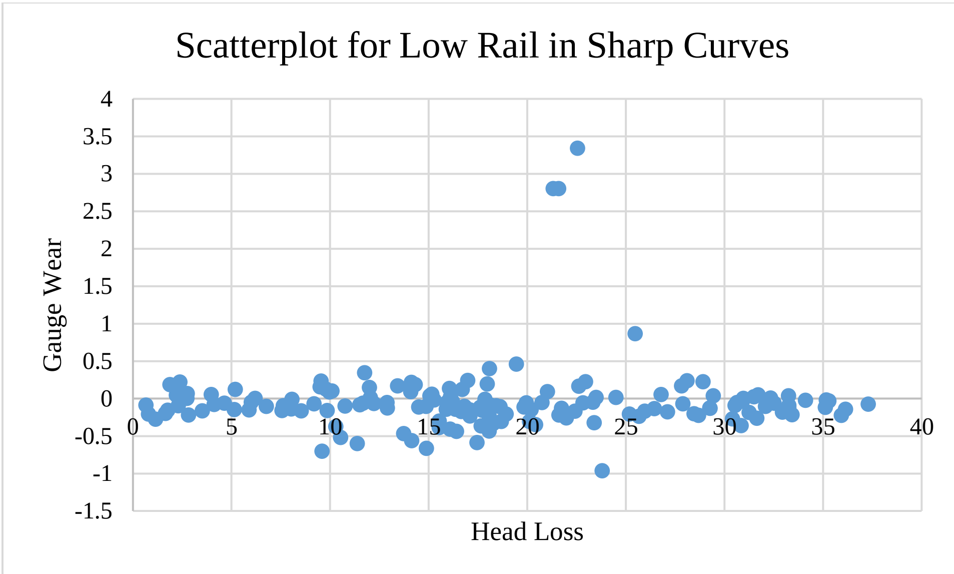
Scatterplot for High Rail in Mild Curves
Vertical Wear
Head Loss
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40

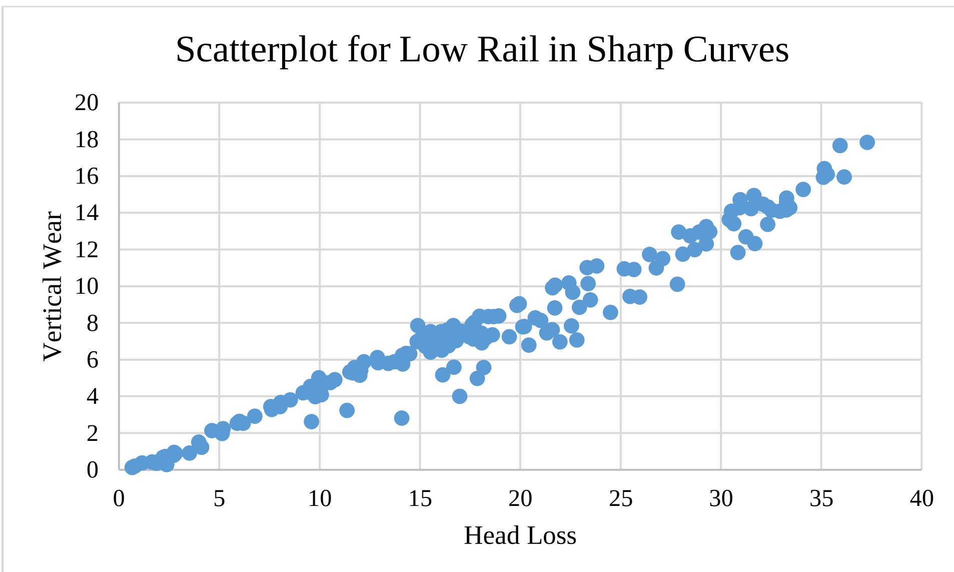

Scatterplot for High Rail in Mild Curves
Grind Quality Index
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
Head Loss

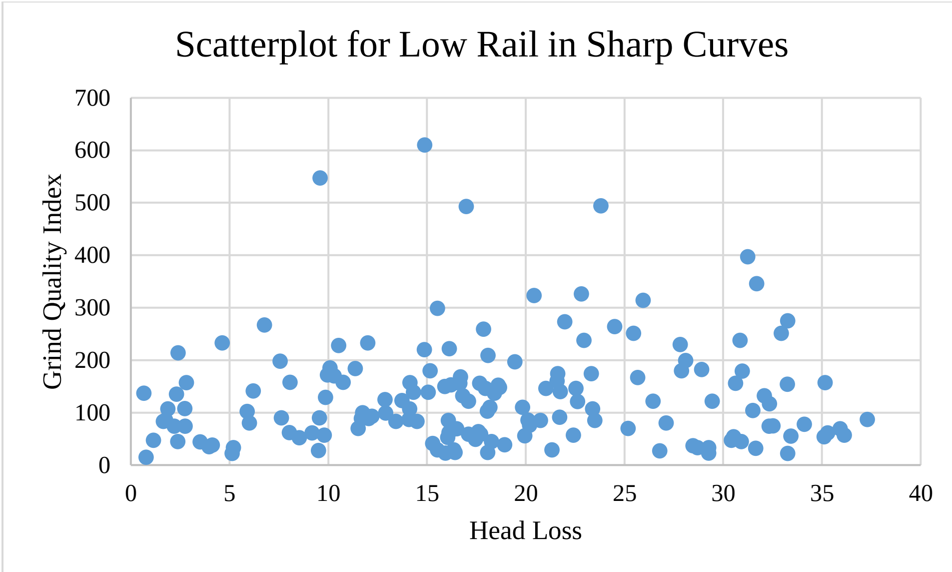

Scatterplot for High Rail in Mild Curves
Vertical Wear
16
14
12
10
8
6
4
2
0
-2
0
2
4
6
8
10
12
14
16
Gauge Wear


Scatterplot for High Rail in Mild Curves
Grind Quality Index
Gauge Wear
600
500
400
300
200
100
0
-2
0
2
4
6
8
10
12
14
16

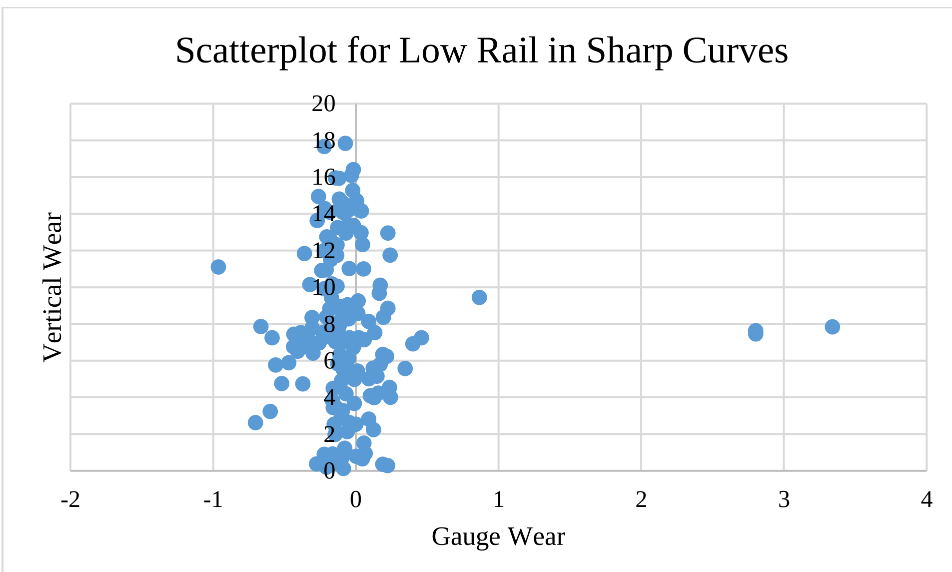

Scatterplot for High Rail in Mild Curves
Grind Quality Index
Vertical Wear
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16


Scatterplot for Low Rail in Sharp Curves
Gauge Wear
Head Loss
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
20
25
30
35
40

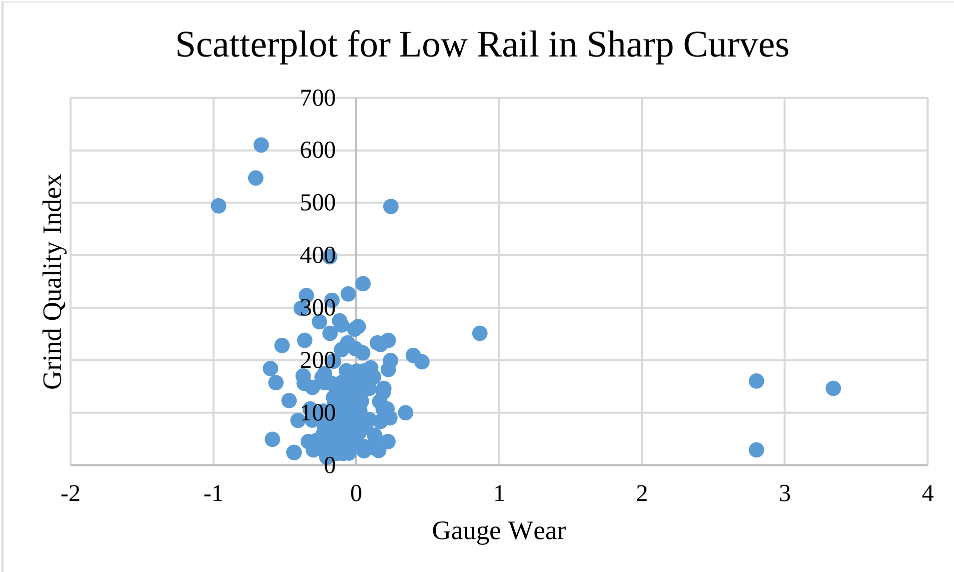

Scatterplot for Low Rail in Sharp Curves
Vertical Wear
Head Loss
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
30
35
40



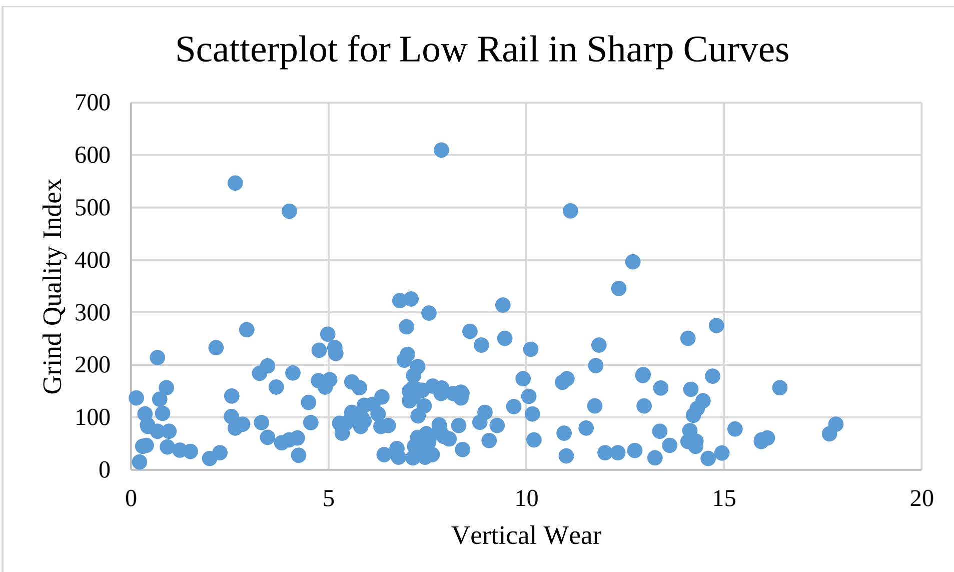
Scatterplot for Low Rail in Sharp Curves
Grind Quality Index
Head Loss
0
100
200
300
400
500
600
700
0
5
10
15
20
25
30
35
40



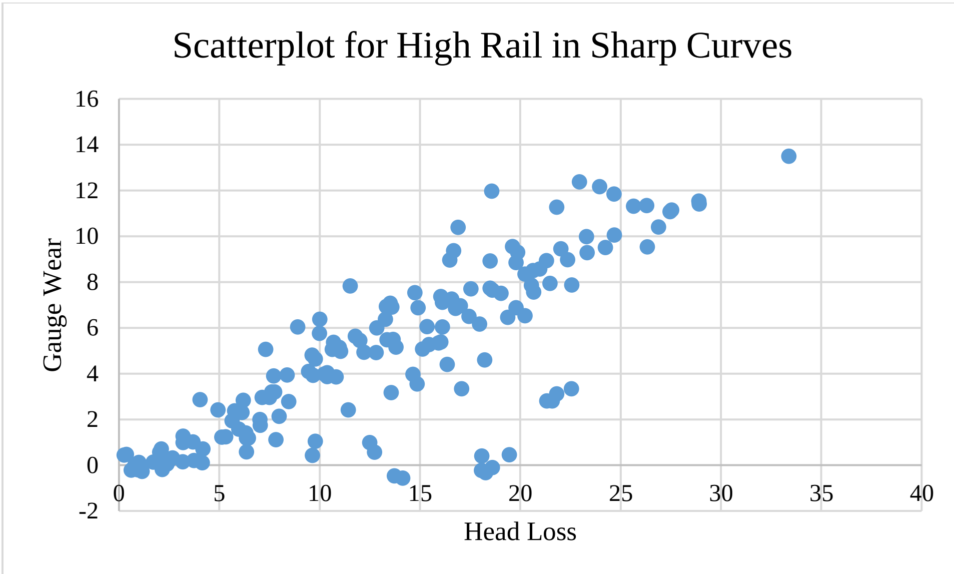
Scatterplot for Low Rail in Sharp Curves
Vertical Wear
Gauge Wear
0
2
4
6
8
10
12
14
16
18
20
-2
-1
0
1
2
3
4

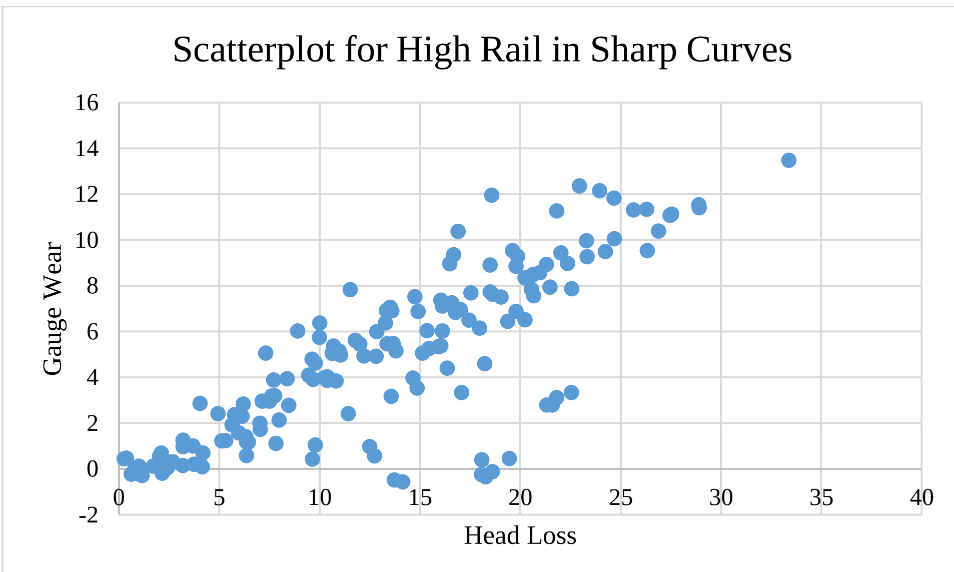


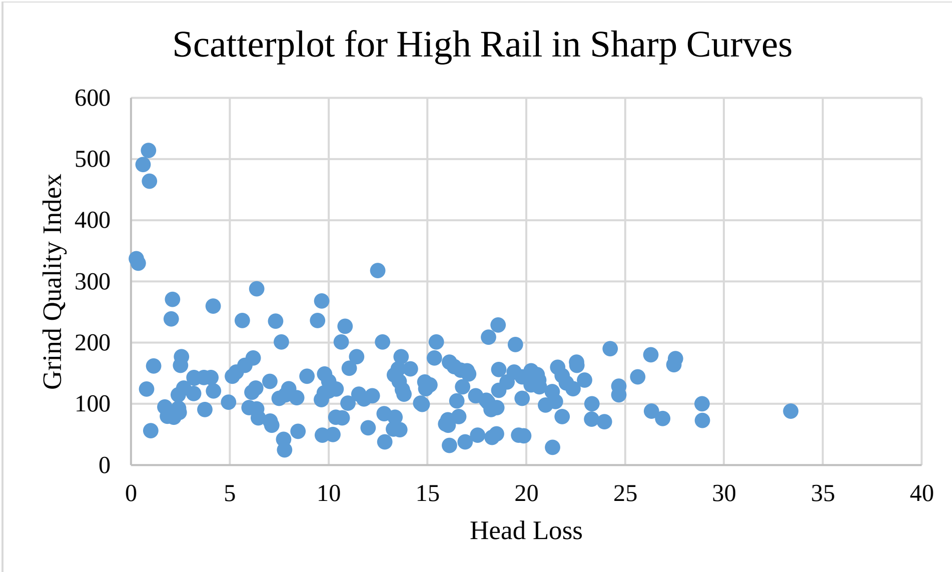
Scatterplot for Low Rail in Sharp Curves
Grind Quality Index
Gauge Wear
700
600
500
400
300
200
100
0
-2
-1
0
1
2
3
4

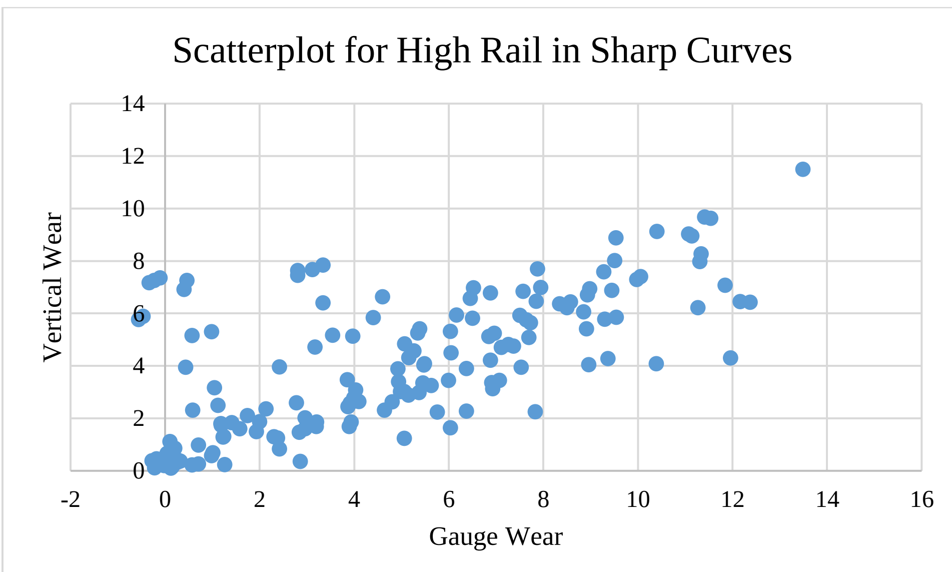


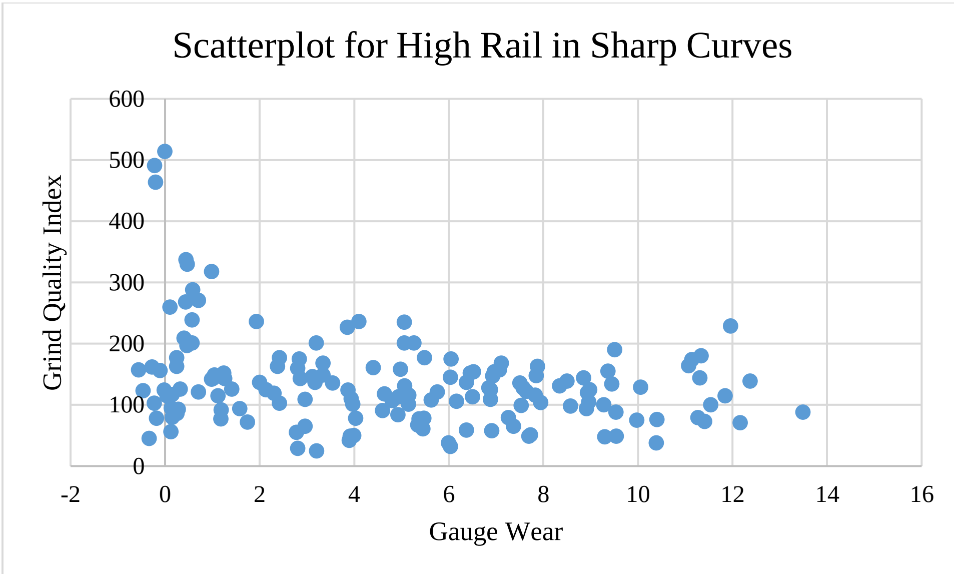
Scatterplot for Low Rail in Sharp Curves
Grind Quality Index
Vertical Wear
700
600
500
400
300
200
100
0
0
5
10
15
20

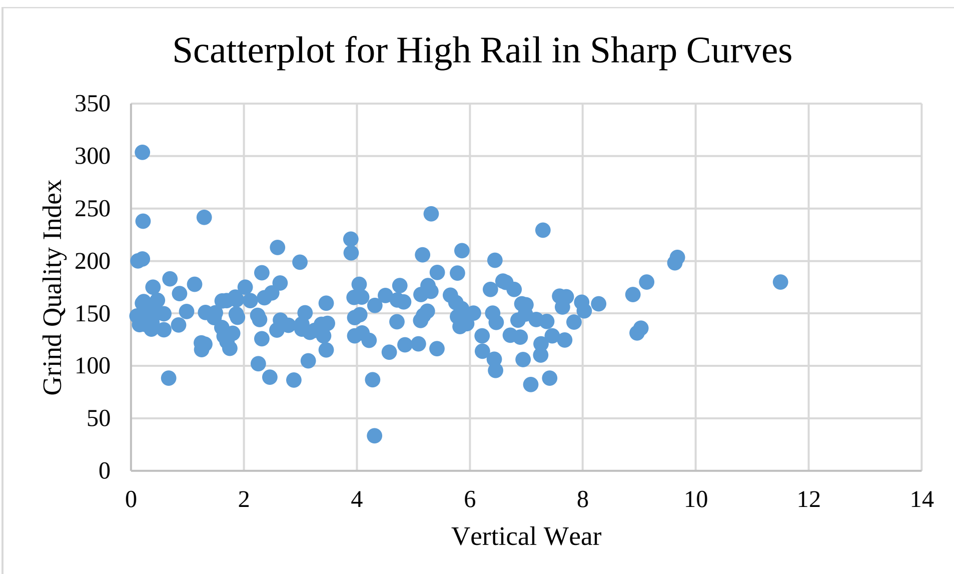

Scatterplot for High Rail in Sharp Curves
Gauge Wear
Head Loss
16
14
12
10
8
6
4
2
0
-2
0
5
10
15
20
25
30
35
40


Scatterplot for High Rail in Sharp Curves
Gauge Wear
Head Loss
16
14
12
10
8
6
4
2
0
-2
0
5
10
15
20
25
30
35
40


Scatterplot for High Rail in Sharp Curves
600
500
400
300
200
100
0
Grind Quality Index
0
5
10
15
20
25
30
35
40
Head Loss

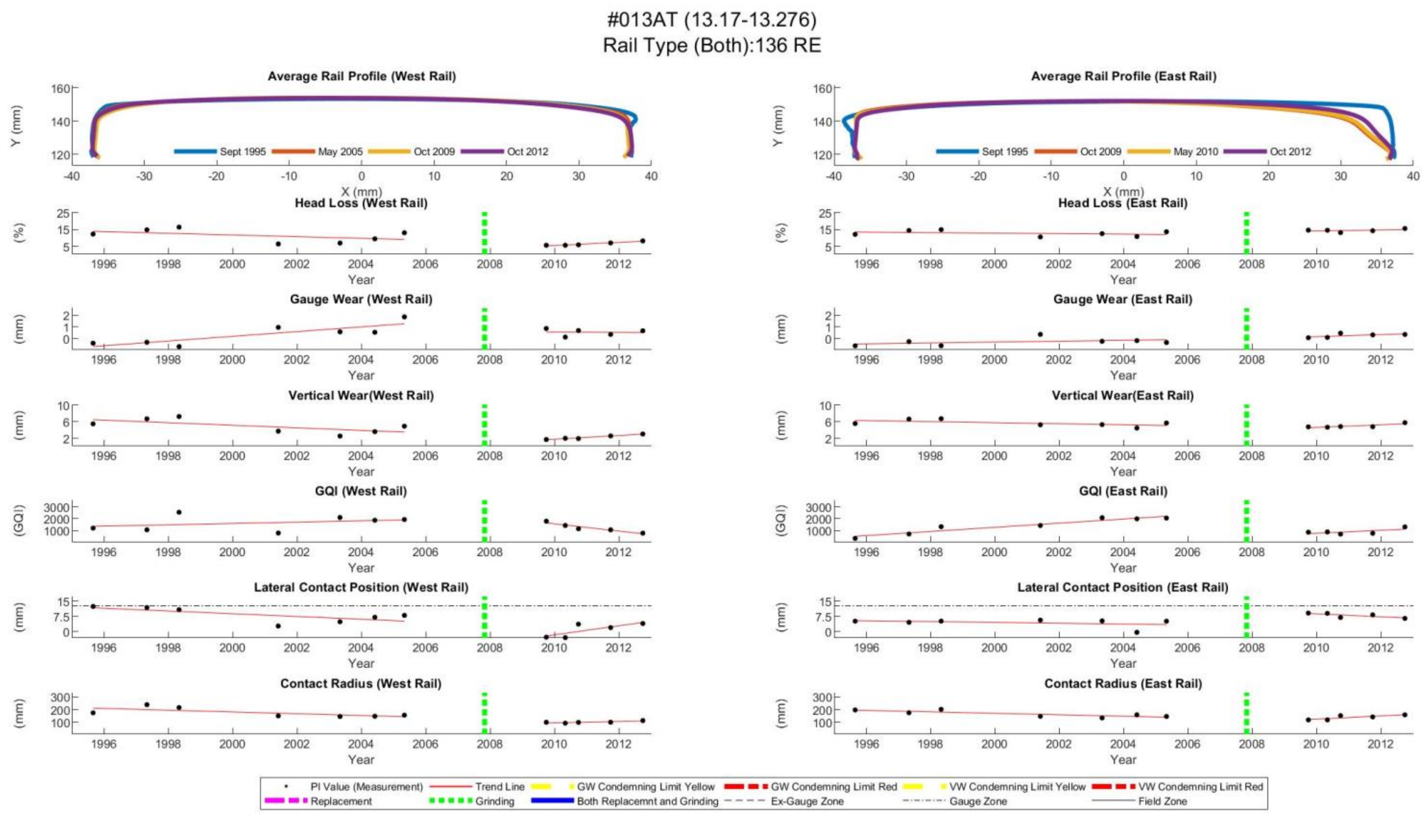

Scatterplot for High Rail in Sharp Curves
14
12
10
8
6
4
2
0
Vertical Wear
-2
0
2
4
6
8
10
12
14
16
Gauge Wear


Scatterplot for High Rail in Sharp Curves
Grind Quality Index
Gauge Wear
0
100
200
300
400
500
600
-2
0
2
4
6
8
10
12
14
16

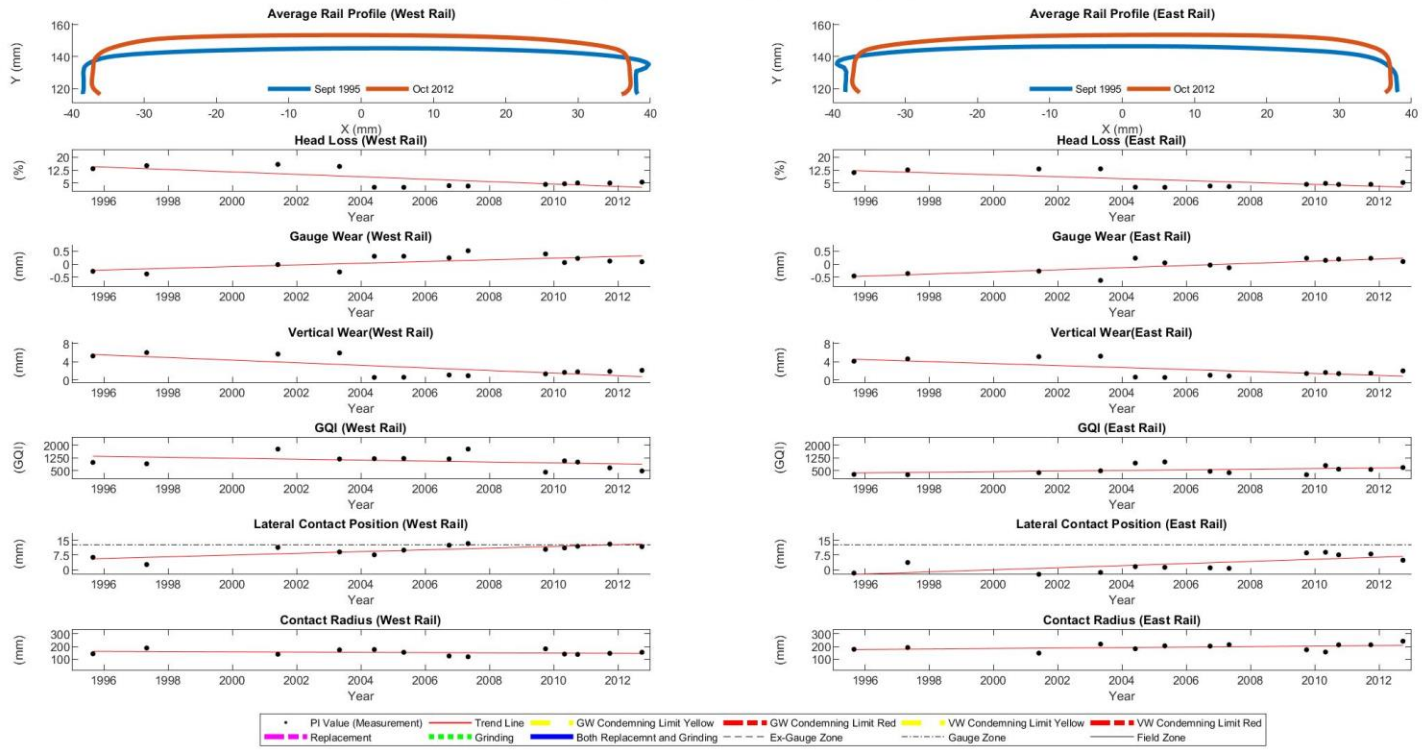

Scatterplot for High Rail in Sharp Curves
Grind Quality Index
Vertical Wear
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
14

APPENDIX D:

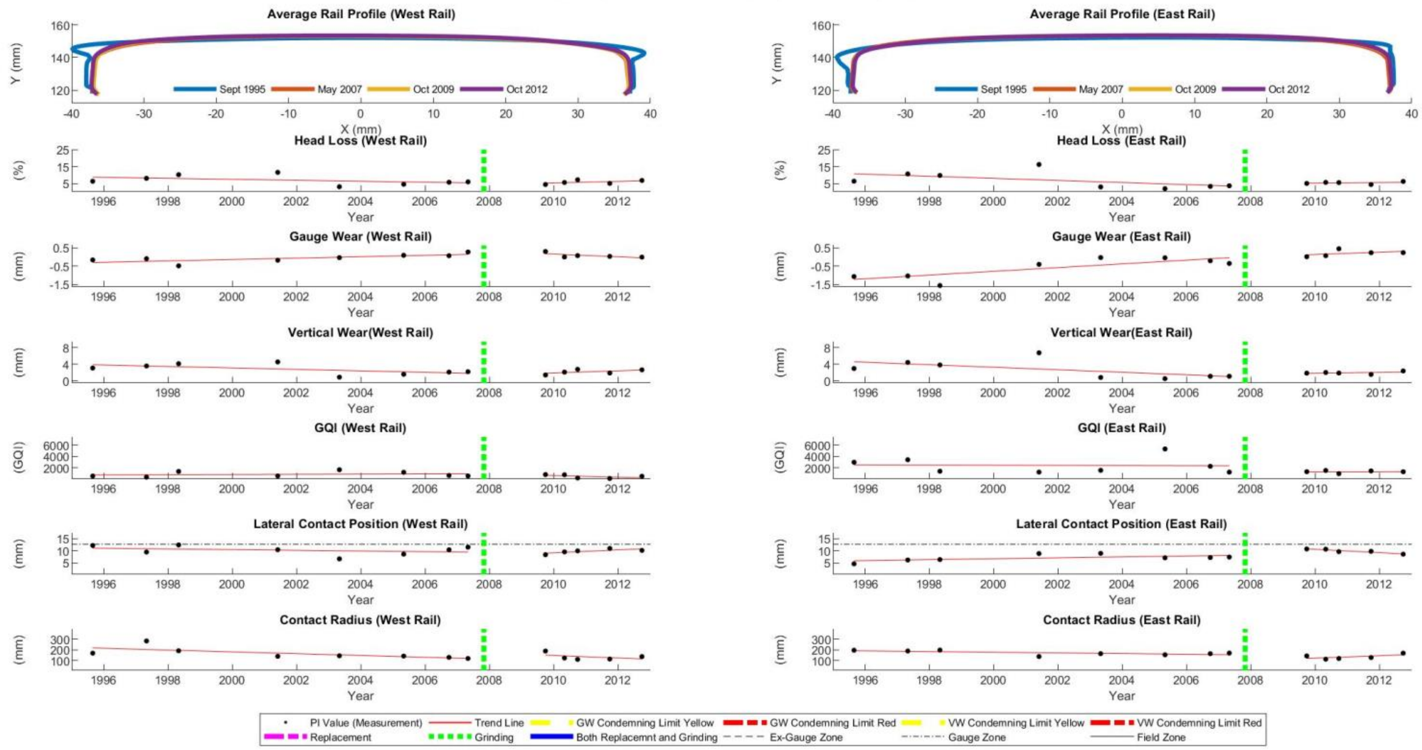
TEMPORAL TRENDING REPORTS


#013AT (13.17-13.276)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
May 2005
Oct 2009
Oct 2012
May 2010
X (mm)
Y (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Lateral Contact Position (West Rail)
Lateral Contact Position (East Rail)
Contact Radius (West Rail)
Contact Radius (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding
Ex-Gauge Zone
Gauge Zone
Field Zone

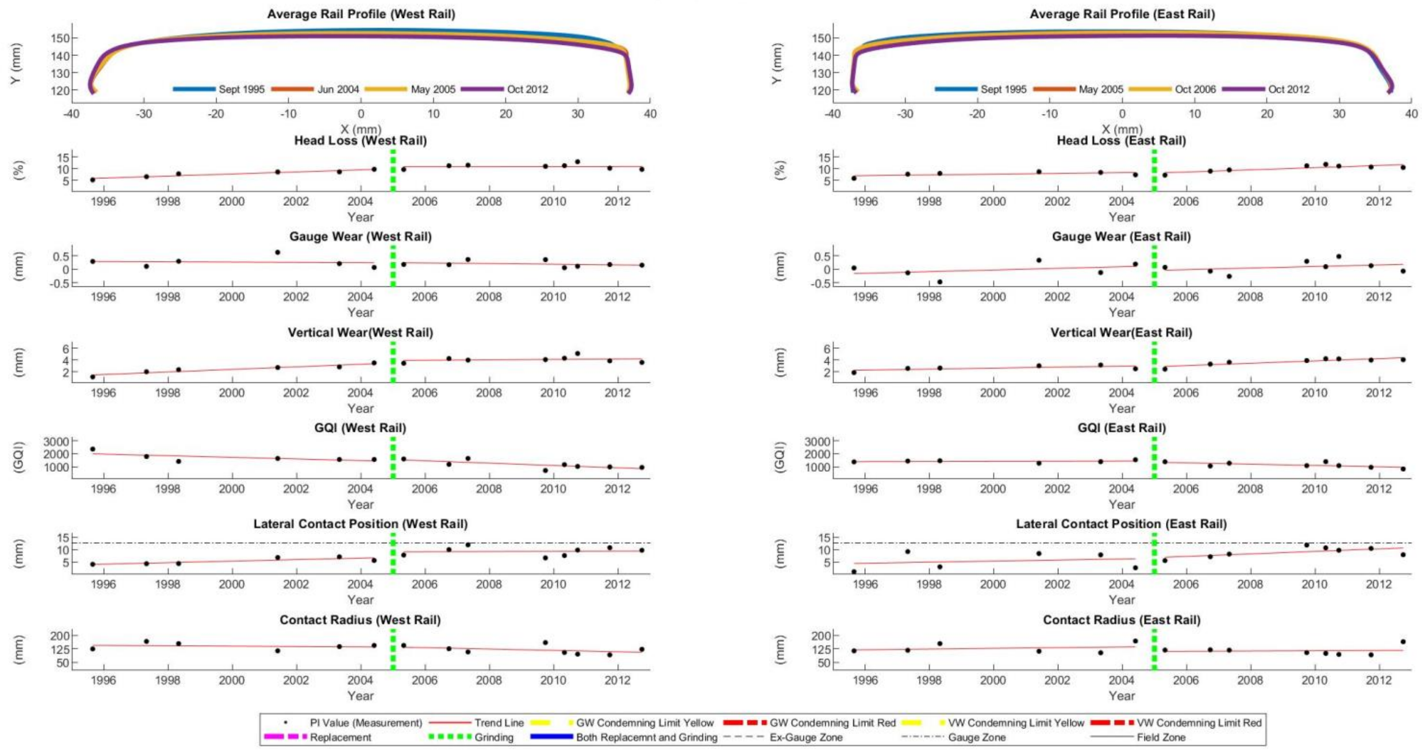
#015CT (15.702-15.878)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)

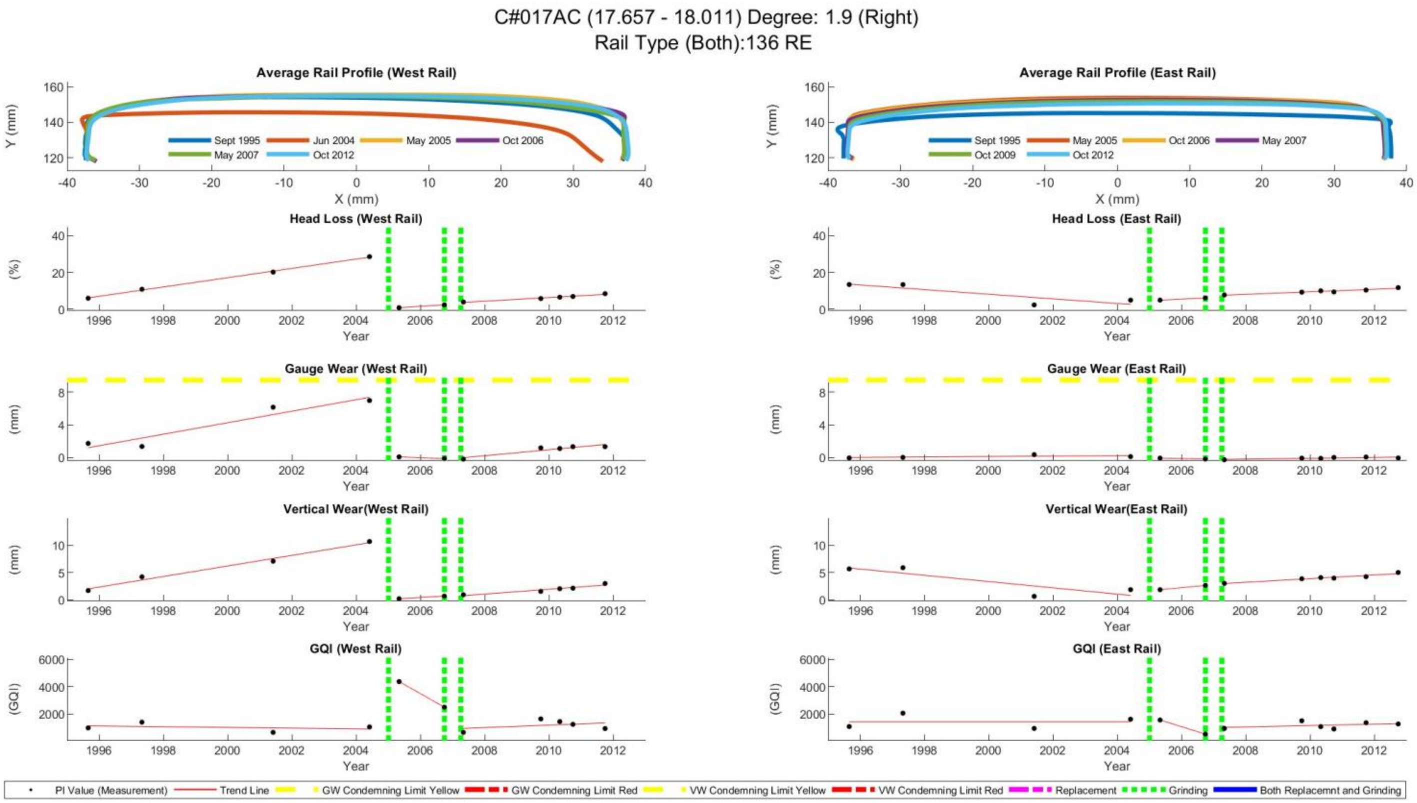


#016BT (16.666-16.858)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)

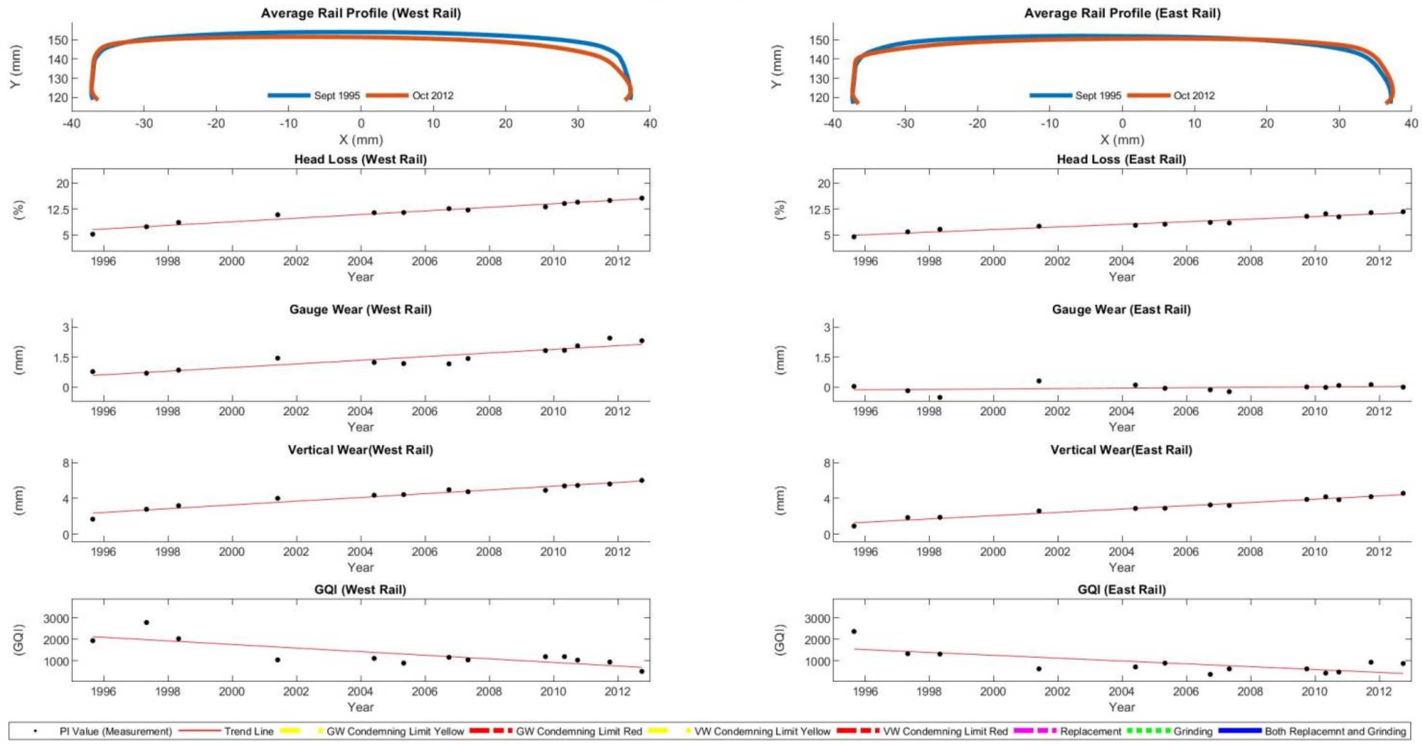


#016CT (17-17.236)
Rail Type (Both):136 RE

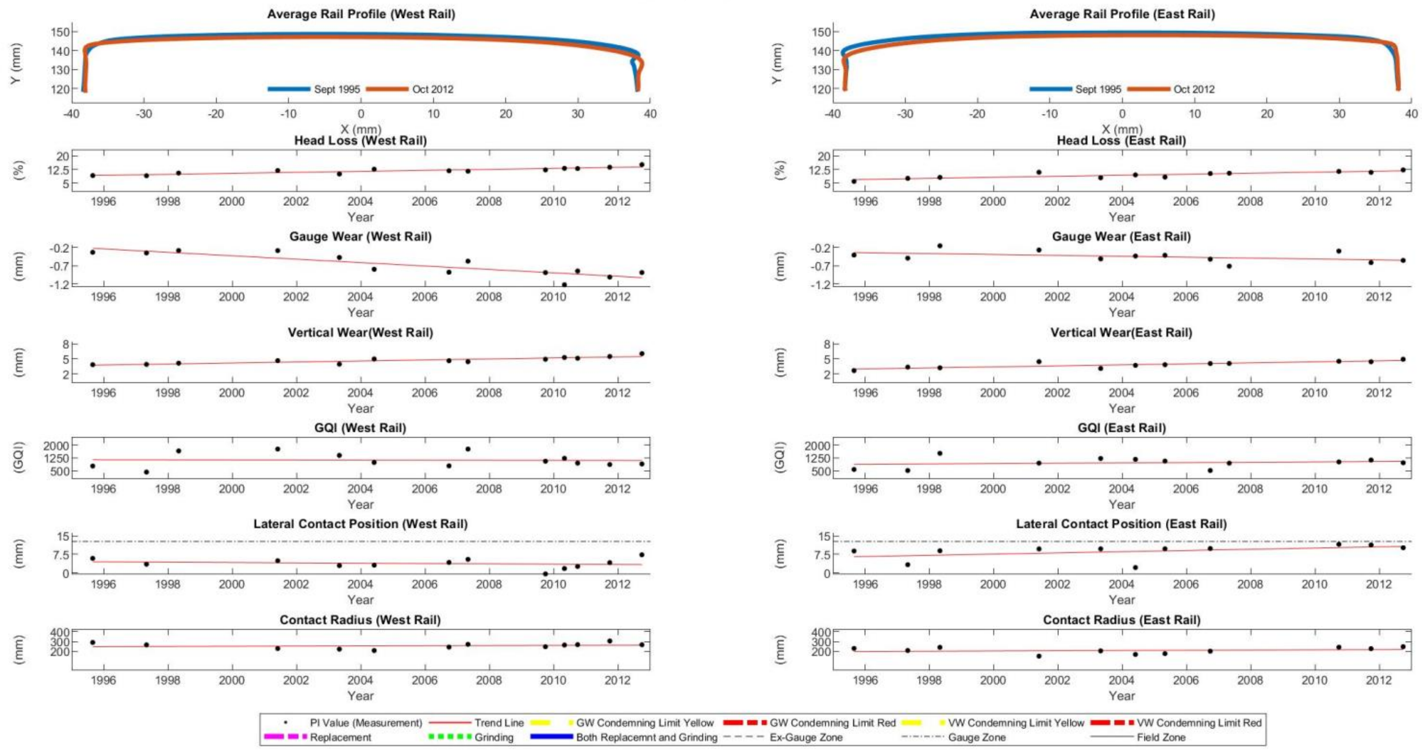



C#017AC (17.657 - 18.011) Degree: 1.9 (Right)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Jun 2004
May 2005
Oct 2006
May 2007
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
(%)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
(mm)
GQI (West Rail)
GQI (East Rail)
(GQI)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

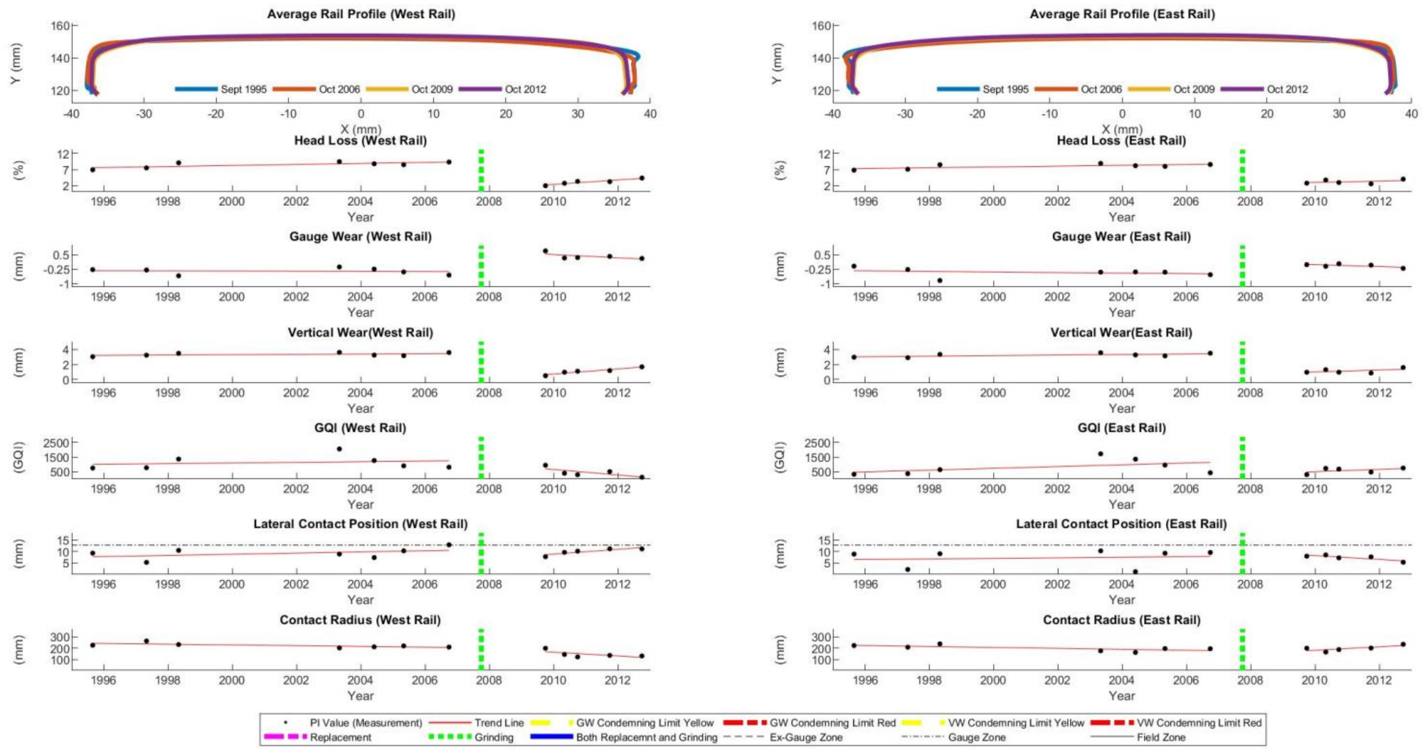
C#018C (18.197 - 18.525) Degree: 1.2 (Right)
Rail Type (Both):136 RE



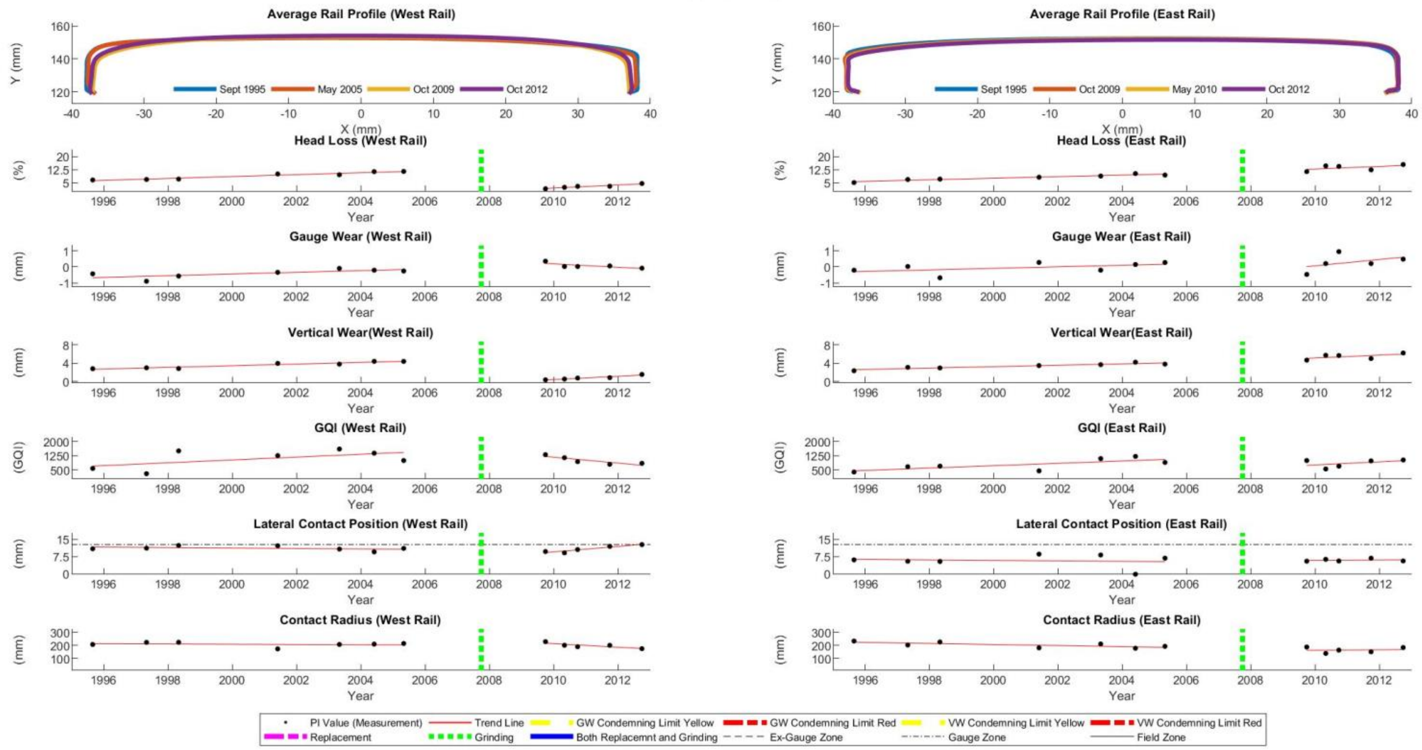
#019AT (19.315-19.475)
Rail Type (Both):132 AREA

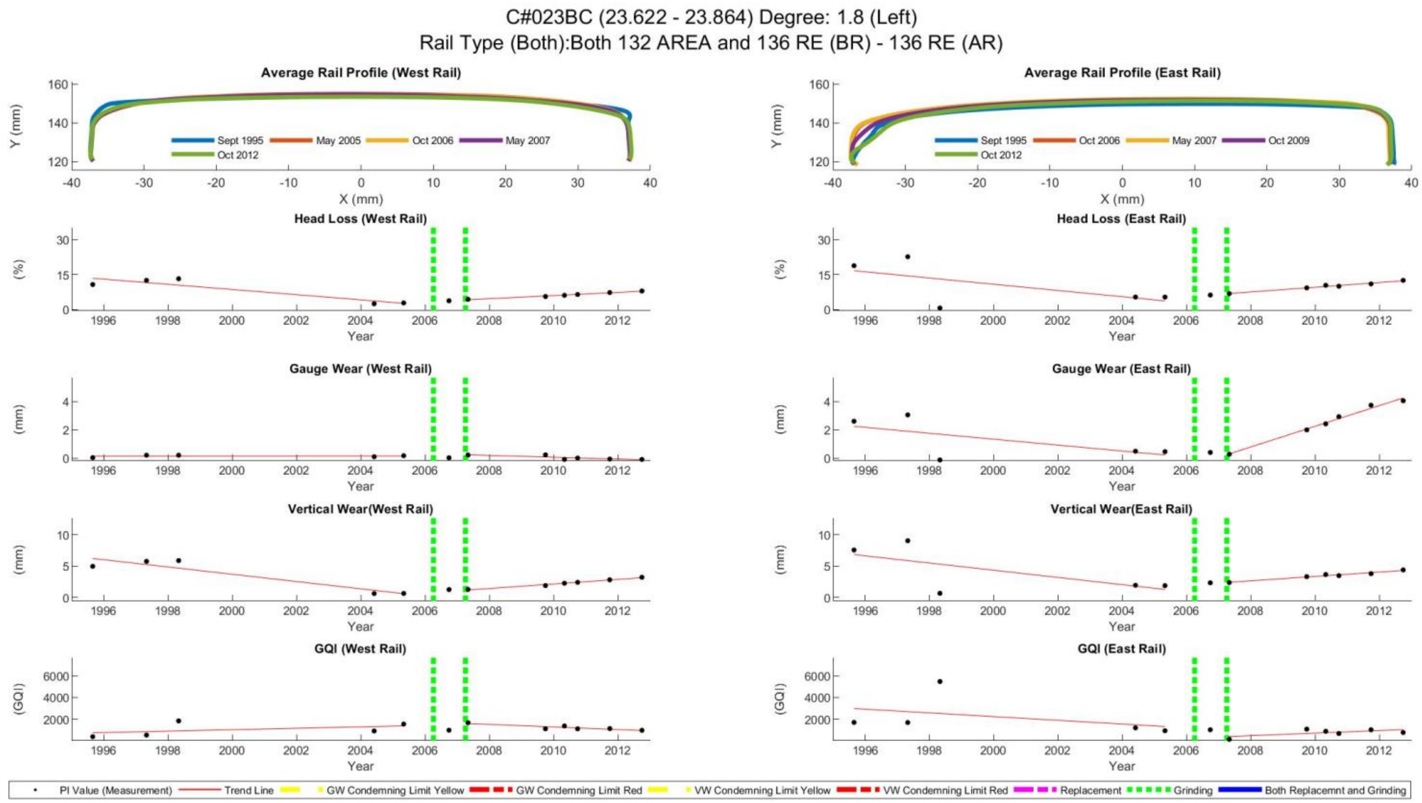


#022BT (22.558-22.855)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)

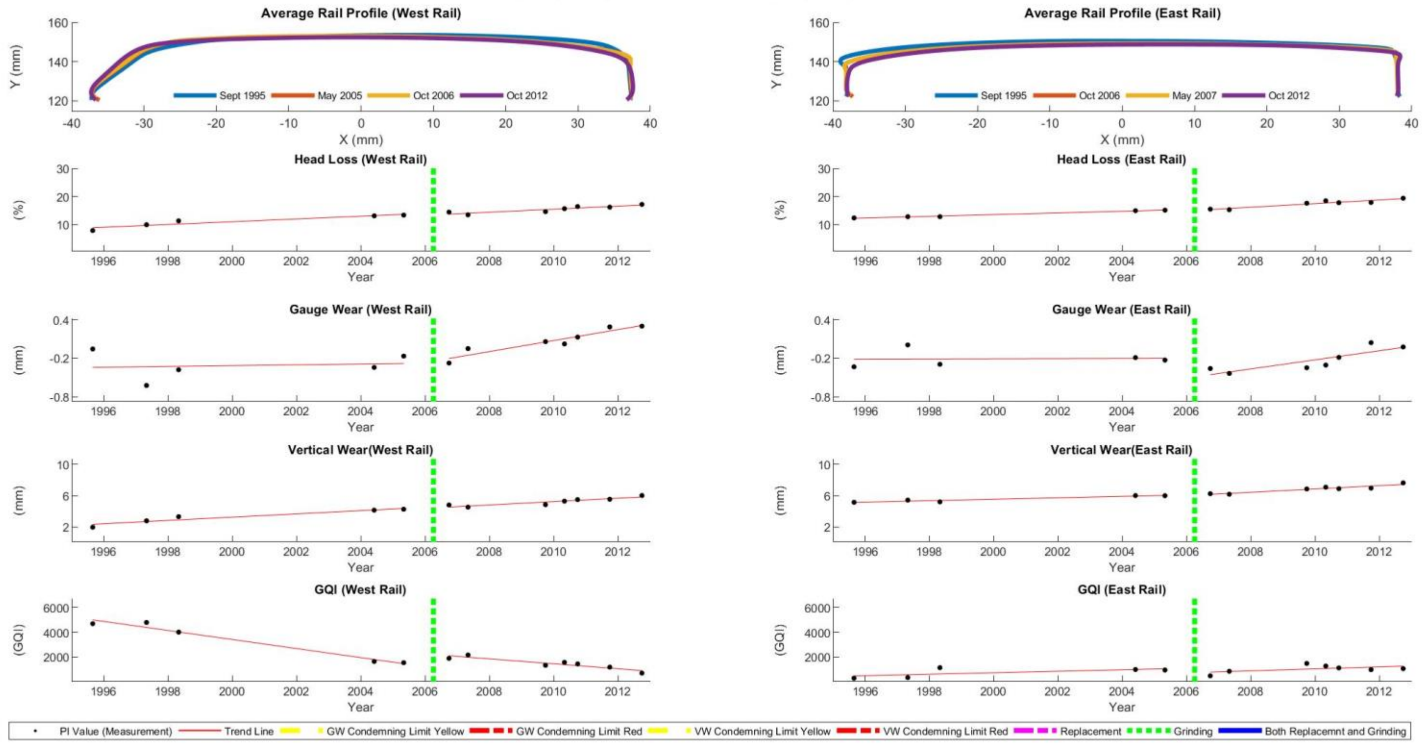


#023T (22.982-23.178)
Rail Type (Both):

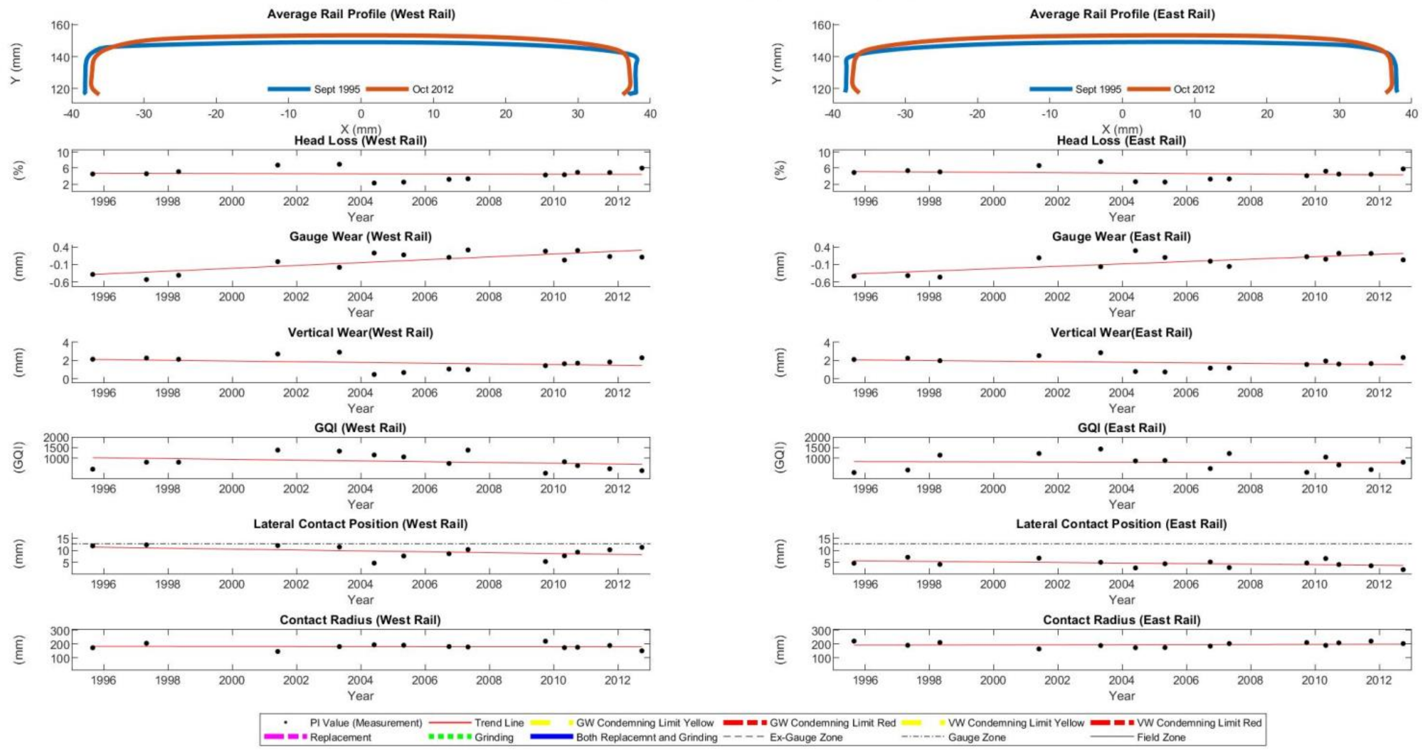



C#023BC (23.622 - 23.864) Degree: 1.8 (Left)
Rail Type (Both):Both 132 AREA and 136 RE (BR) - 136 RE (AR)
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
May 2005
Oct 2006
May 2007
Oct 2009
Oct 2012
X (mm)
Y (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

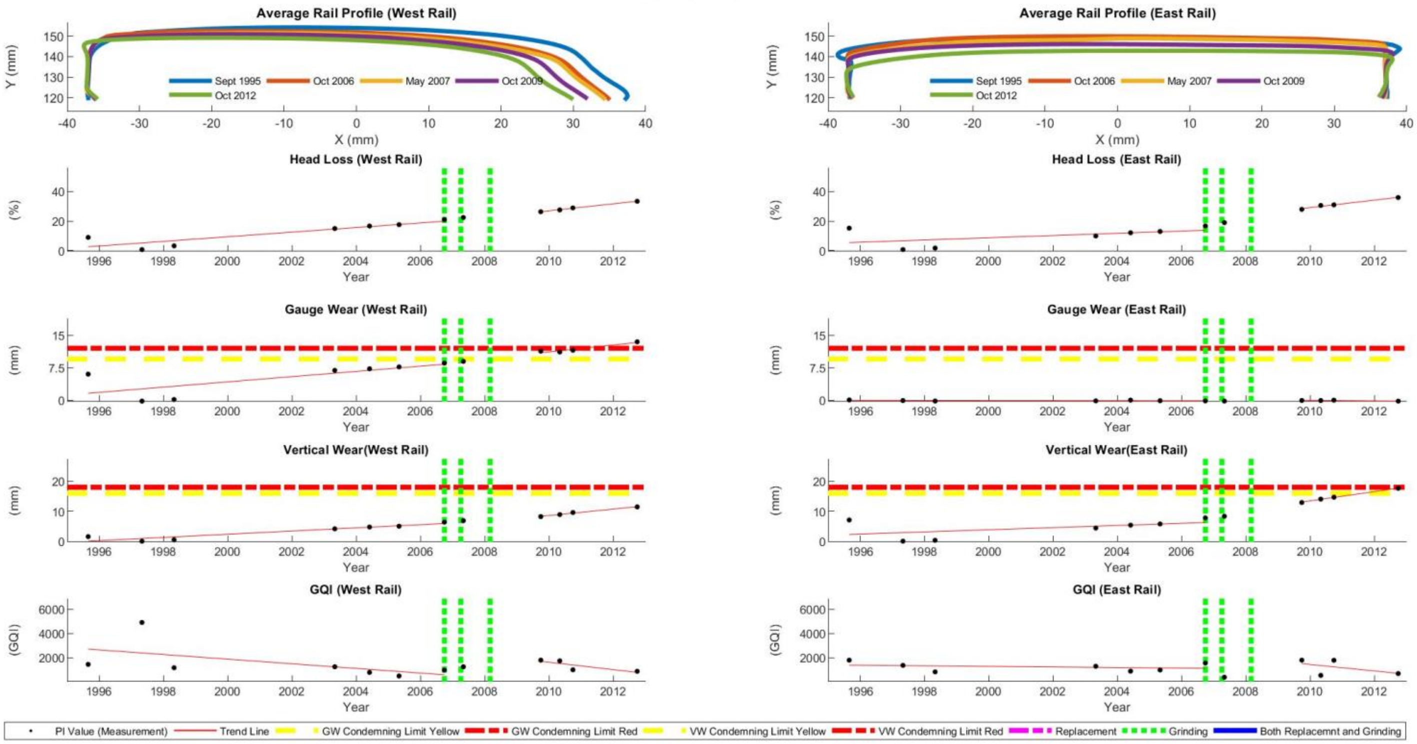
C#024C (24.064 - 24.227) Degree: 1.1 (Right)
Rail Type (West): 136 RE - Rail Type (East): 132 AREA



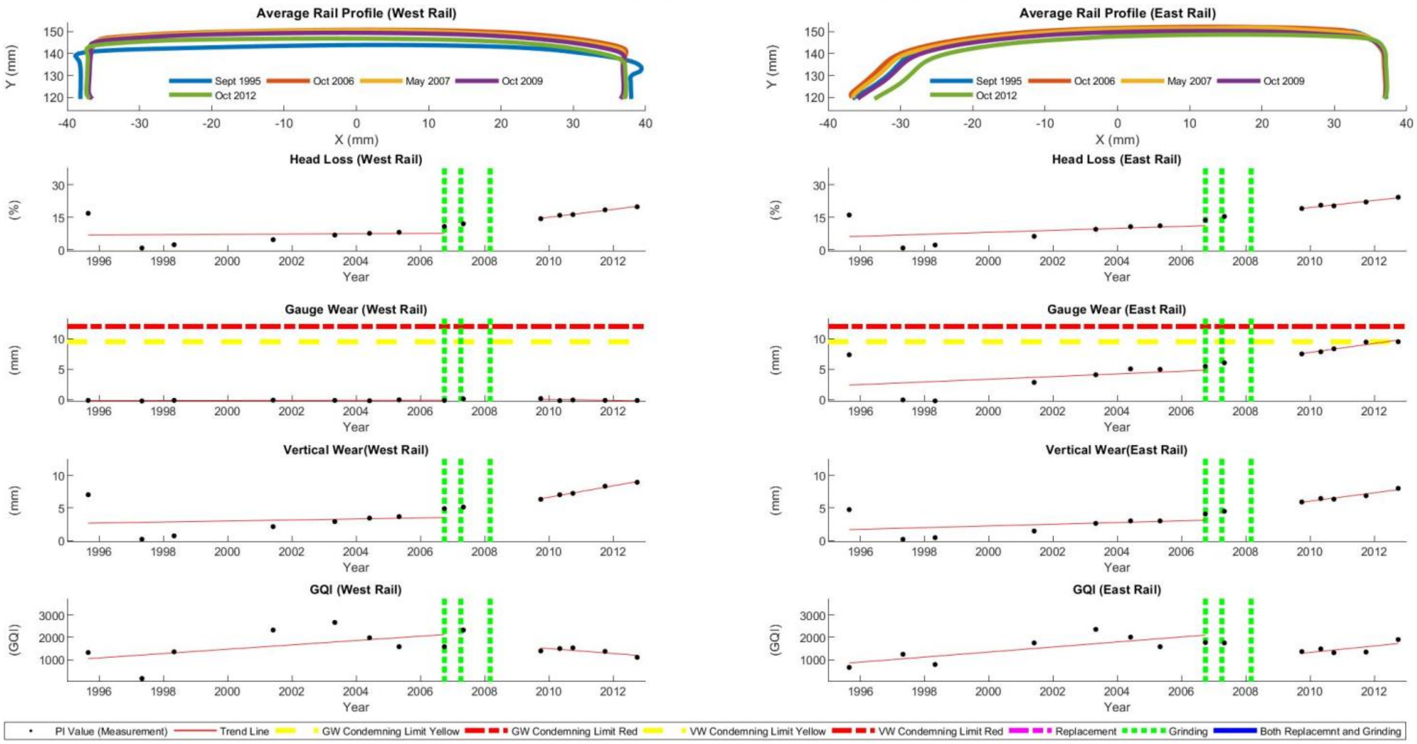
#024BT (24.627-24.939)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)



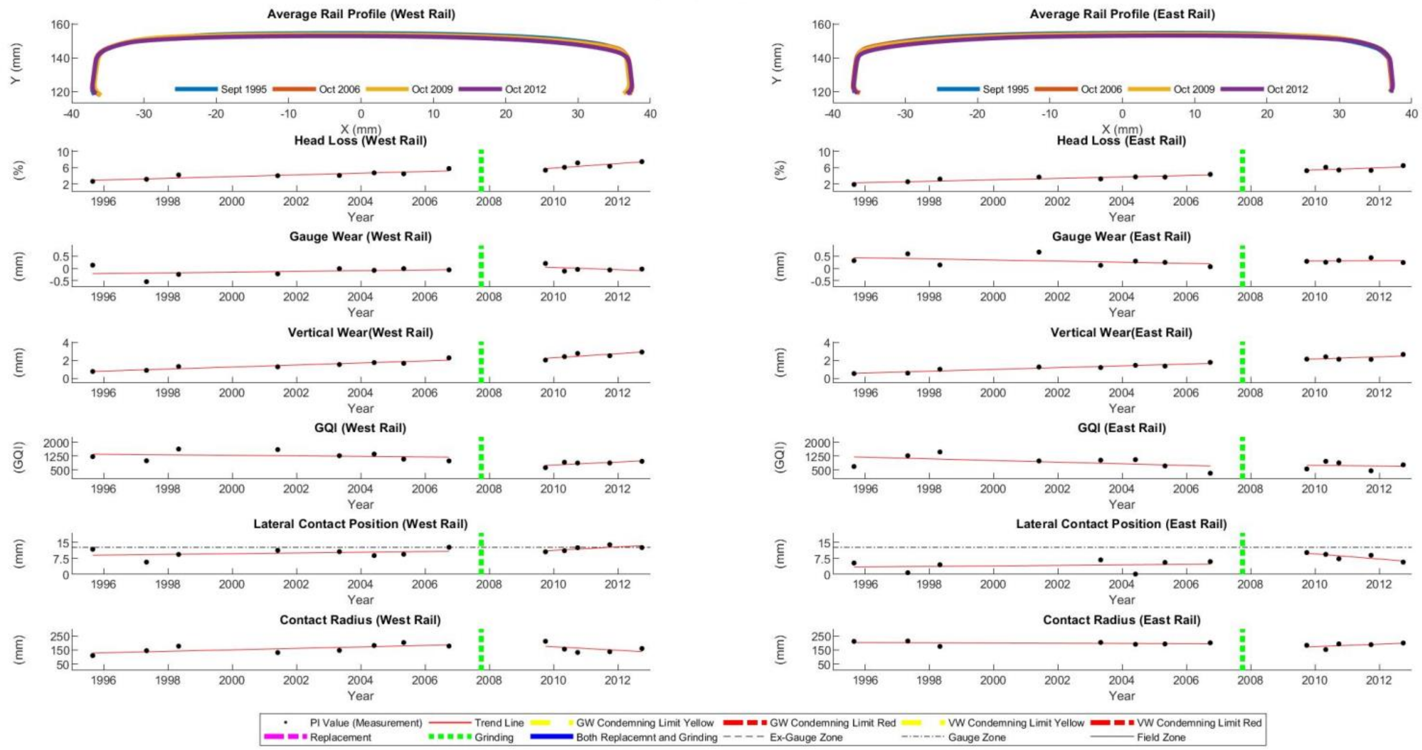
C#025C (24.924 - 25.201) Degree: 4.4 (Right)
Rail Type (Both):136 RE



C#025AC (25.208 - 25.571) Degree: 3 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE

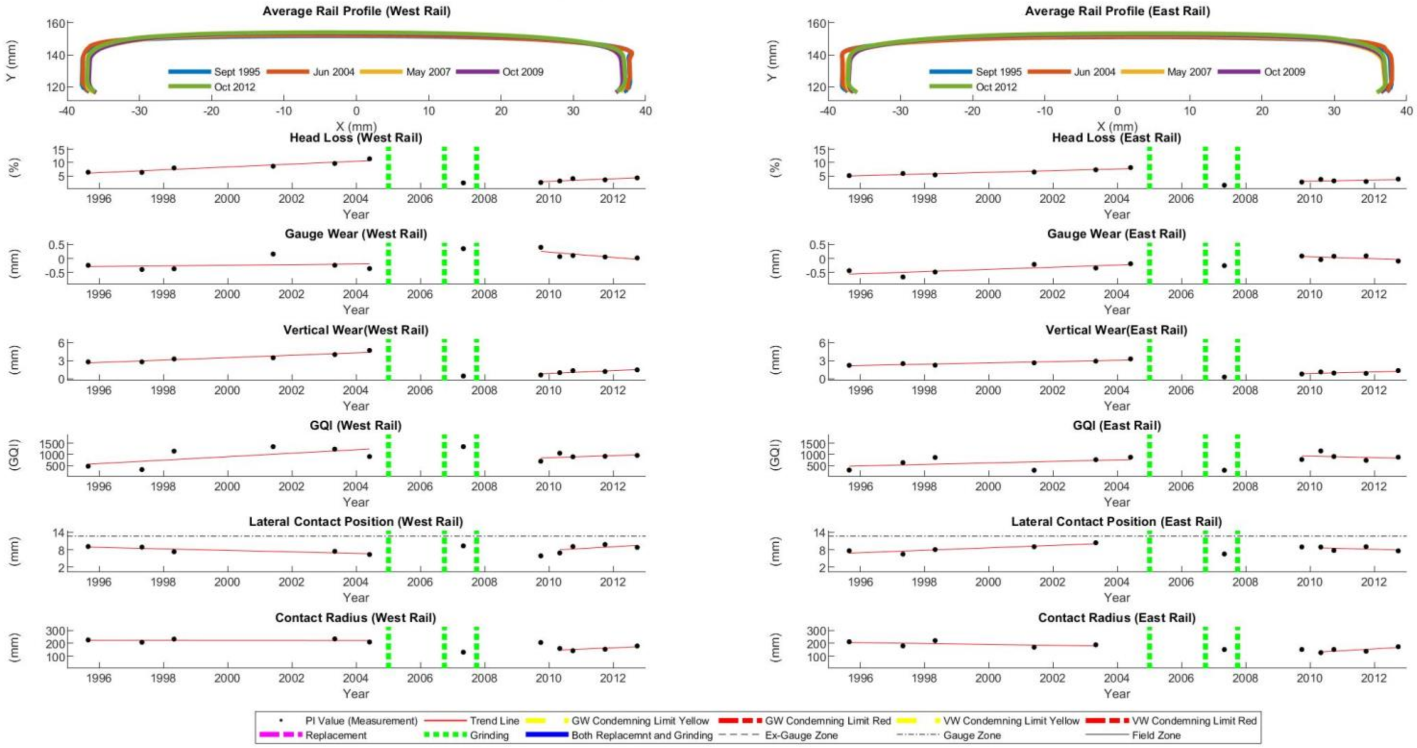


#027T (27.142-27.689)
Rail Type (Both):136 RE

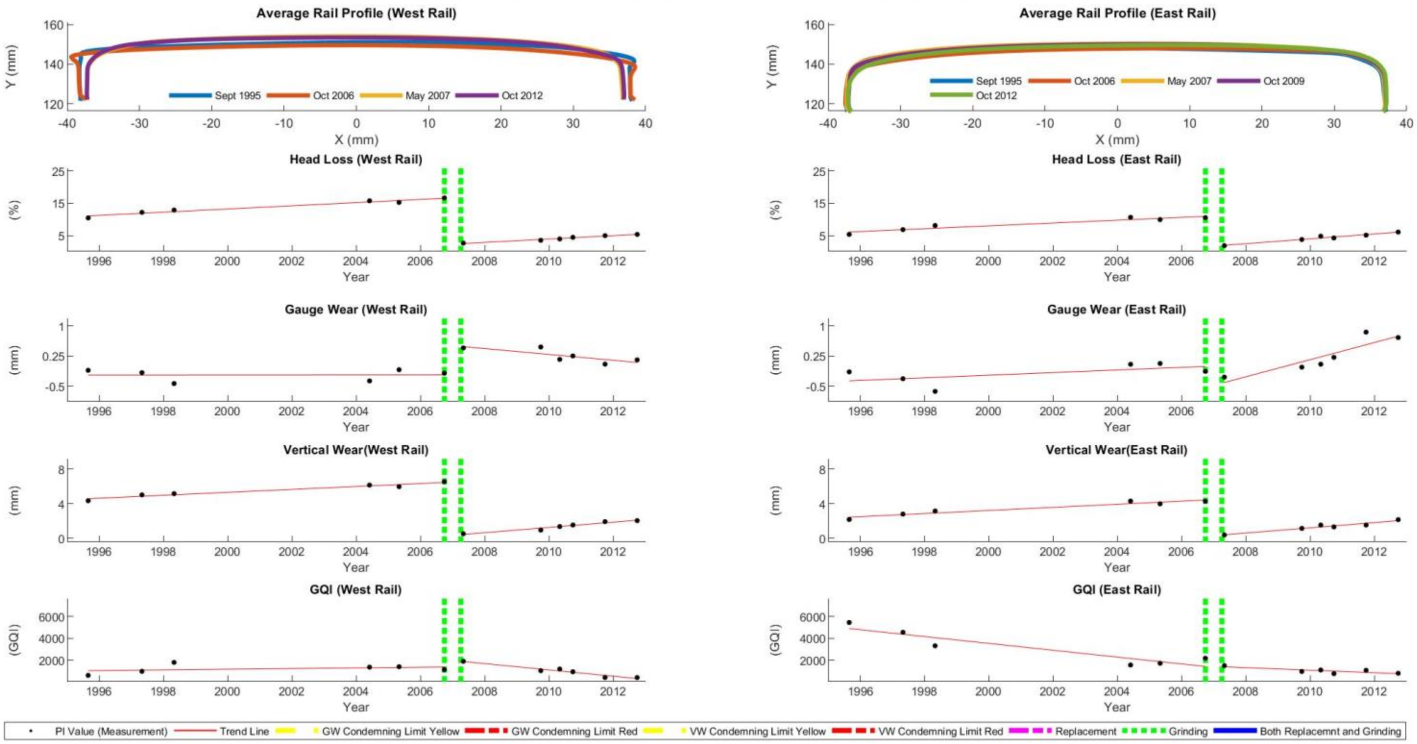


#027AT (27.828-28.241)

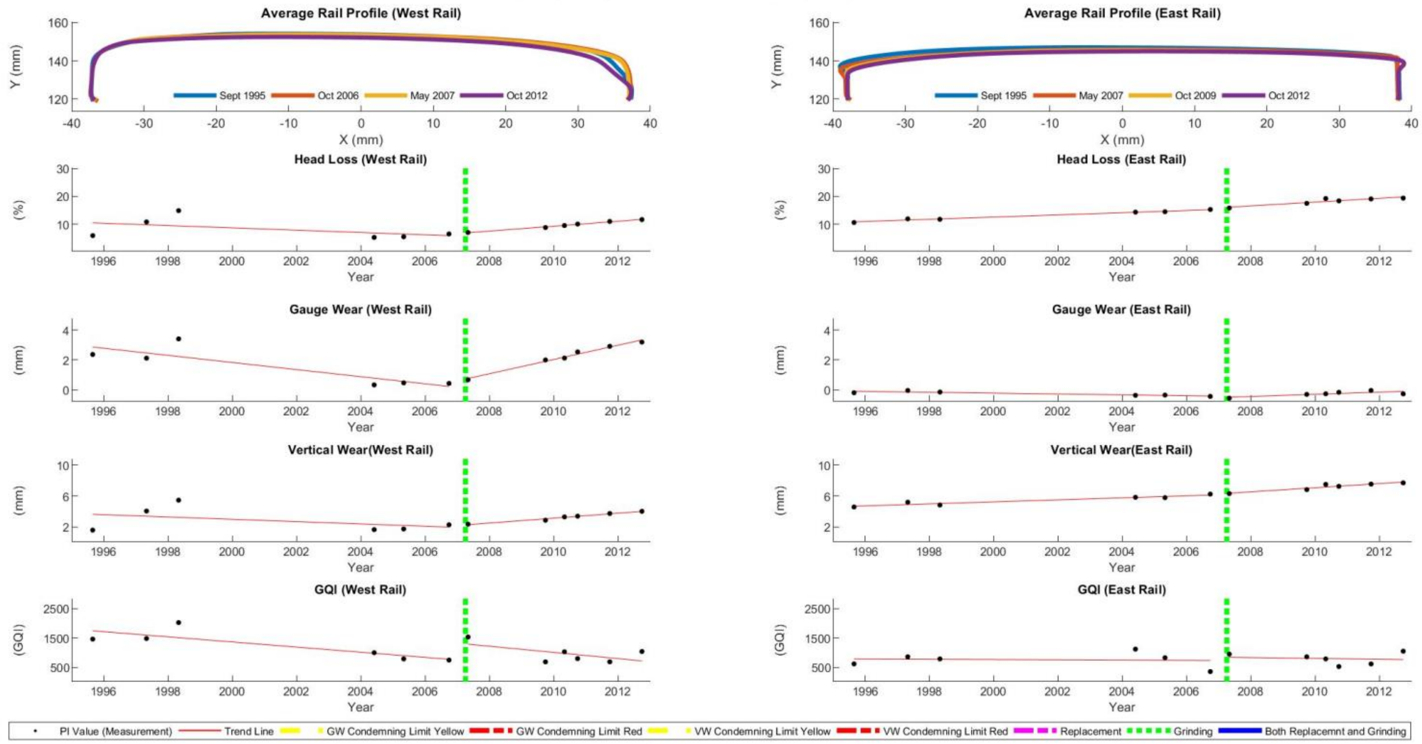
Rail Type (Both):132 ARE (BR) - 136 RE (AR)



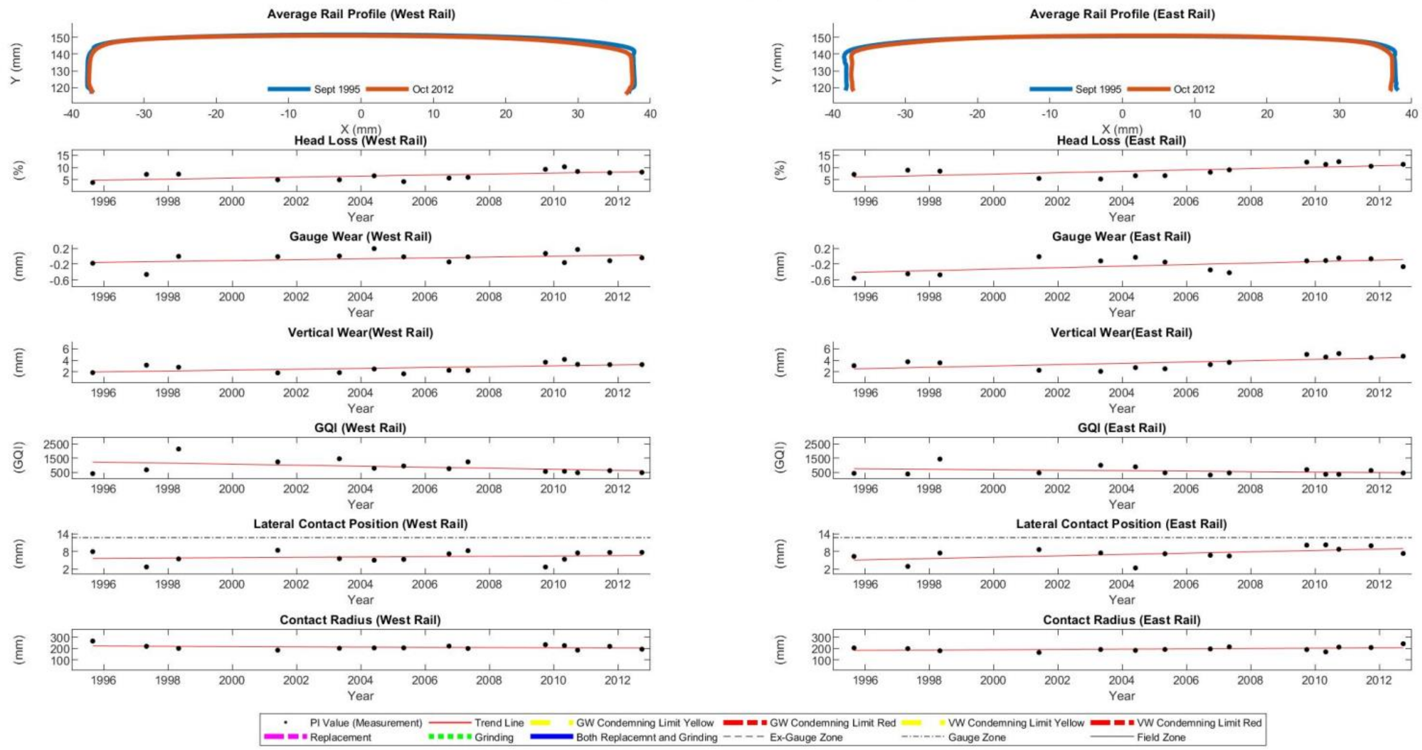
C#029C (28.96 - 29.142) Degree: 1.5 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE

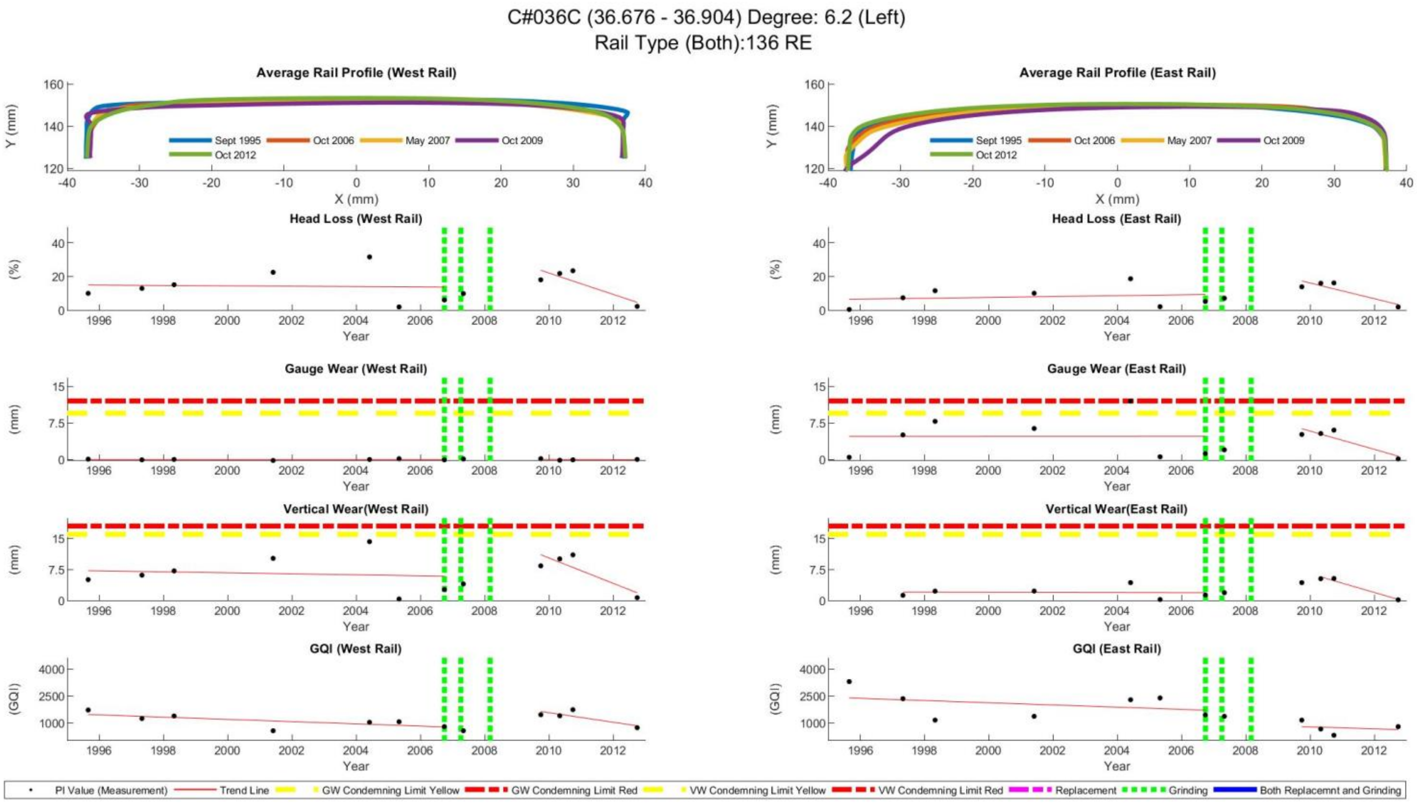


C#029AC (29.196 - 29.478) Degree: 1.5 (Right)
Rail Type (West): 136 RE - Rail Type (East): 132 AREA

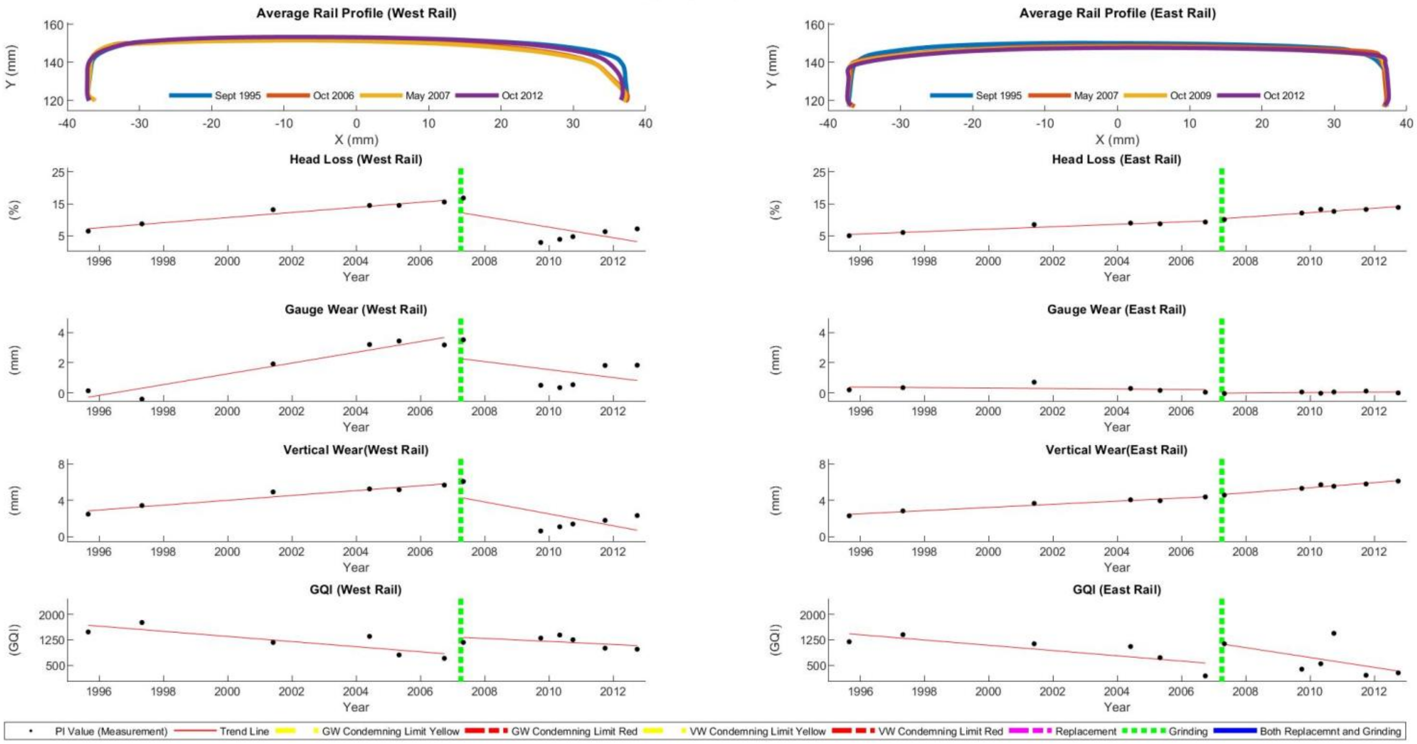


#032BT (32.77-32.958)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)

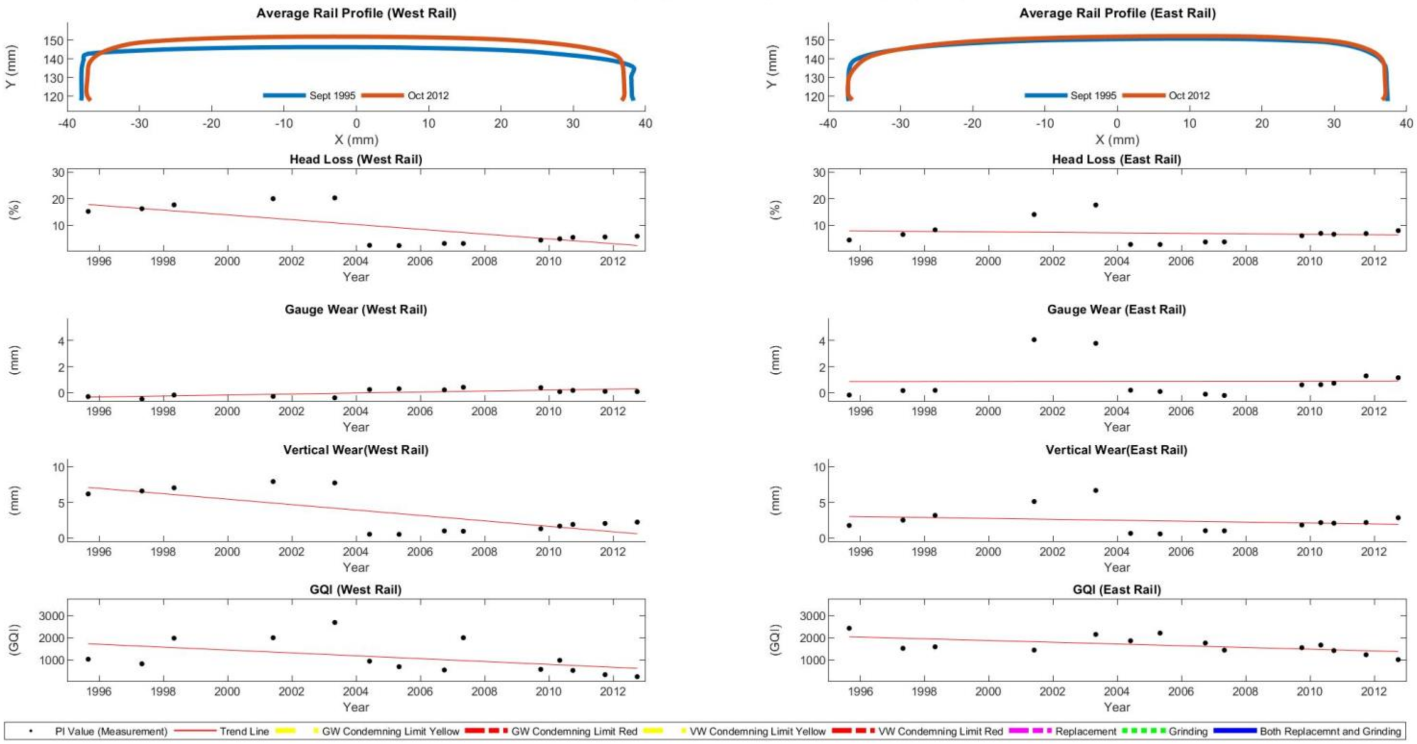



C#036C (36.676 - 36.904) Degree: 6.2 (Left)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Oct 2006
May 2007
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

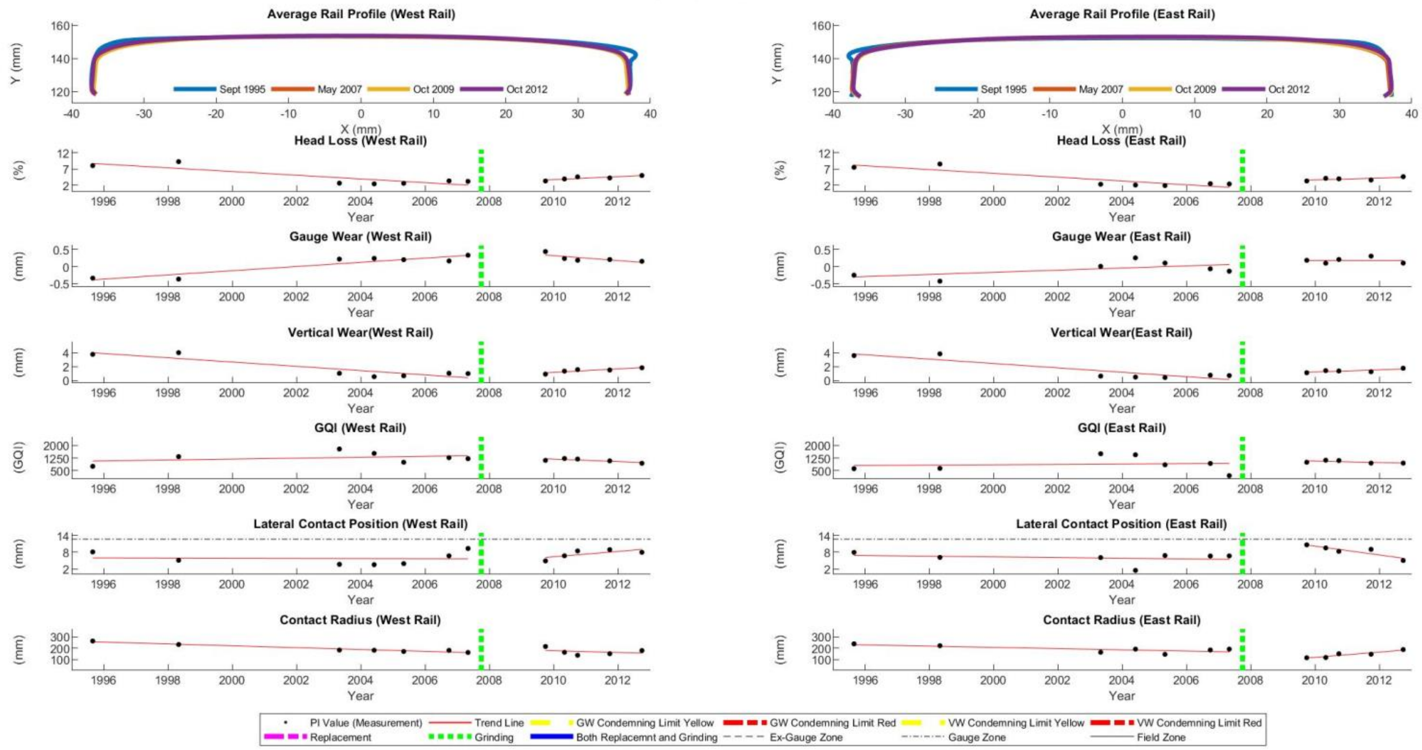
C#038C (37.866 - 38.058) Degree: 1.5 (Right)
Rail Type (Both):136 RE



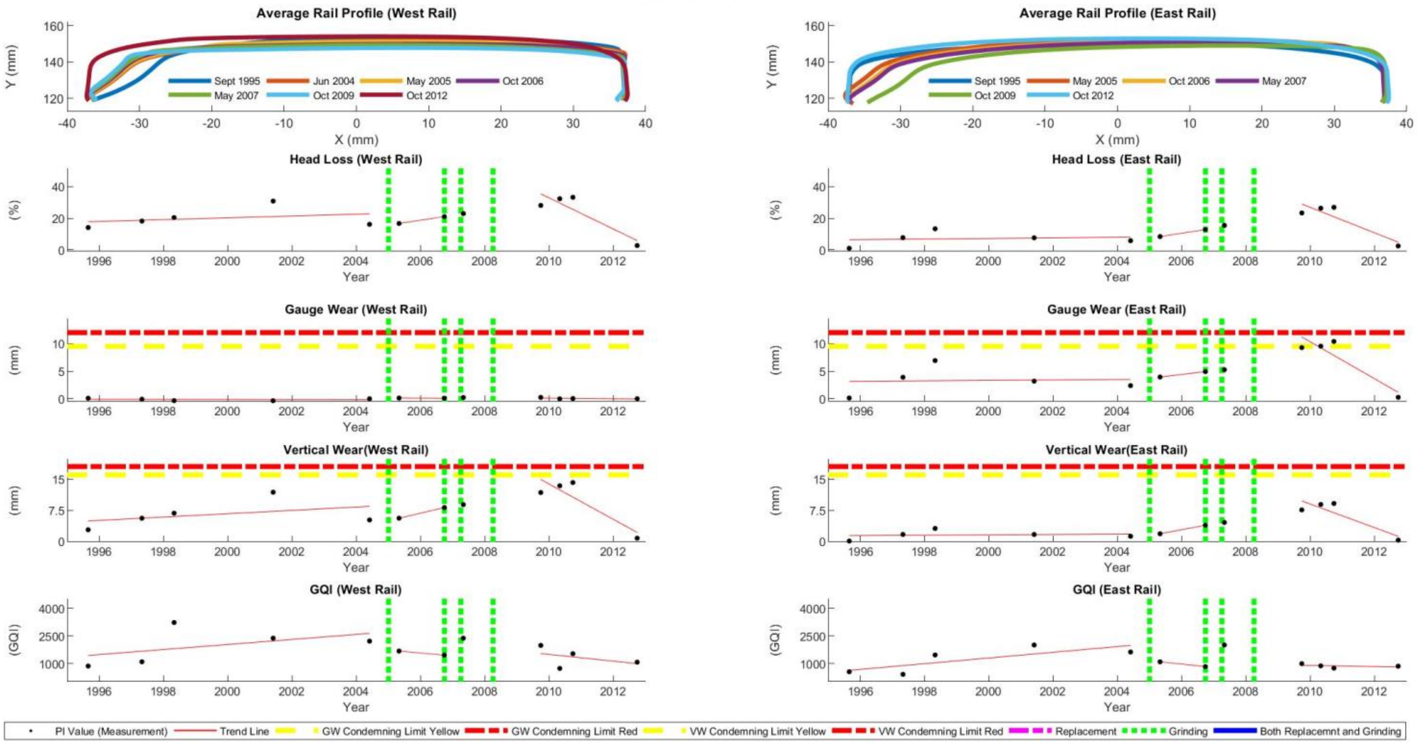
C#038AC (38.427 - 38.679) Degree: 1 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE



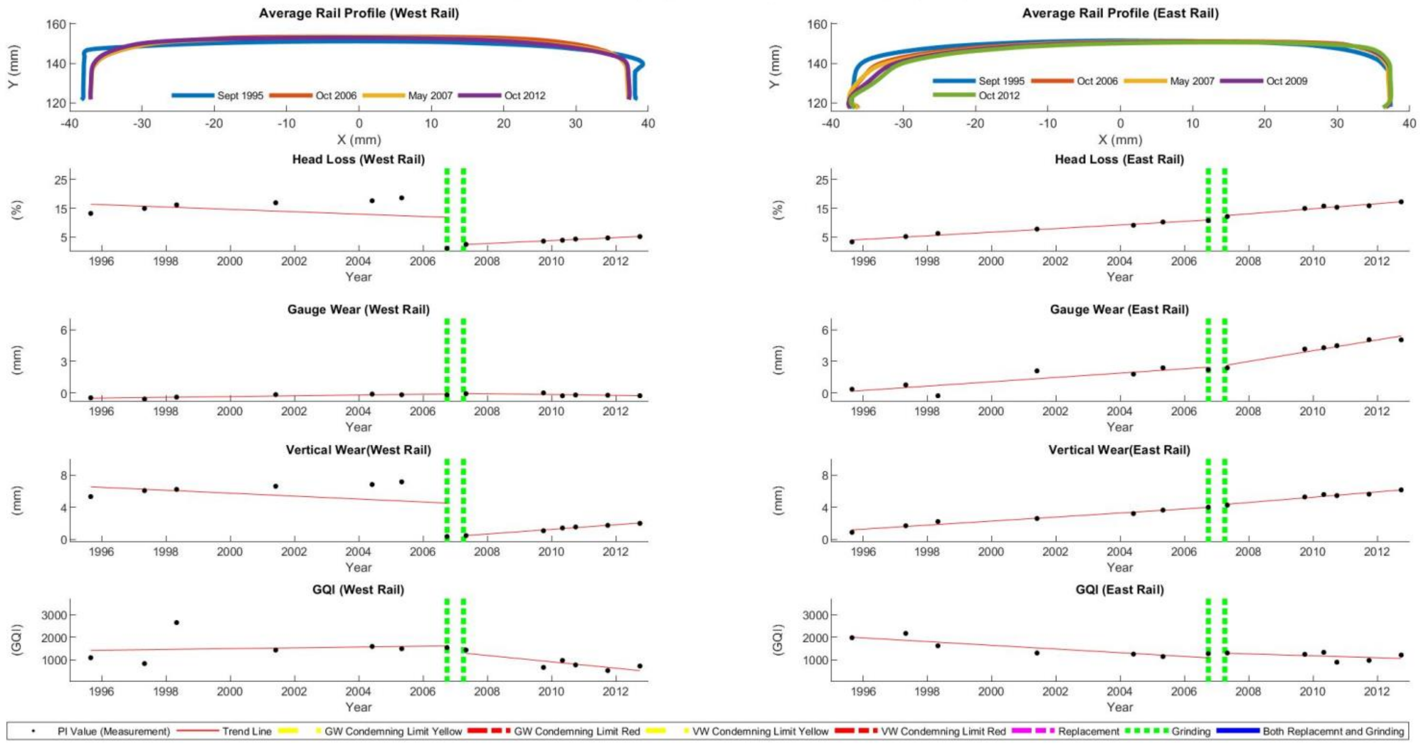
#038AT (38.691-38.99)
Rail Type (Both):136 RE



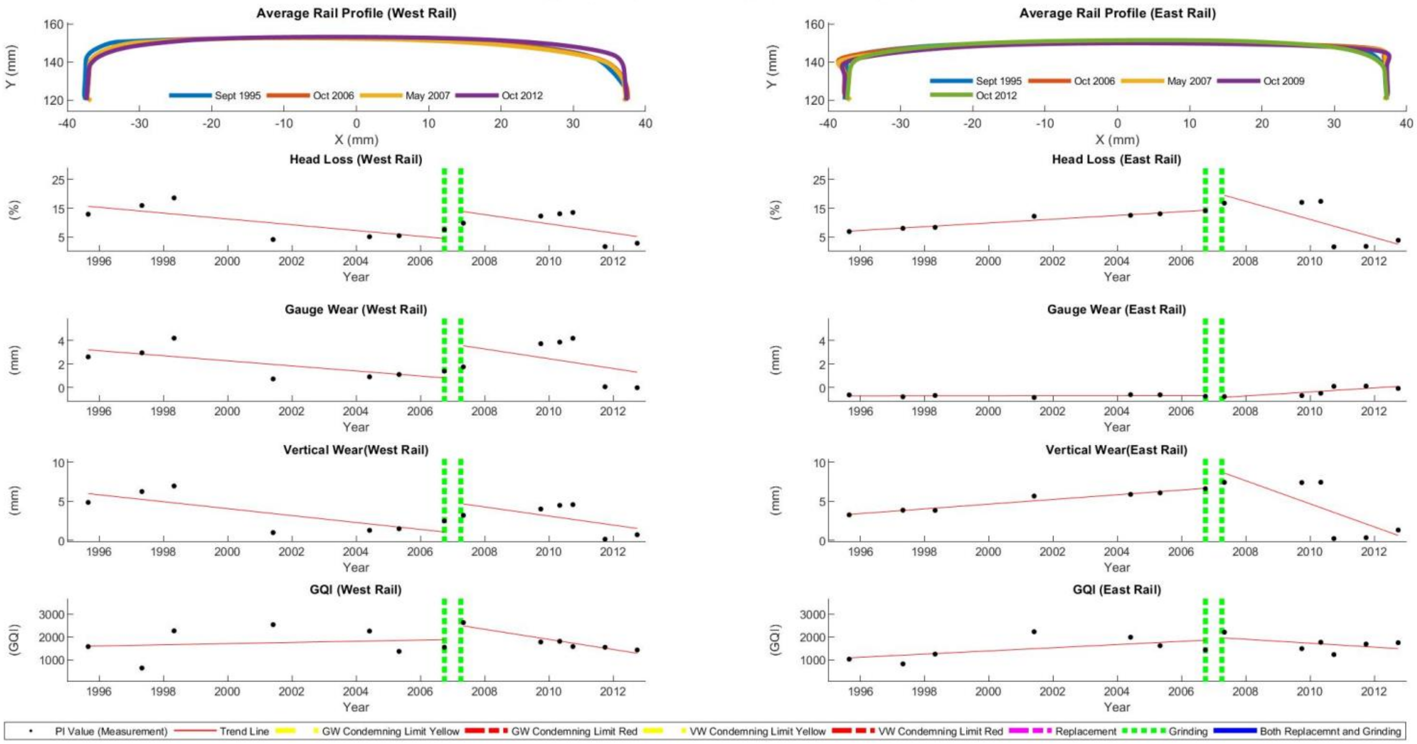
C#039BC (39.642 - 39.952) Degree: 5.6 (Left)
Rail Type (Both):136 RE



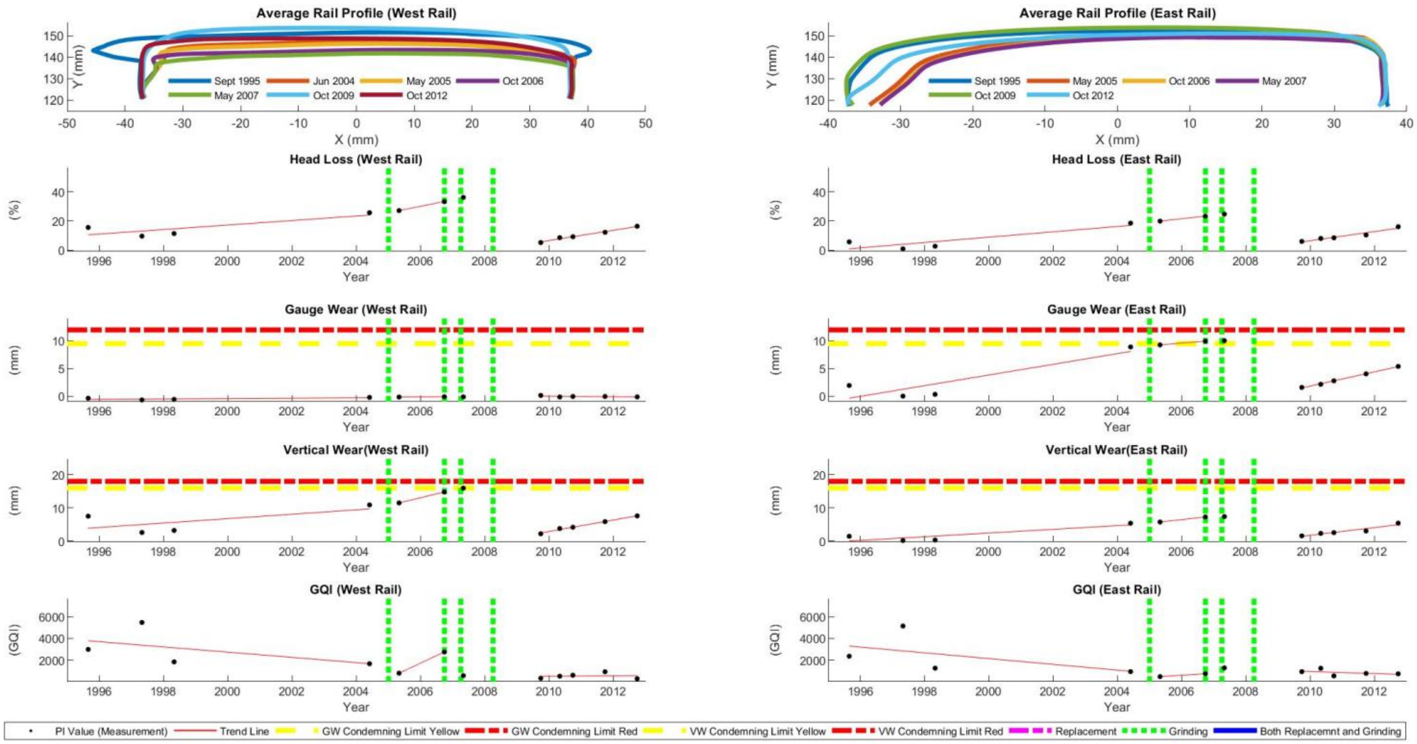
C#041C (40.876 - 41.106) Degree: 0.4 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE



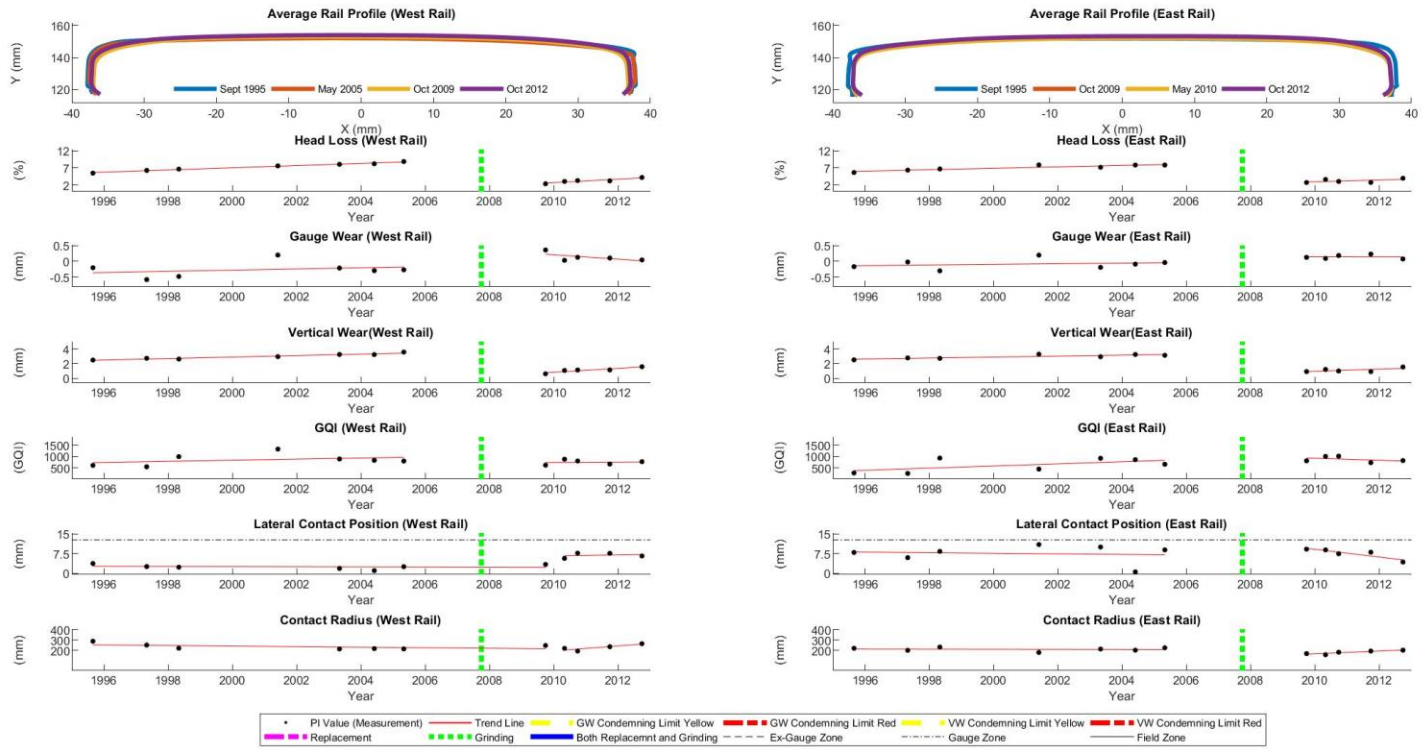
C#042BC (42.32 - 42.502) Degree: 2 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)



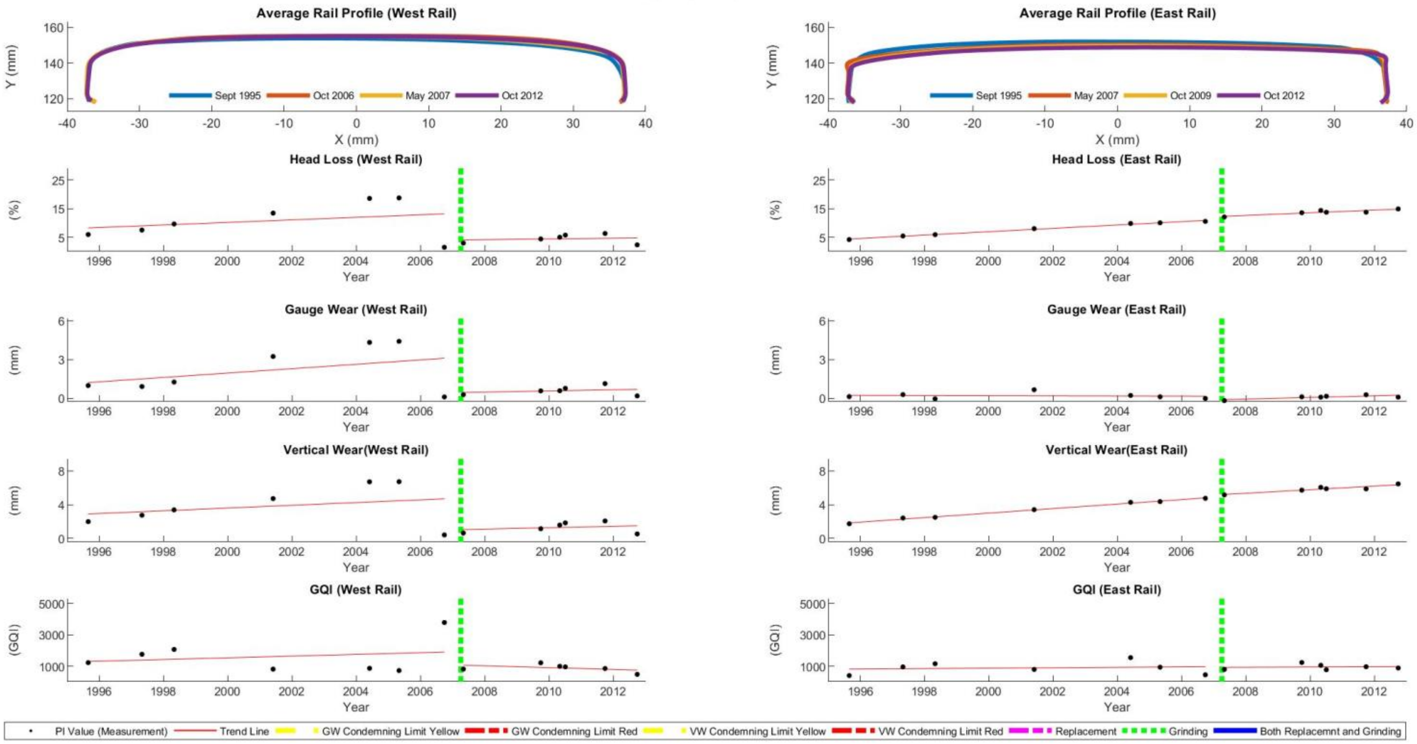
C#042CC (42.592 - 42.915) Degree: 4 (Left)
Rail Type (Both):136 RE



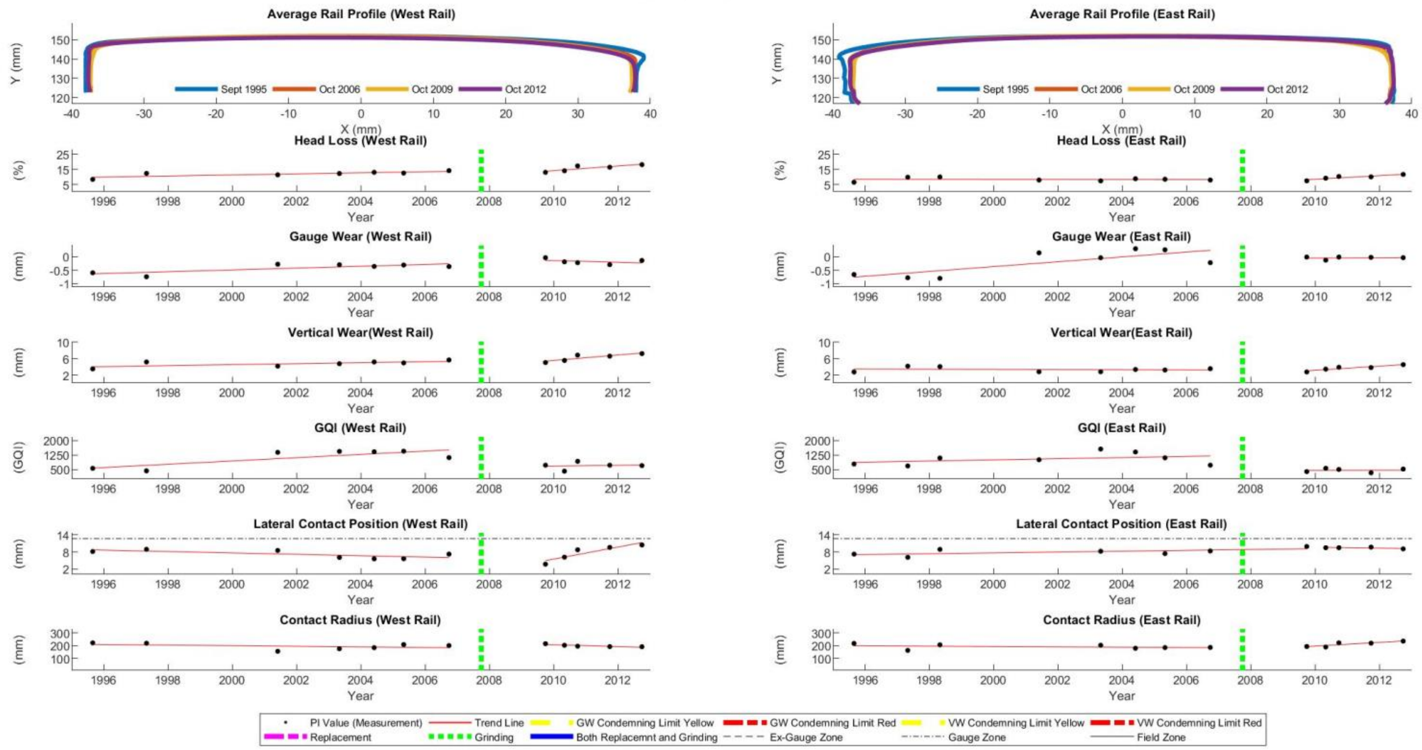
#042CT (42.908-43.247)
Rail Type (Both):136 RE



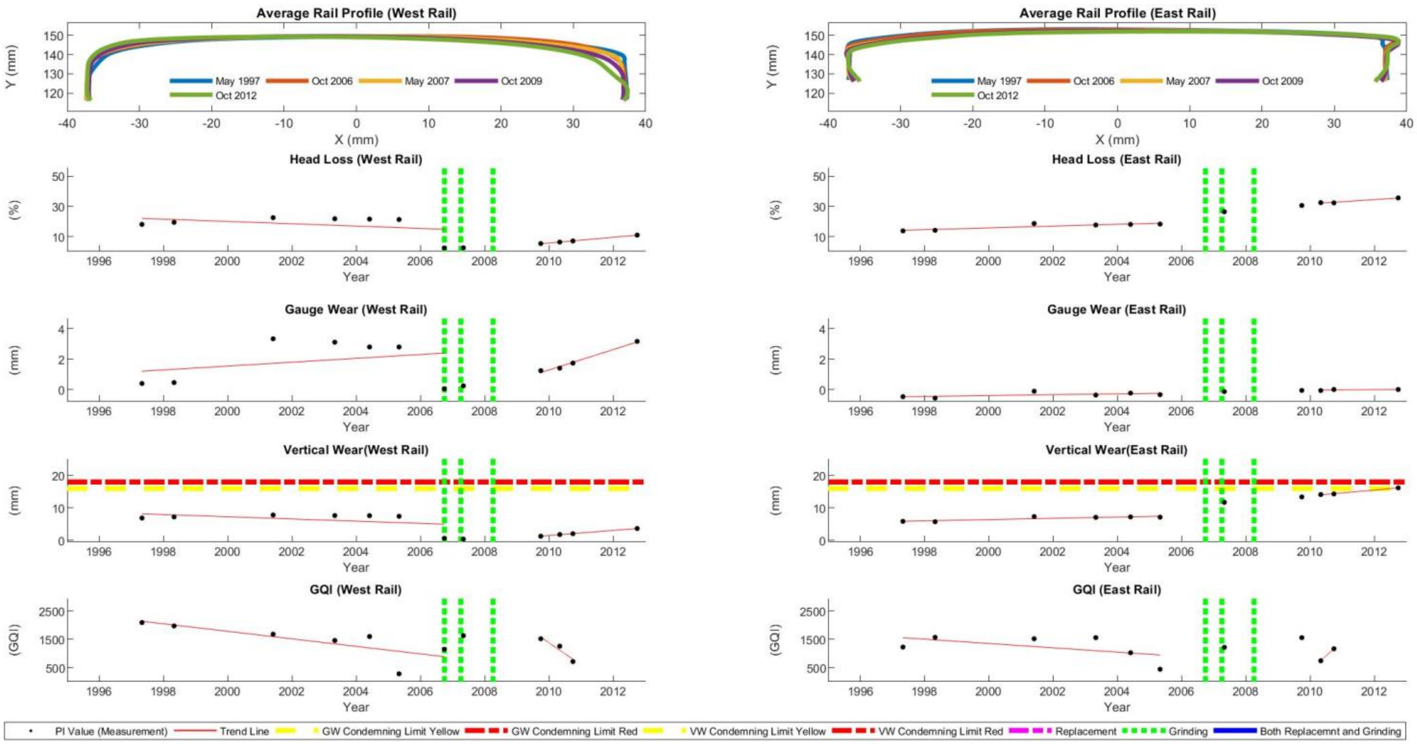
C#043C (43.239 - 43.858) Degree: 1.4 (Right)
Rail Type (Both):136 RE



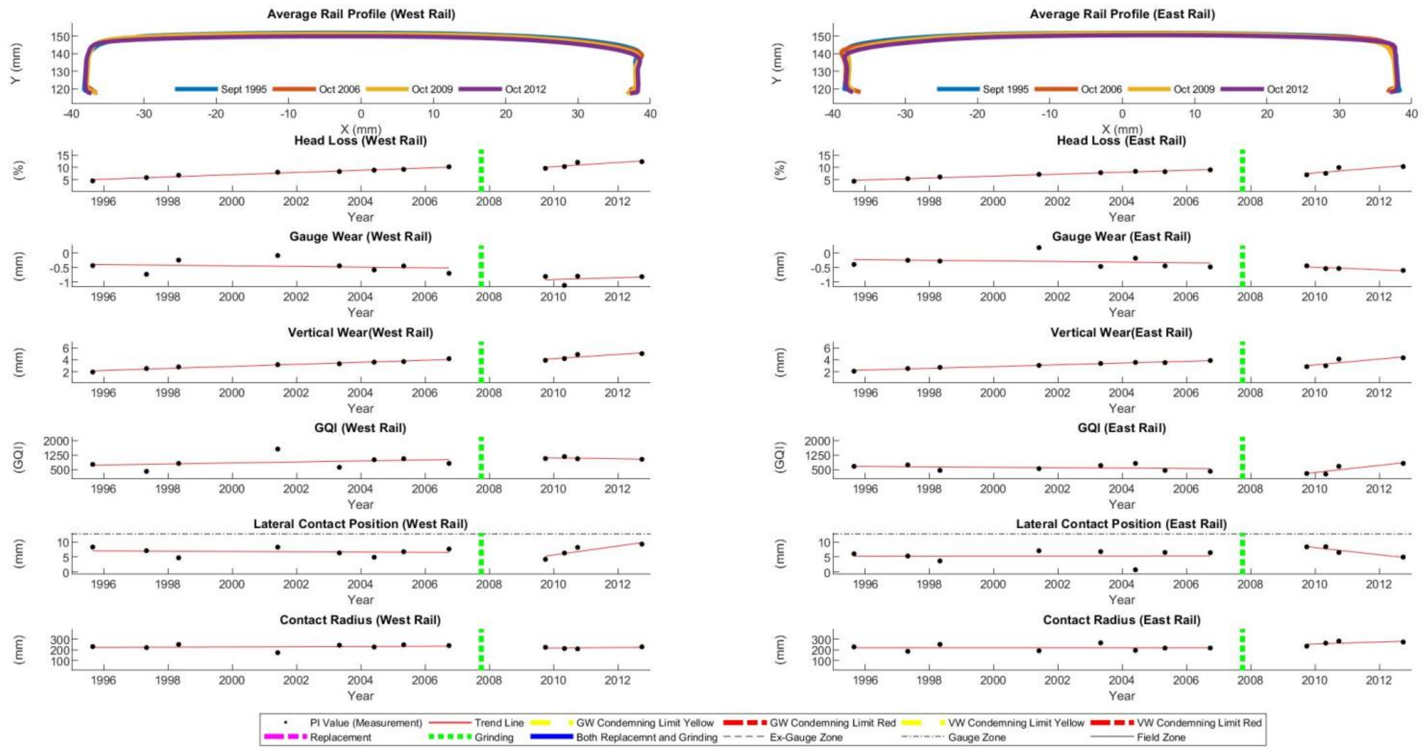
#044BT (44.795-44.931)
Rail Type (Both):132 AREA



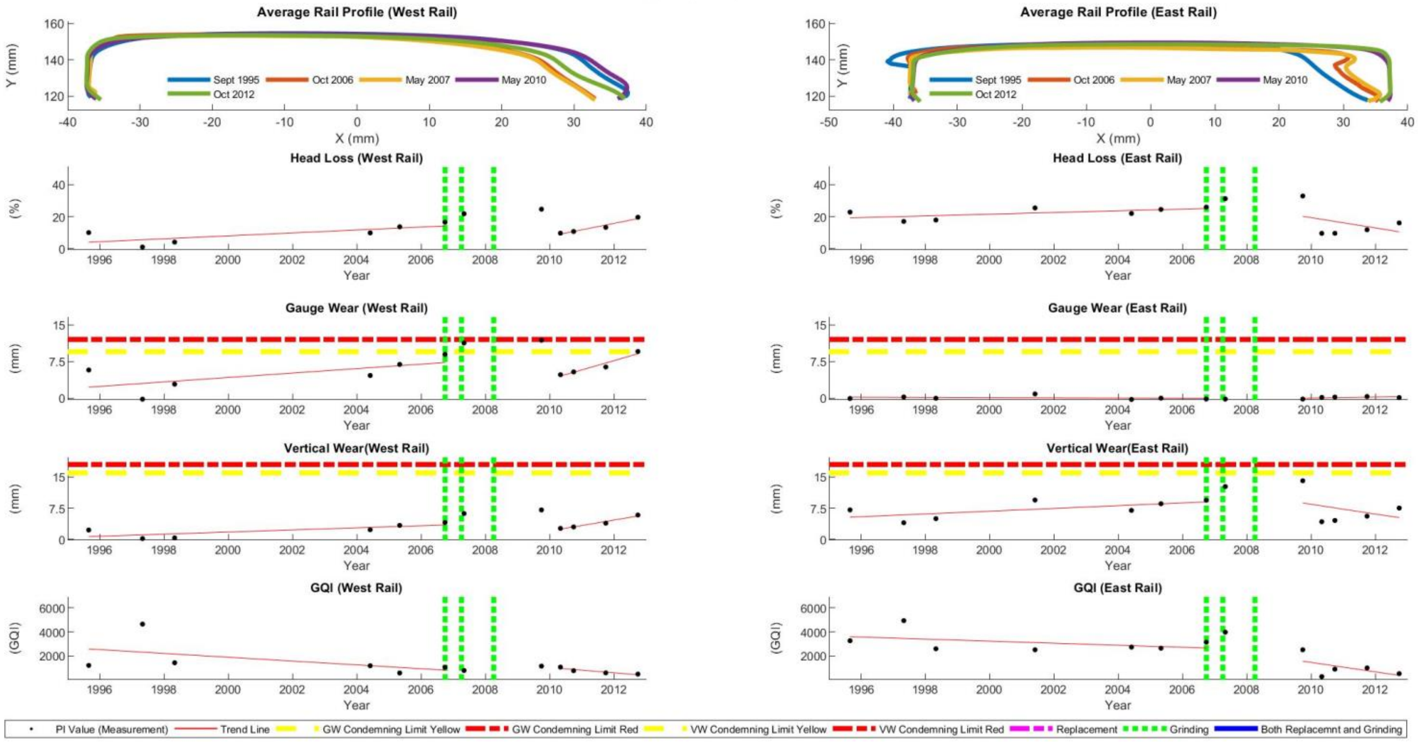
C#045AC (45.693 - 45.867) Degree: 3 (Right)
Rail Type (Both):136 RE



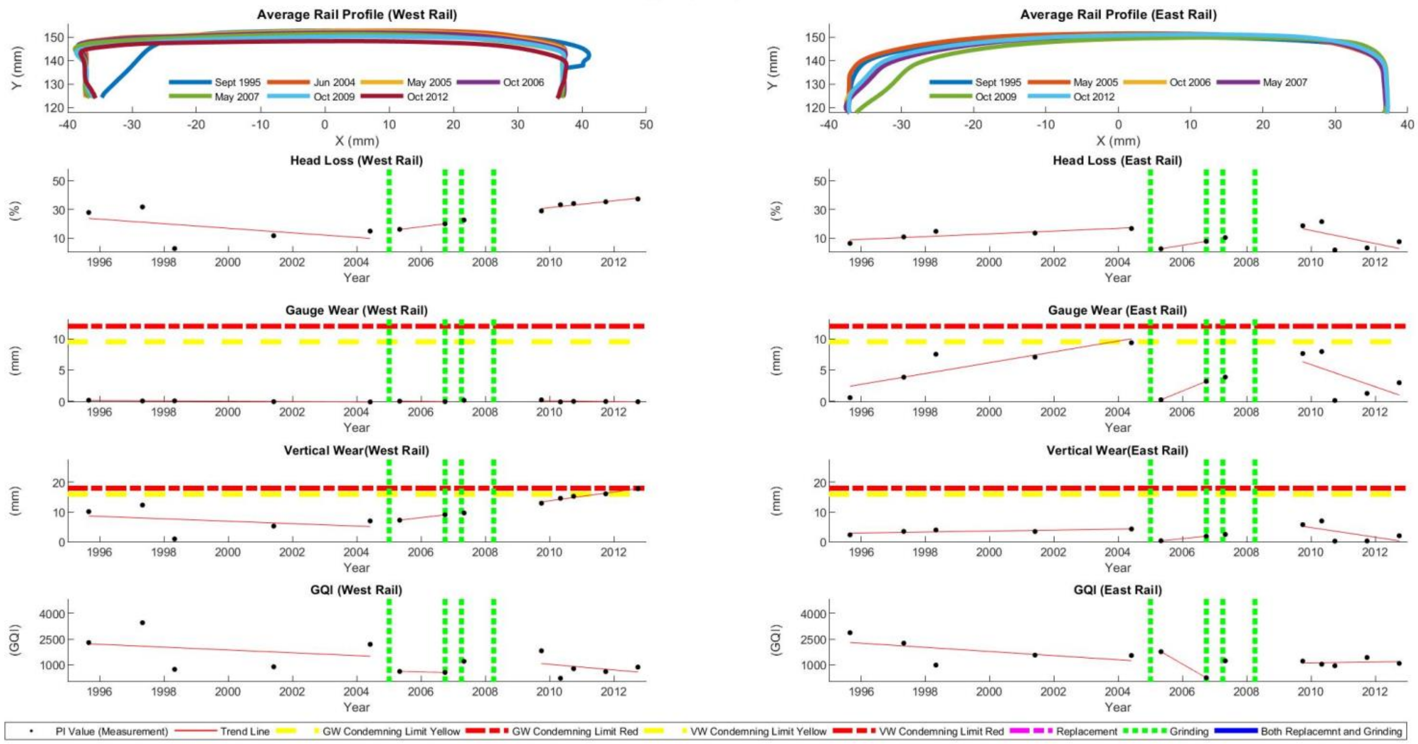
#046AT (46.205-46.492)
Rail Type (Both):132 AREA



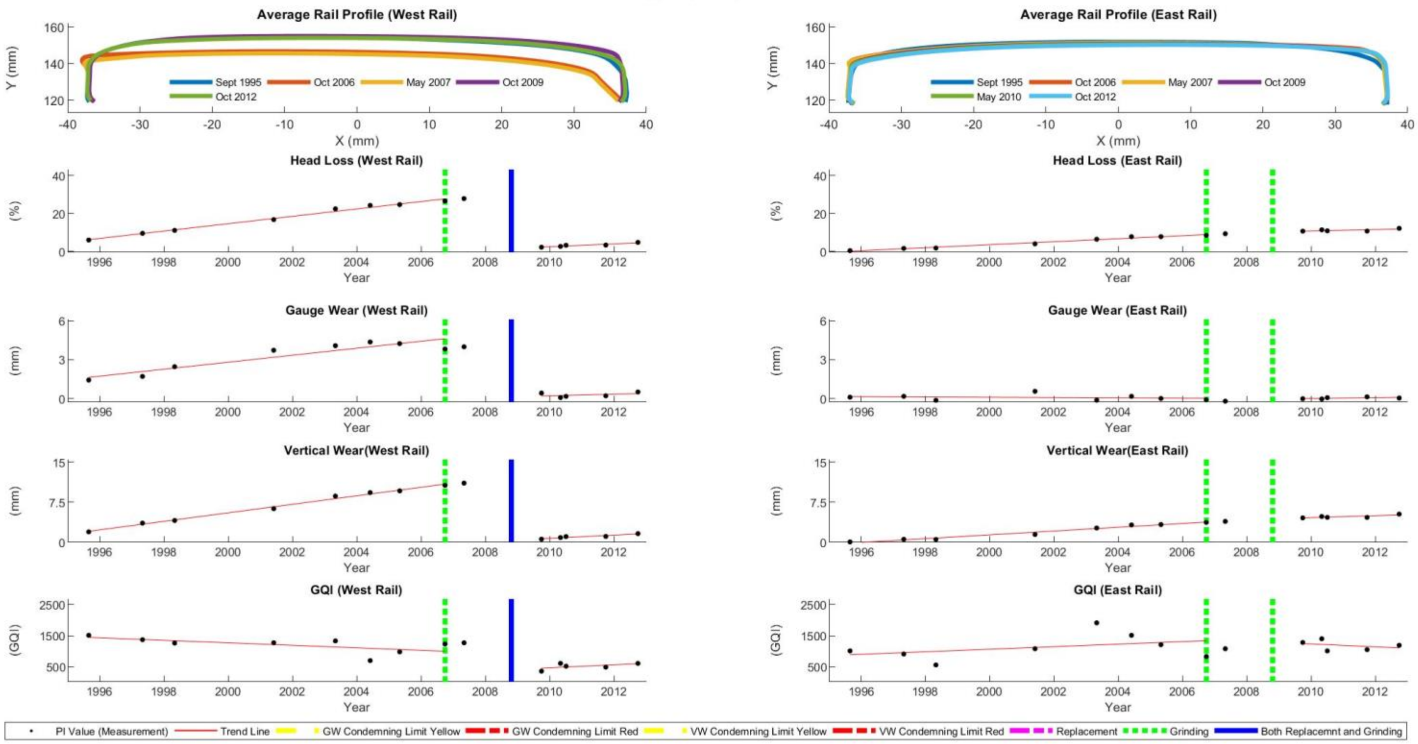
C#046BC (46.479 - 46.744) Degree: 5.9 (Right)
Rail Type (Both):136 RE



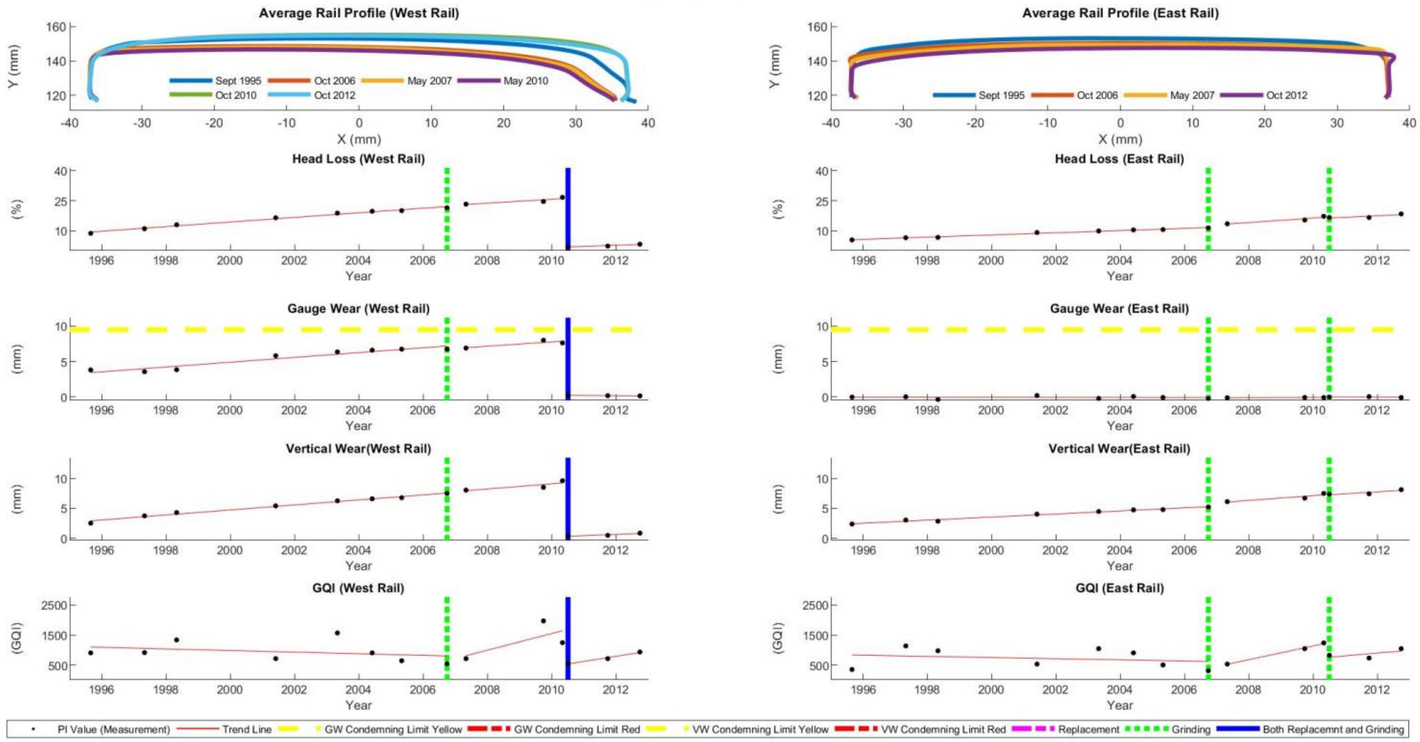
C#047AC (47.079 - 47.389) Degree: 5 (Left)
Rail Type (Both):136 RE



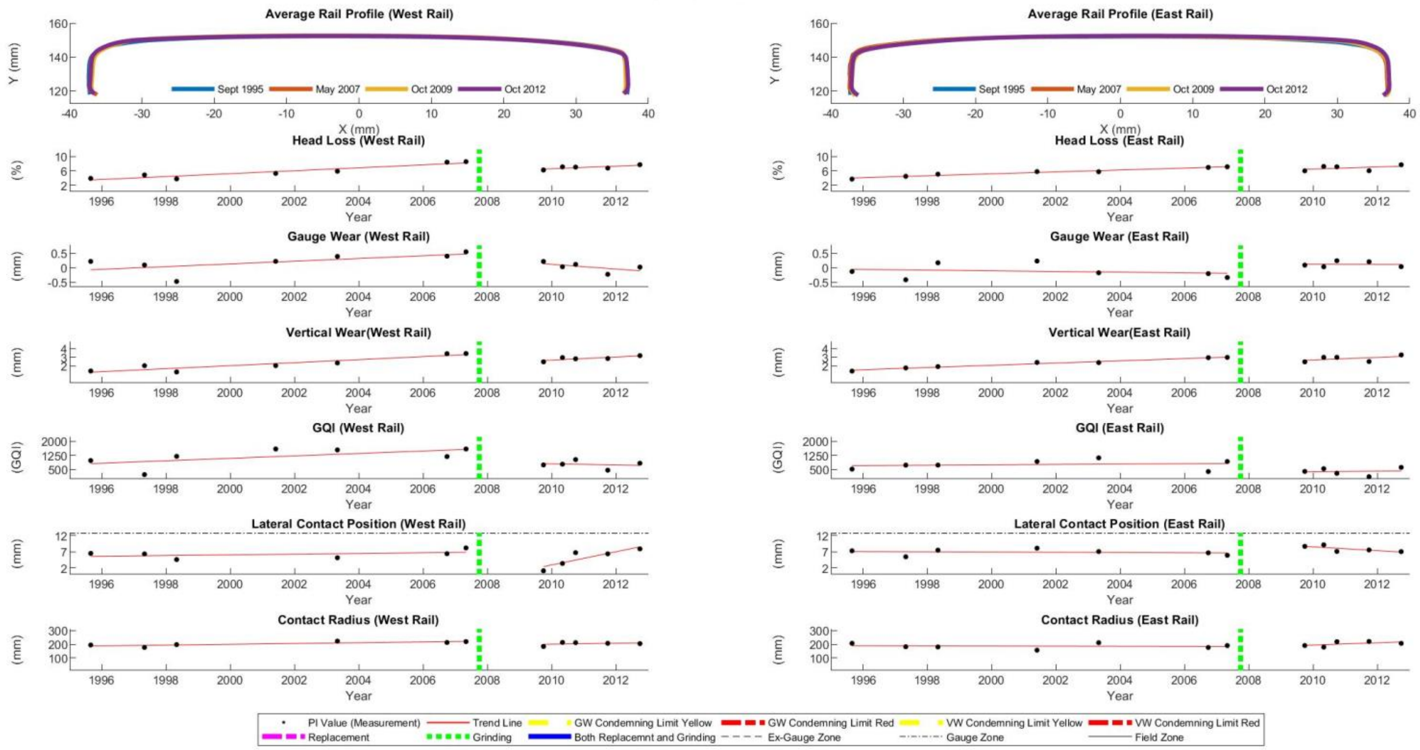
C#048C (47.589 - 48.062) Degree: 1 (Right)
Rail Type (Both):136 RE

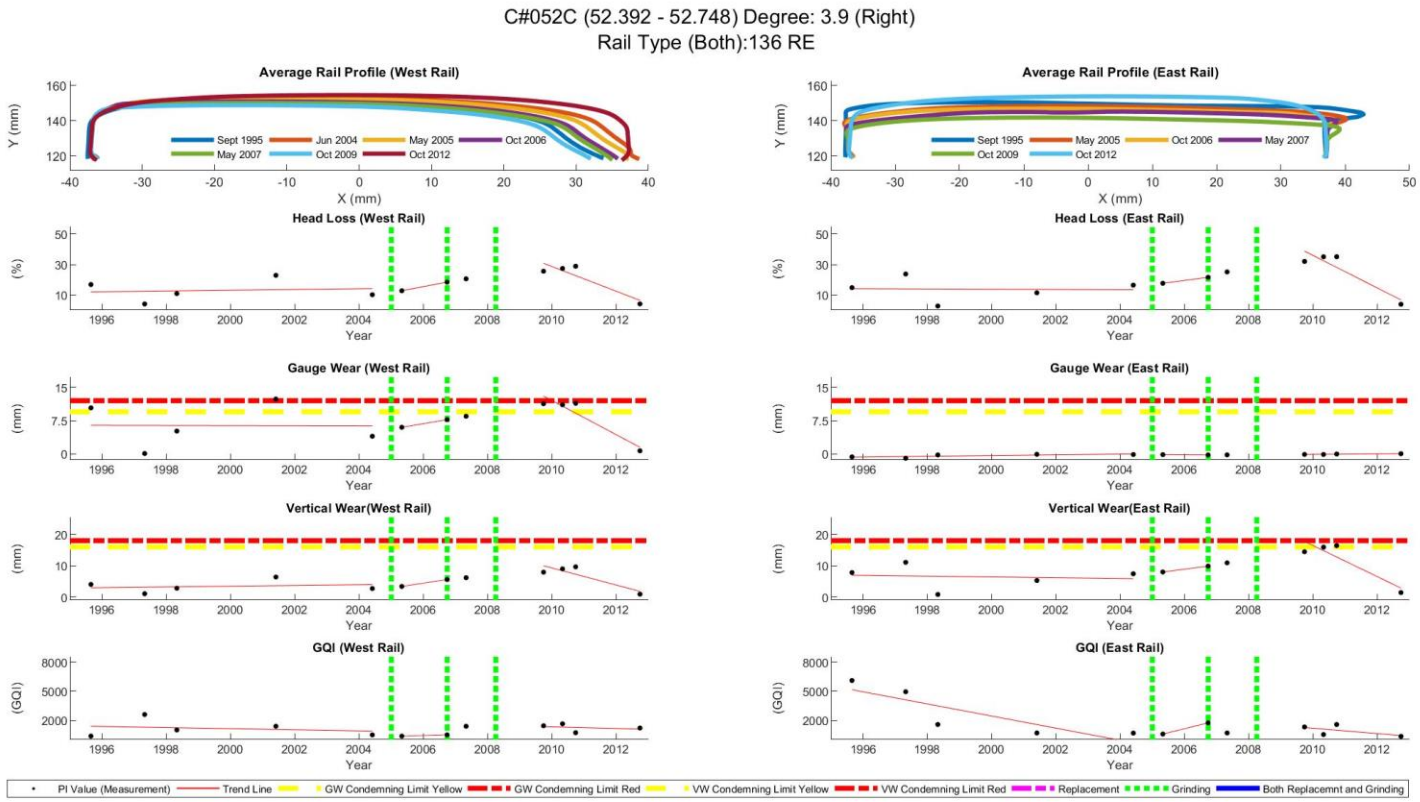


C#048BC (48.527 - 49.045) Degree: 1.7 (Right)
Rail Type (Both):136 RE

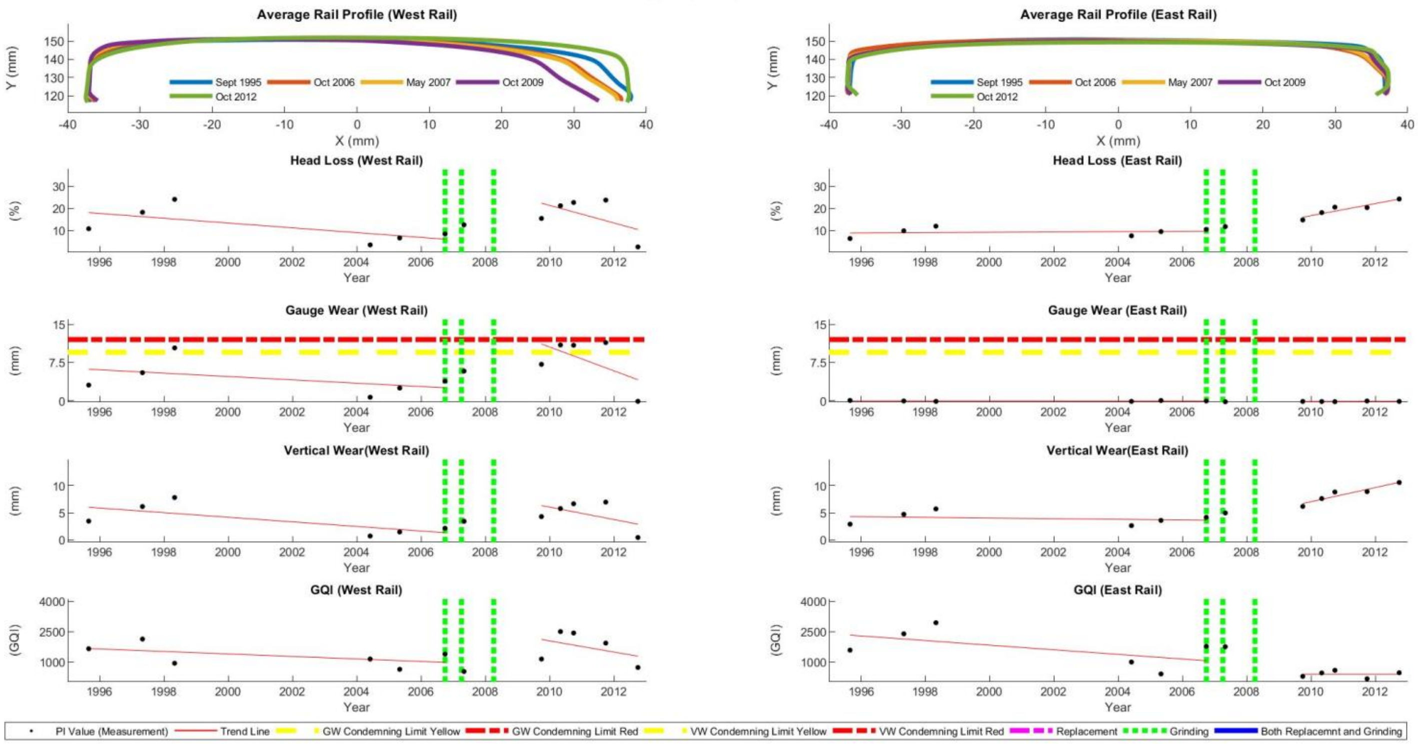


#048BT (49.041-49.172)
Rail Type (Both):136 RE

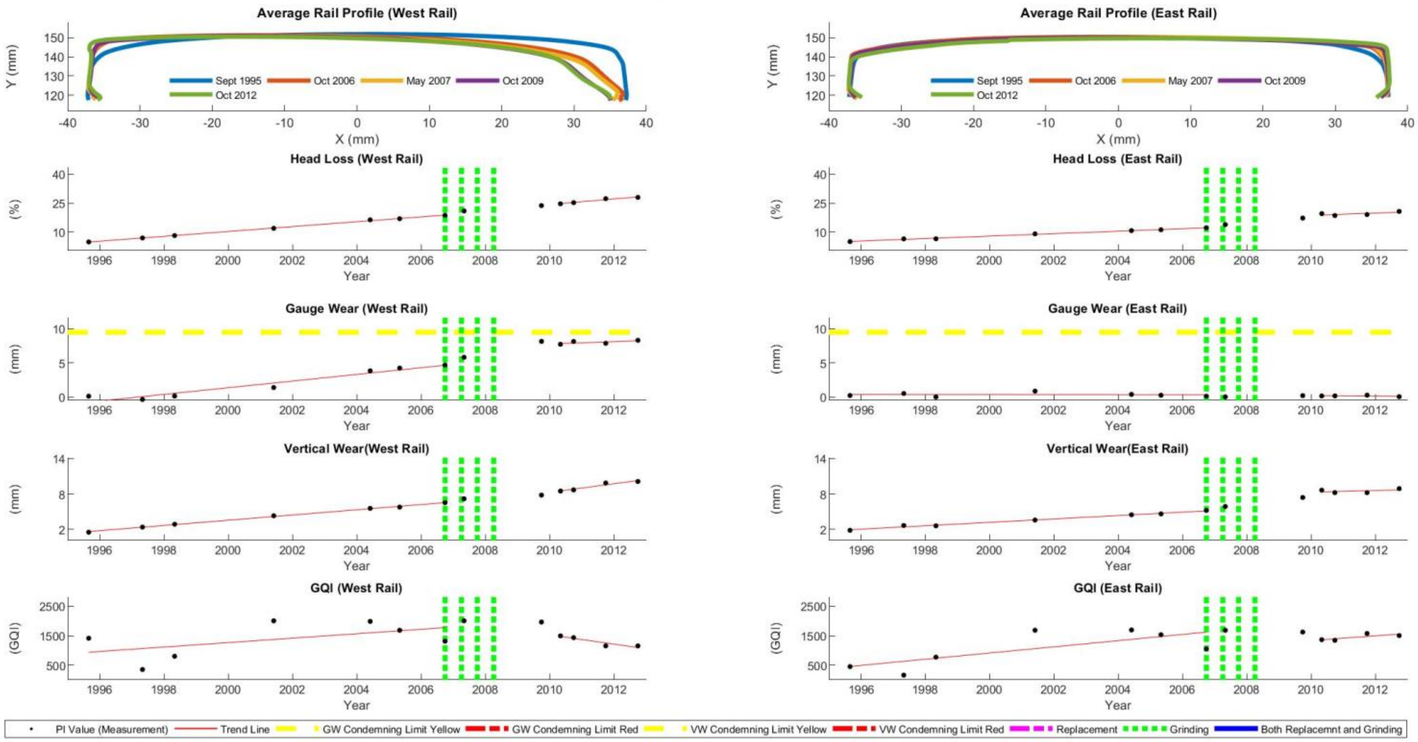



C#052C (52.392 - 52.748) Degree: 3.9 (Right)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Jun 2004
May 2005
Oct 2006
May 2007
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
(%)
Year
Gauge Wear (West Rail)
Gauge Wear (East Rail)
(mm)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
(GQI)
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

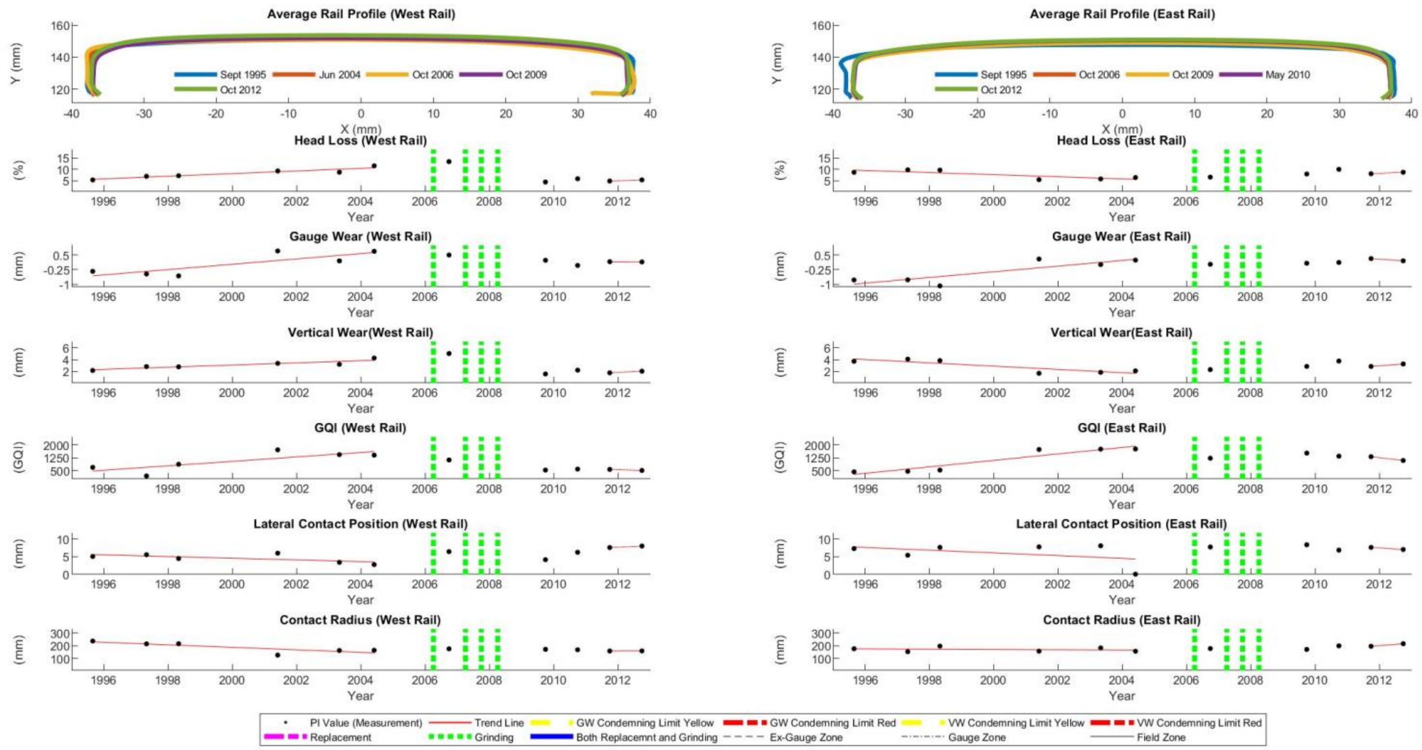
C#055BC (55.435 - 55.661) Degree: 3 (Right)
Rail Type (Both):136 RE



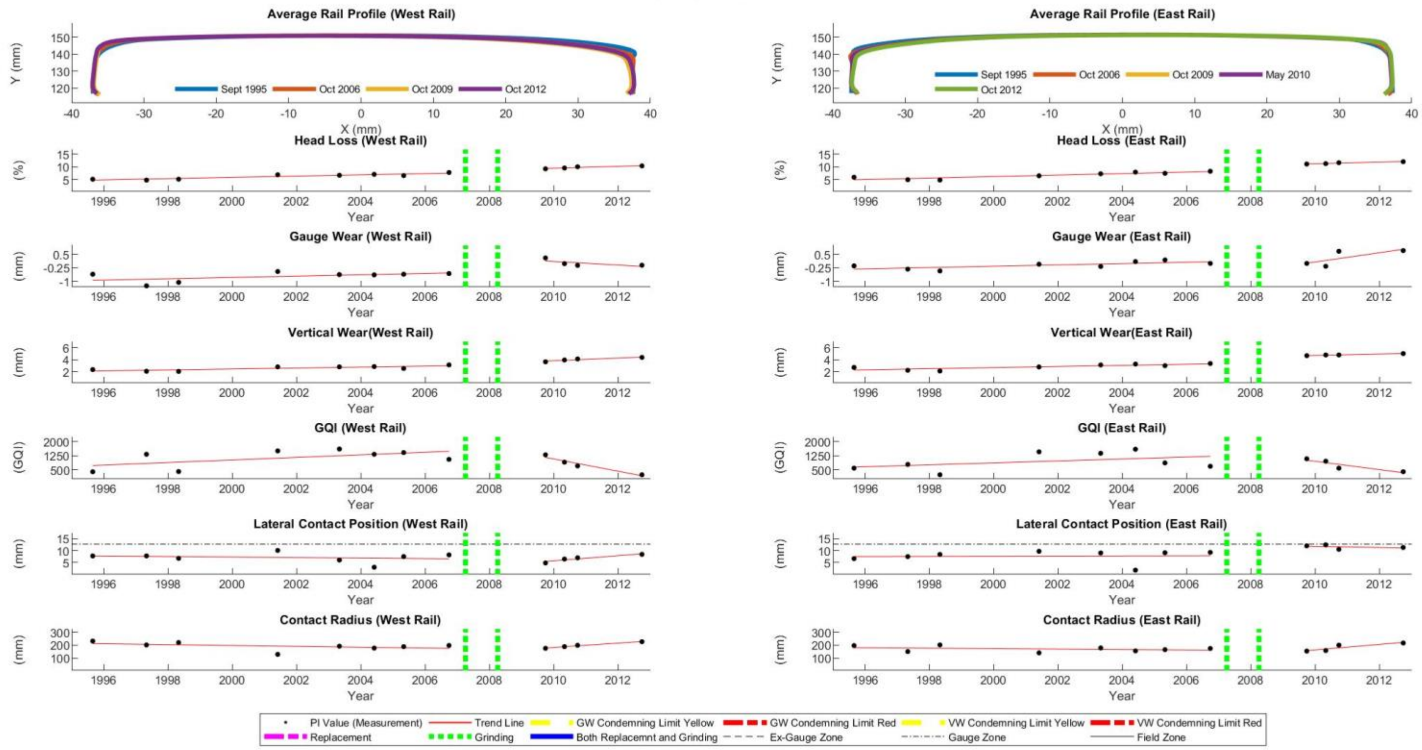
C#057AC (57.106 - 57.28) Degree: 2 (Right)
Rail Type (Both):136 RE



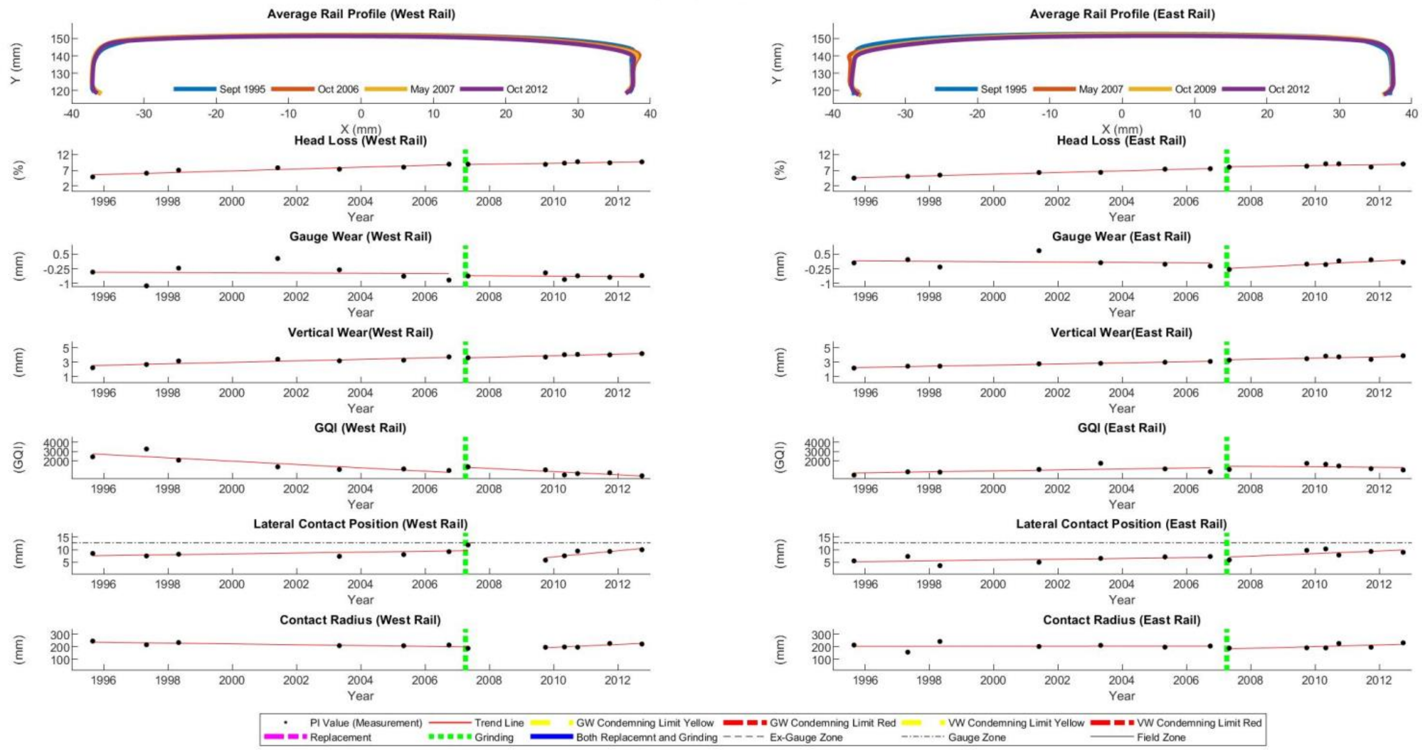
#057BT (57.48-57.982)
Rail Type (Both):136 RE



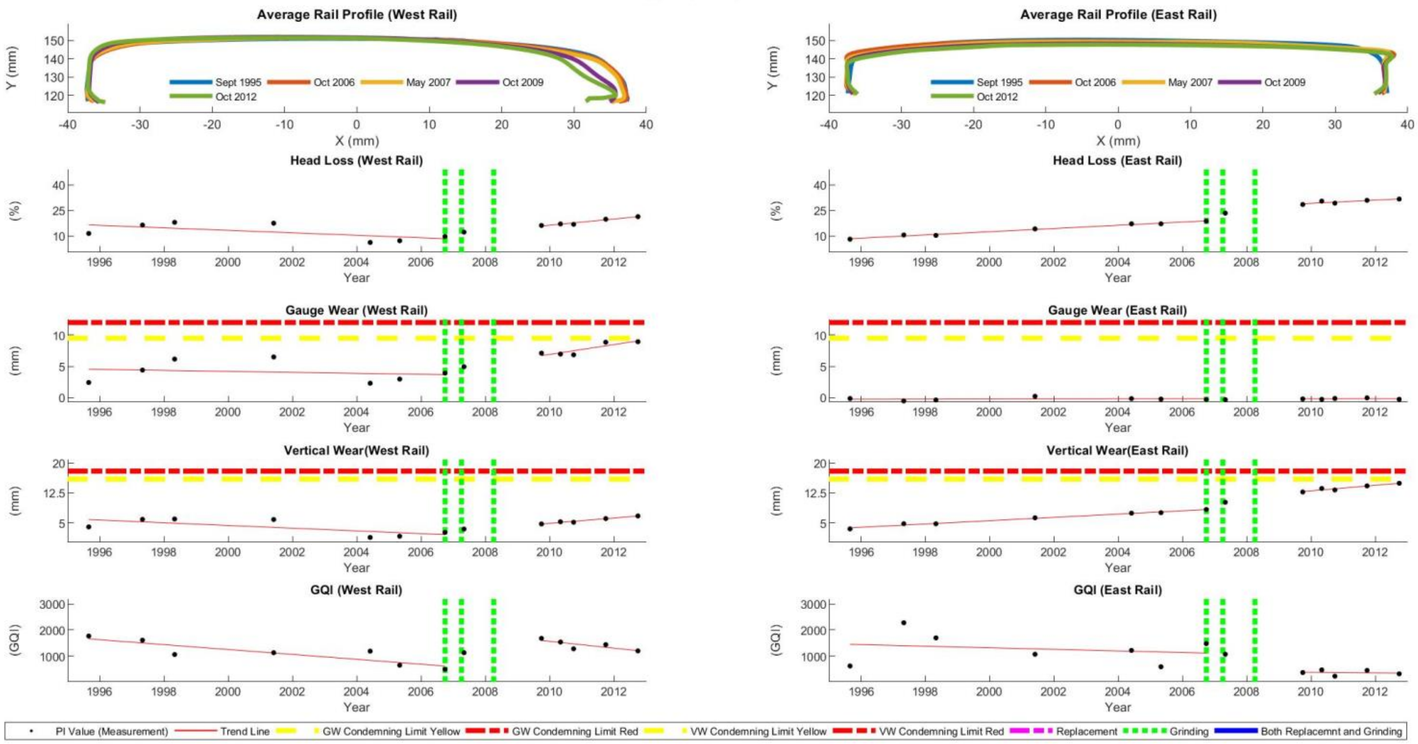
#060AT (60.283-60.45)
Rail Type (Both):136 RE



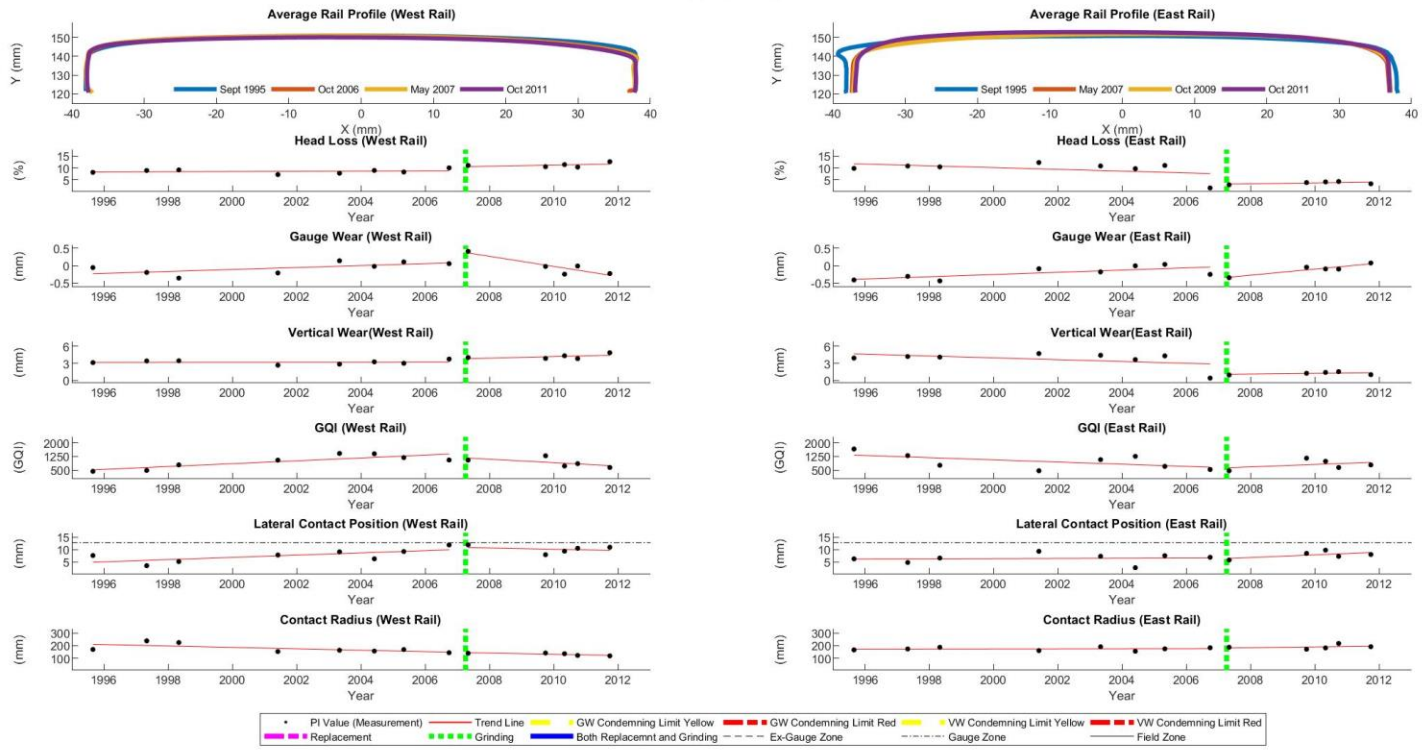
#061BT (61.64-62.024)
Rail Type (Both):136 RE



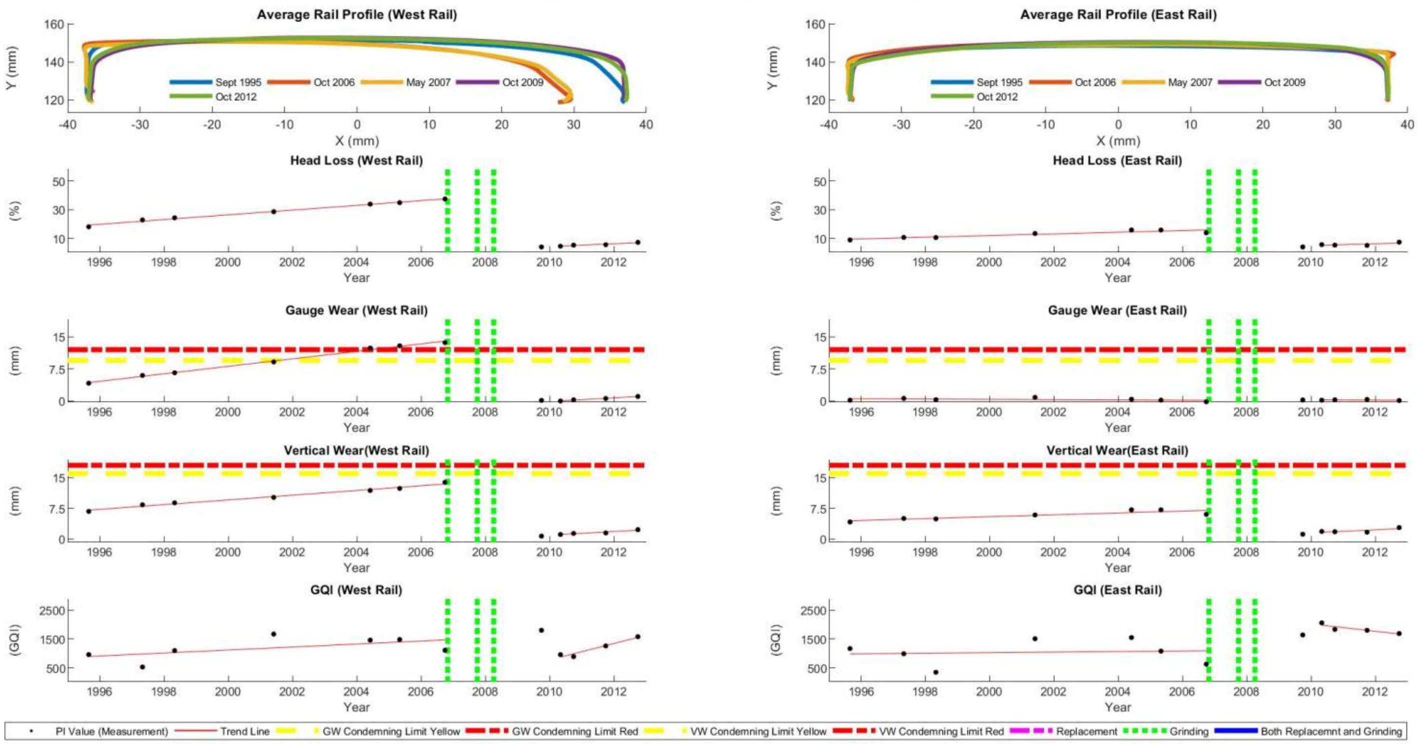
C#062C (62.011 - 62.237) Degree: 3.1 (Right)
Rail Type (Both):136 RE



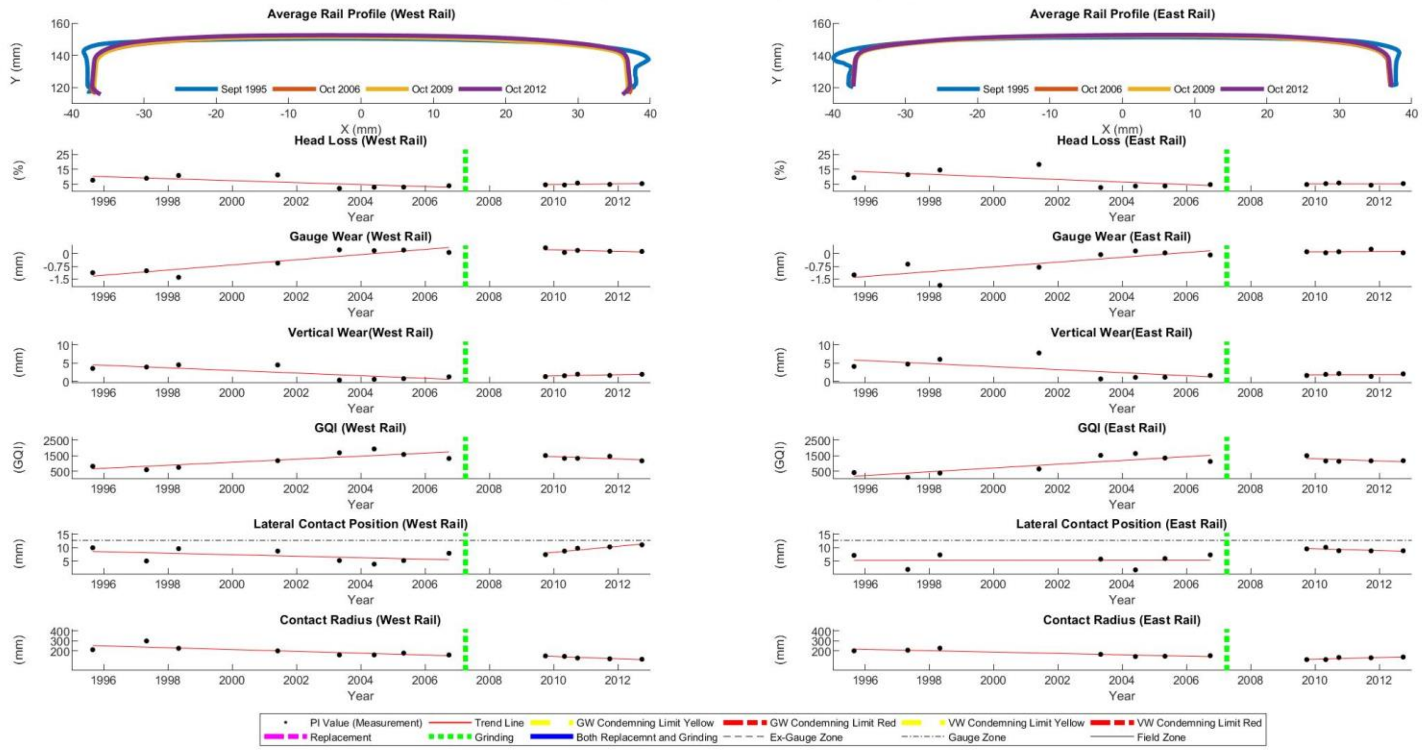
#067CT (67.99-68.186)
Rail Type (Both):



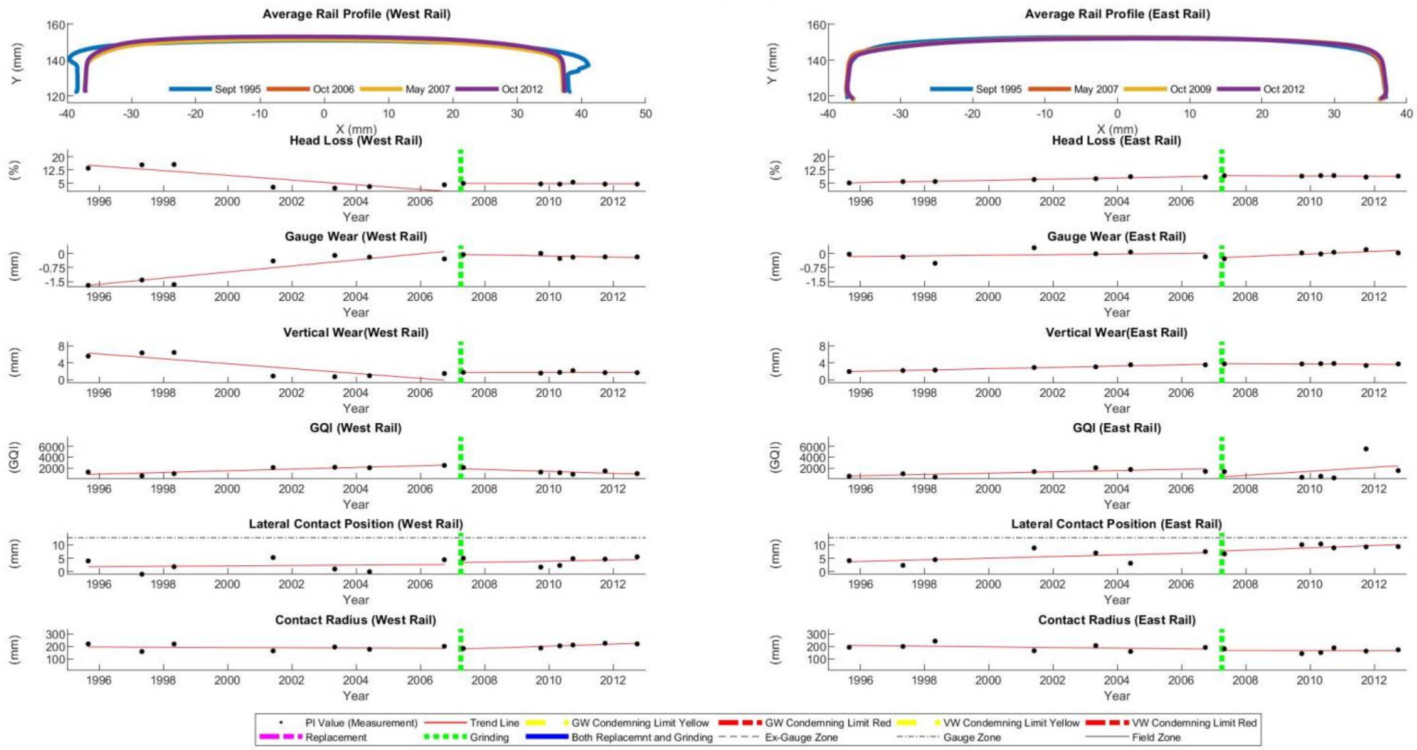
C#069C (68.948 - 69.164) Degree: 2.5 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)



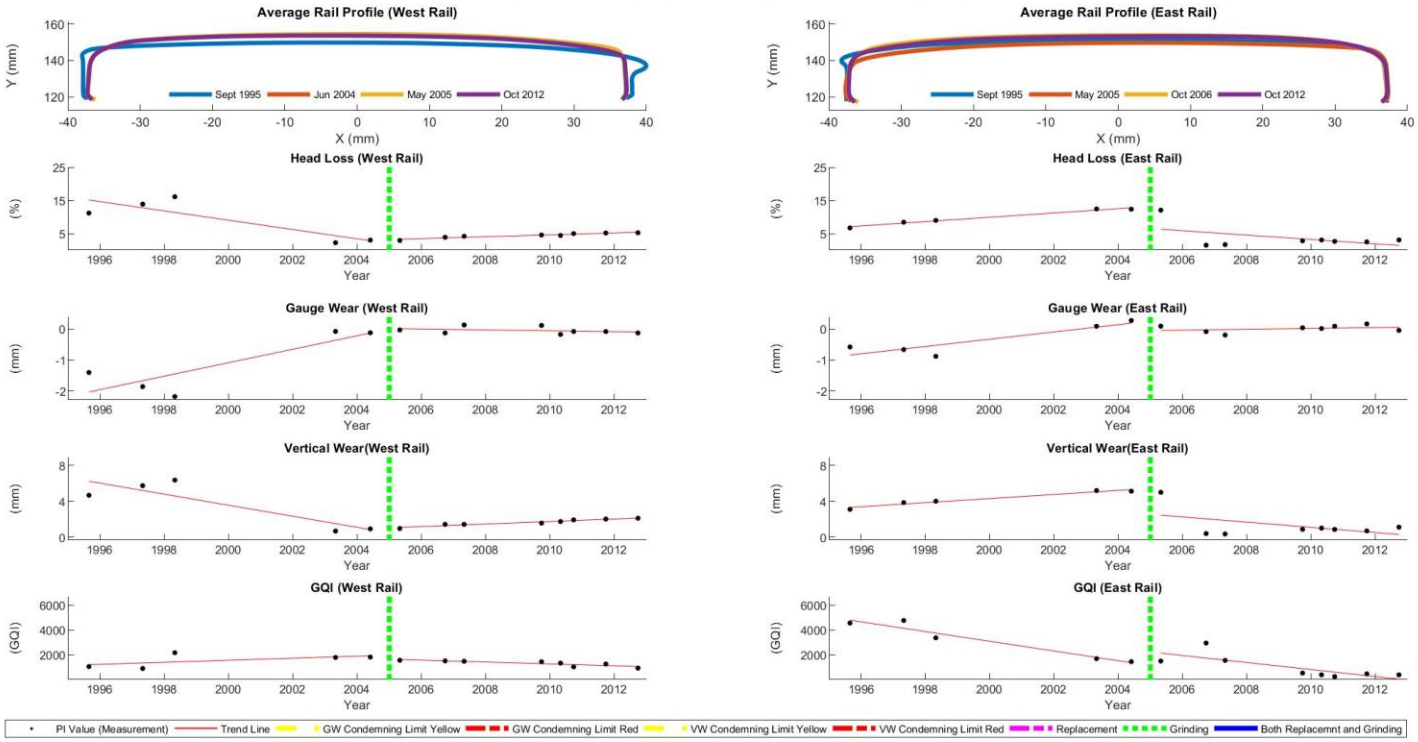
#070BT (70.353-70.568)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)



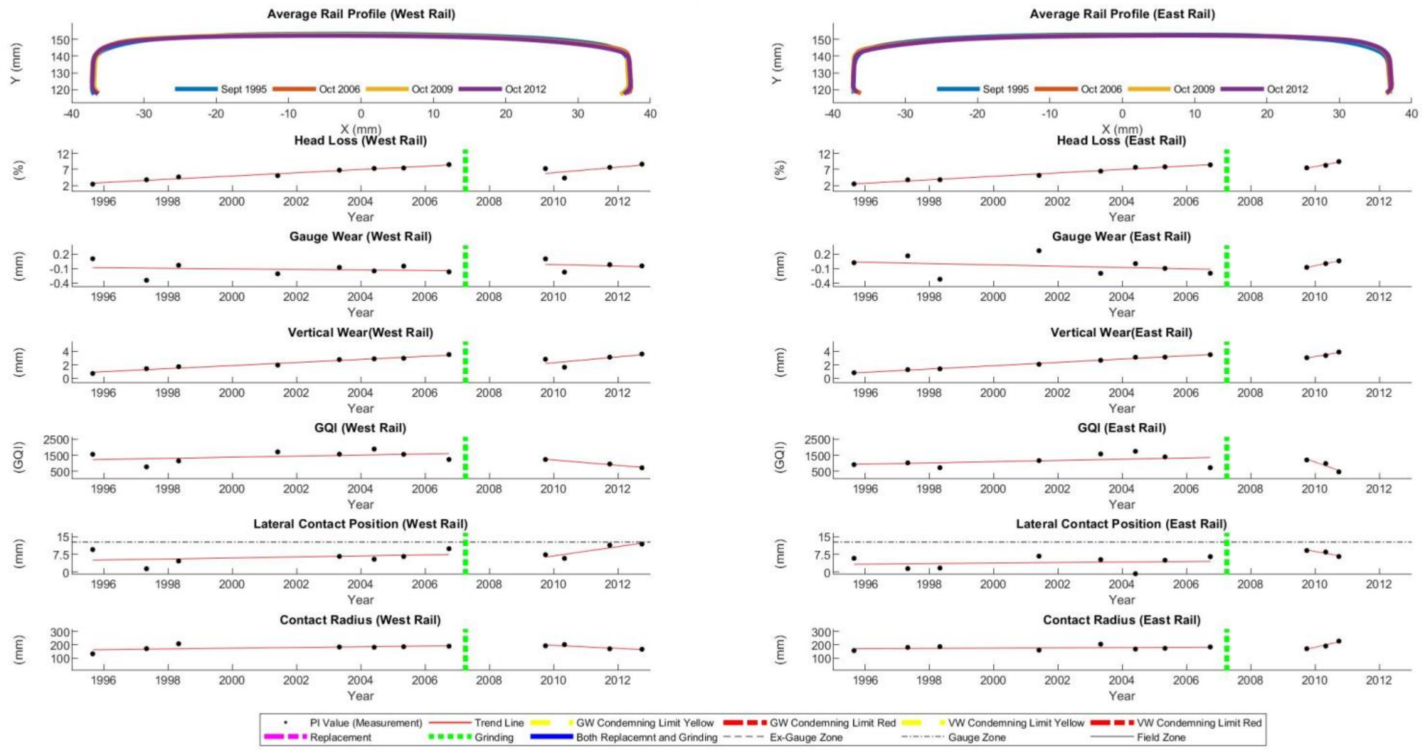
#075AT (75.543-75.801)
Rail Type (Both):

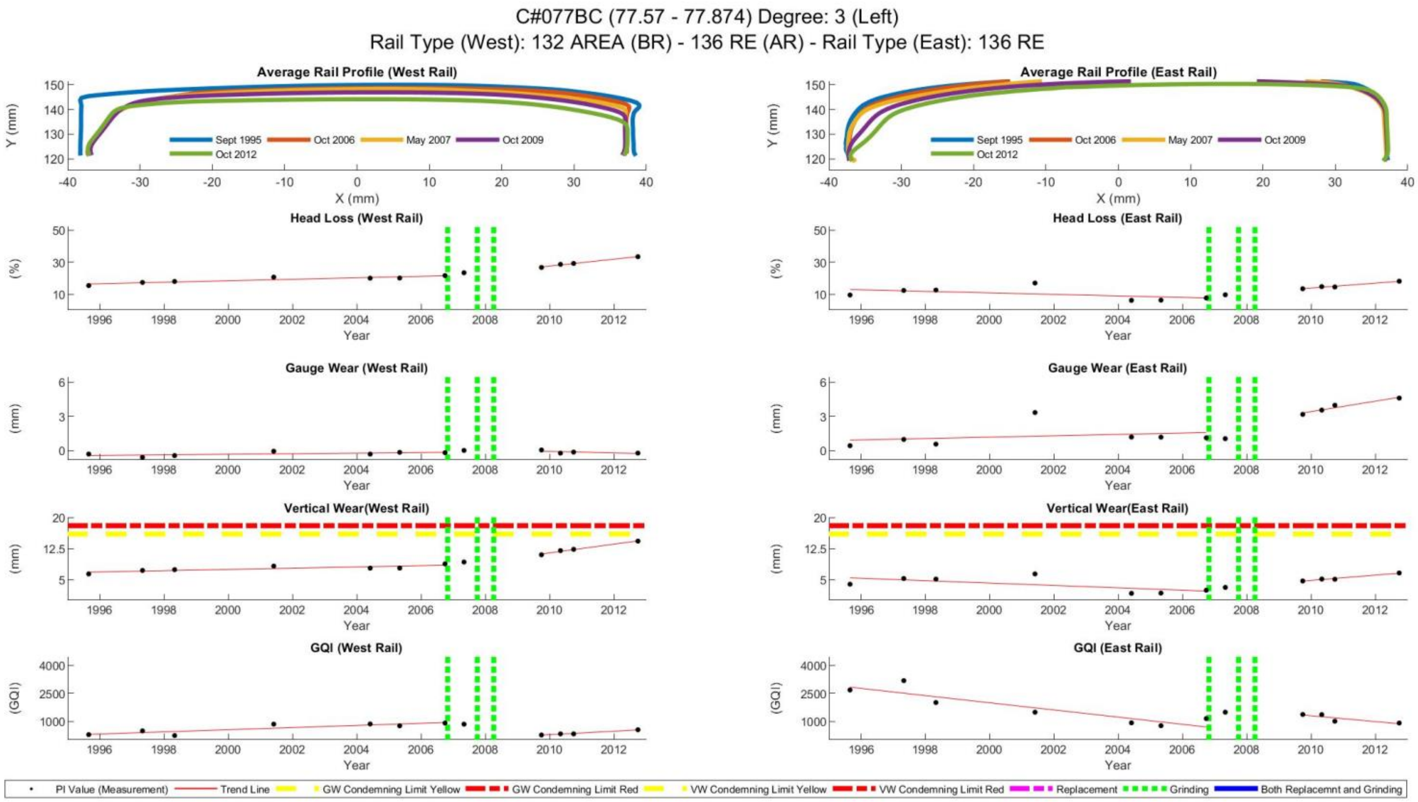


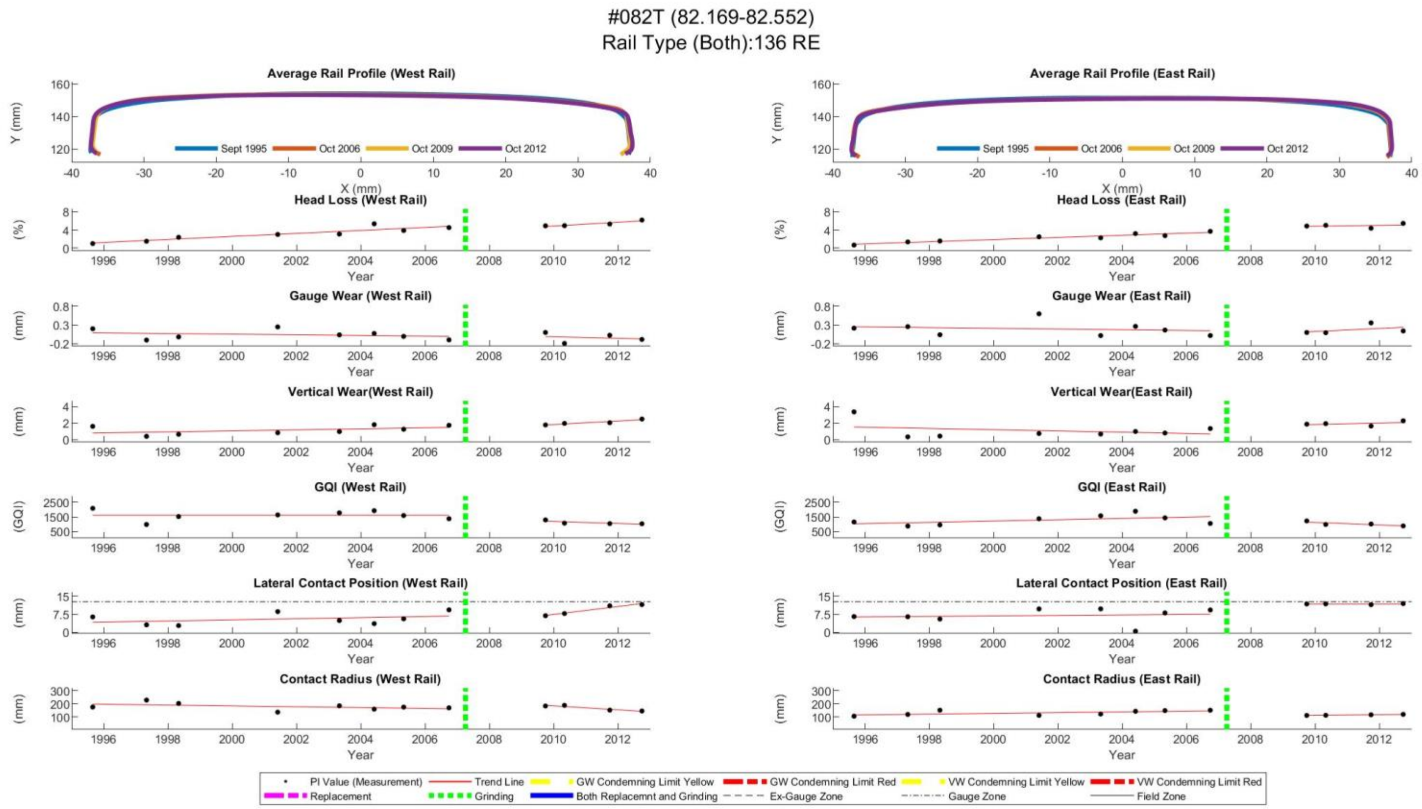
C#076C (75.821 - 76.208) Degree: 0.5 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE



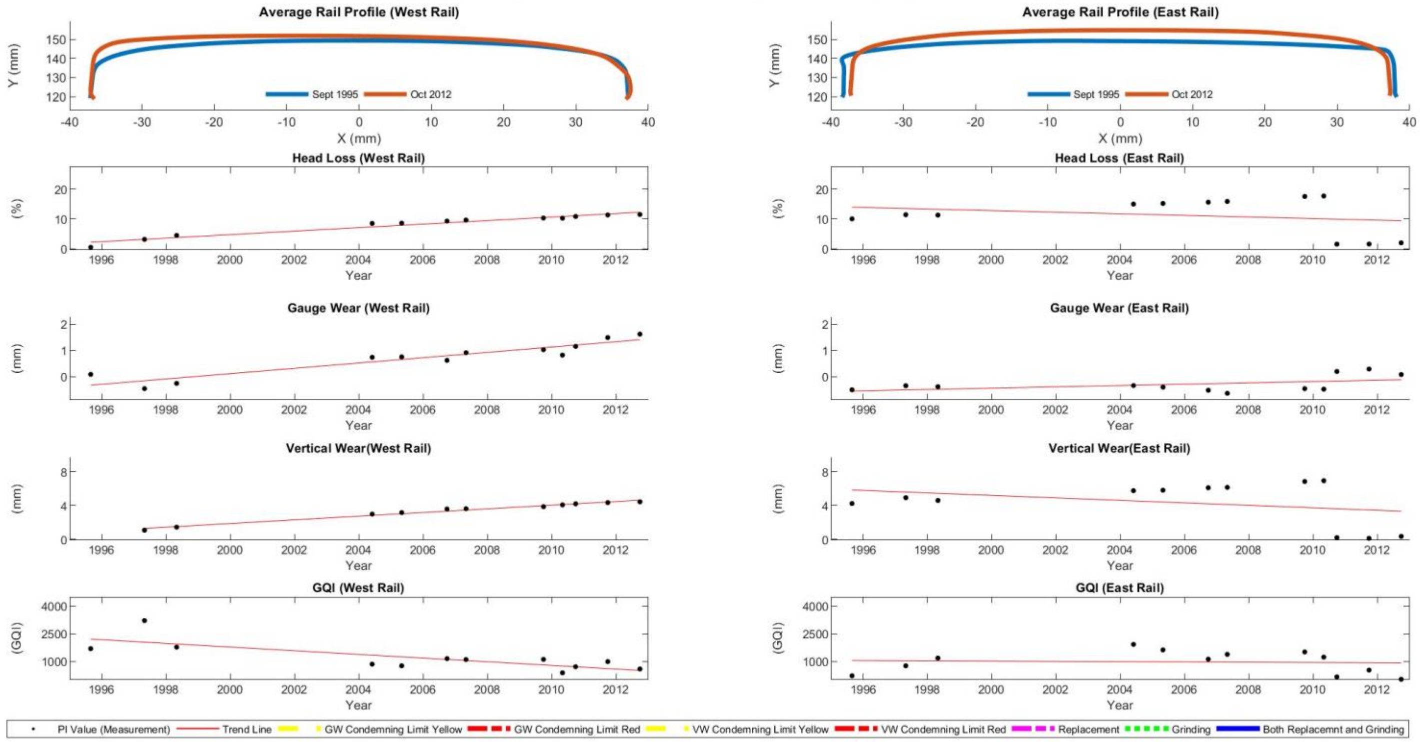
#077AT (77.261-77.569)
Rail Type (Both):136 RE



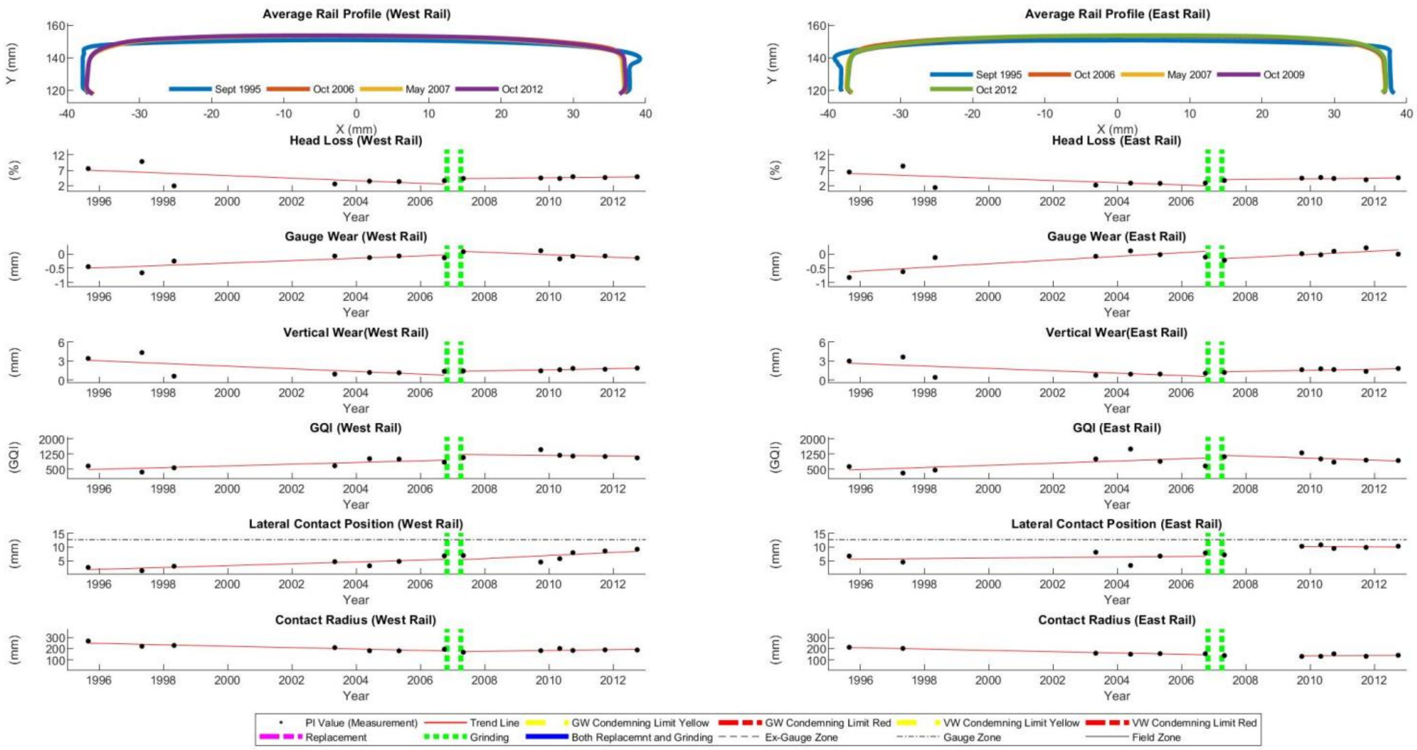

C#077BC (77.57 - 77.874) Degree: 3 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Oct 2006
May 2007
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding


#082T (82.169-82.552)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Oct 2006
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Lateral Contact Position (West Rail)
Lateral Contact Position (East Rail)
Contact Radius (West Rail)
Contact Radius (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding
Ex-Gauge Zone
Gauge Zone
Field Zone

C#082AC (82.532 - 82.814) Degree: 1 (Right)
Rail Type (West): 136 RE - Rail Type (East): 132 AREA (BR) - 136 RE (AR)

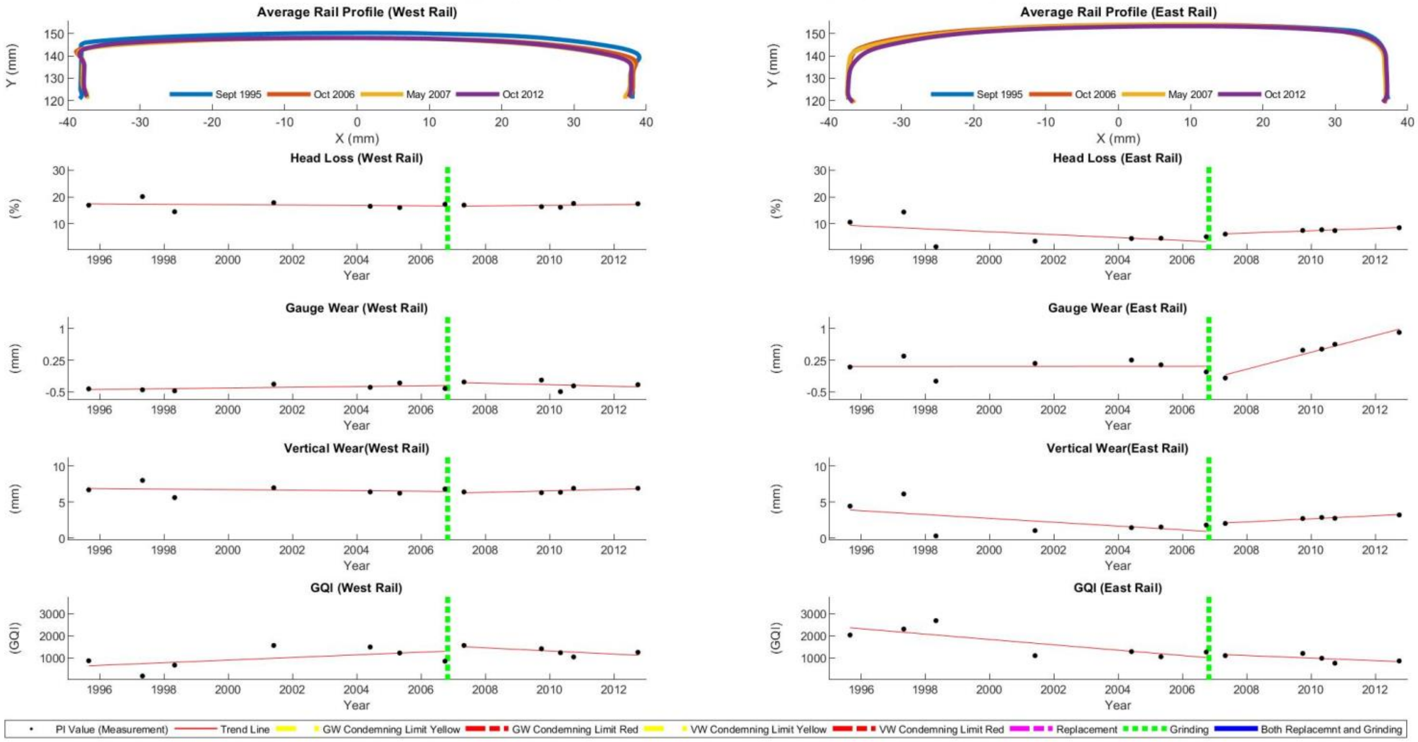


#083T (83.496-83.959)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)

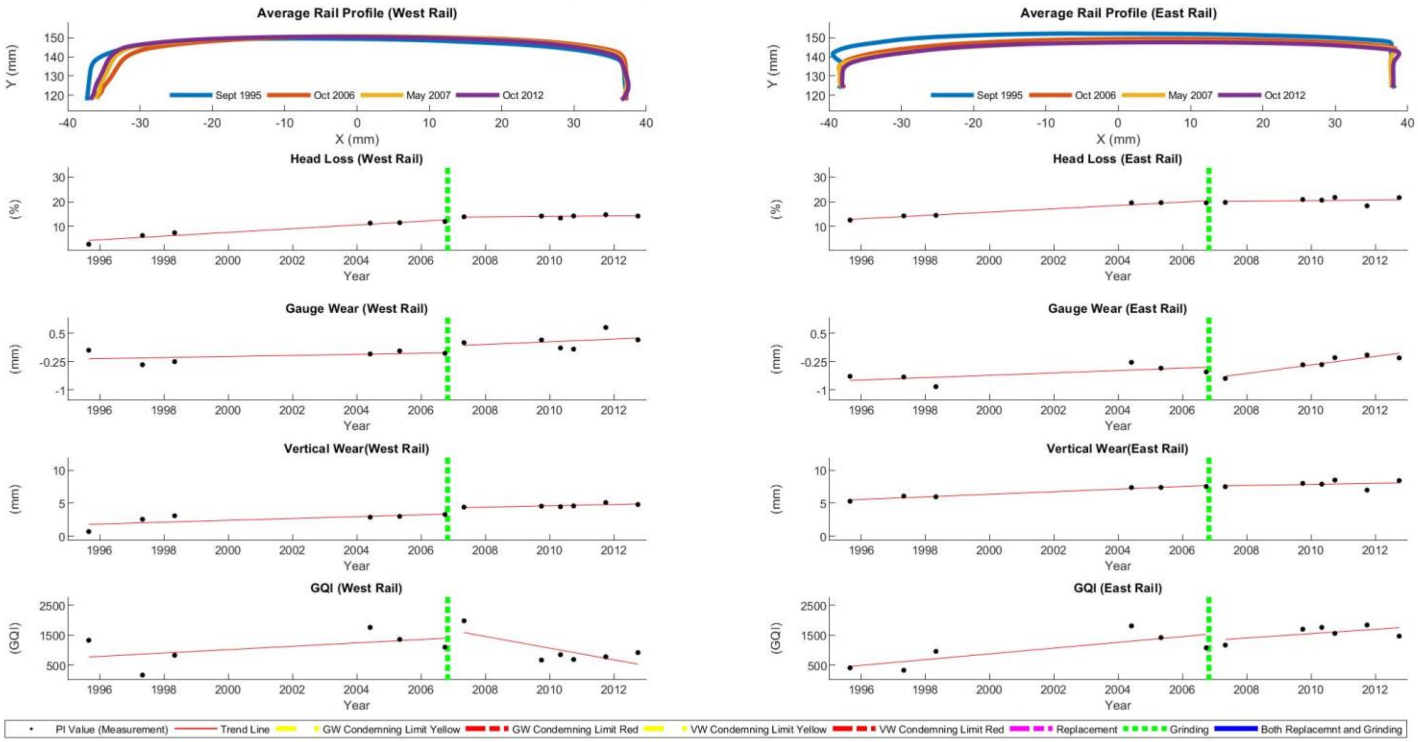


C#084C (83.941 - 84.177) Degree: 1.3 (Left)

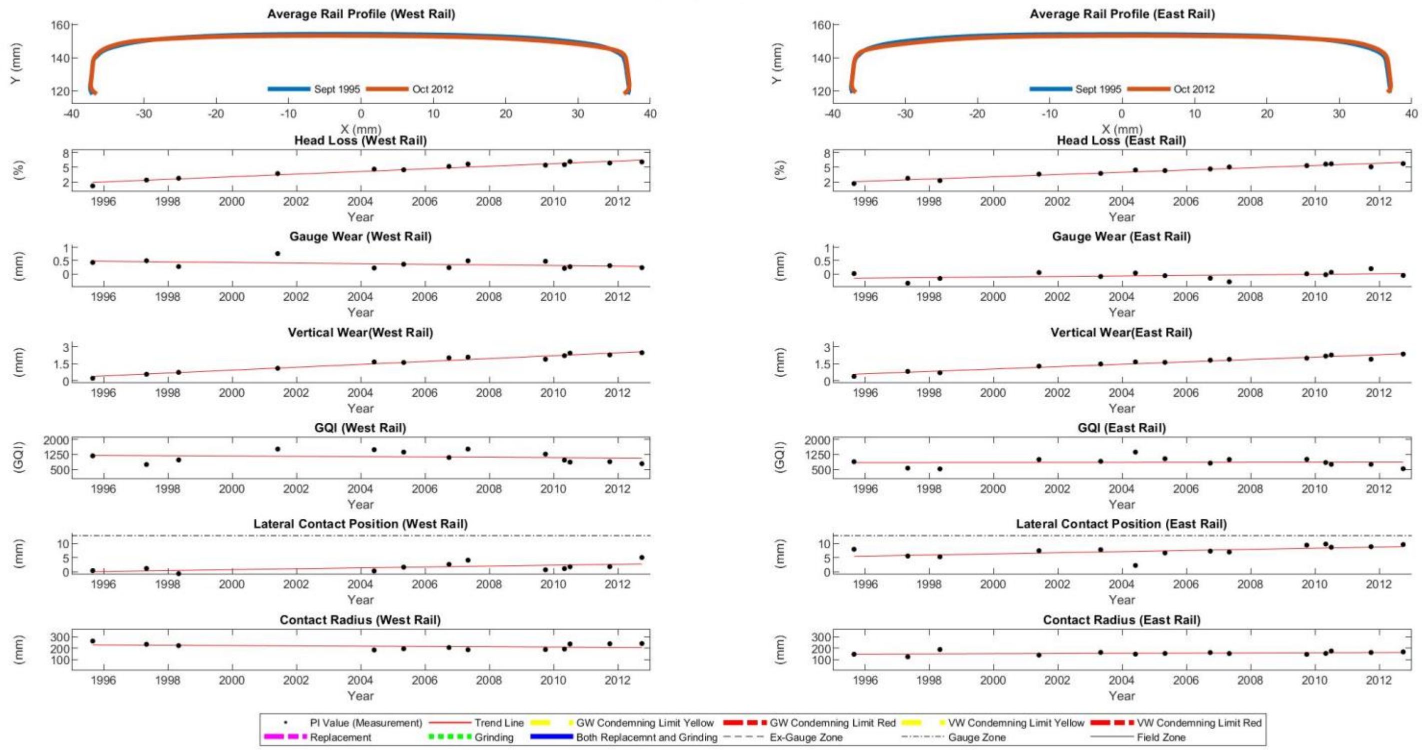
Rail Type (Both):Both 132 AREA and 136 RE (BR) -136 RE (AR)



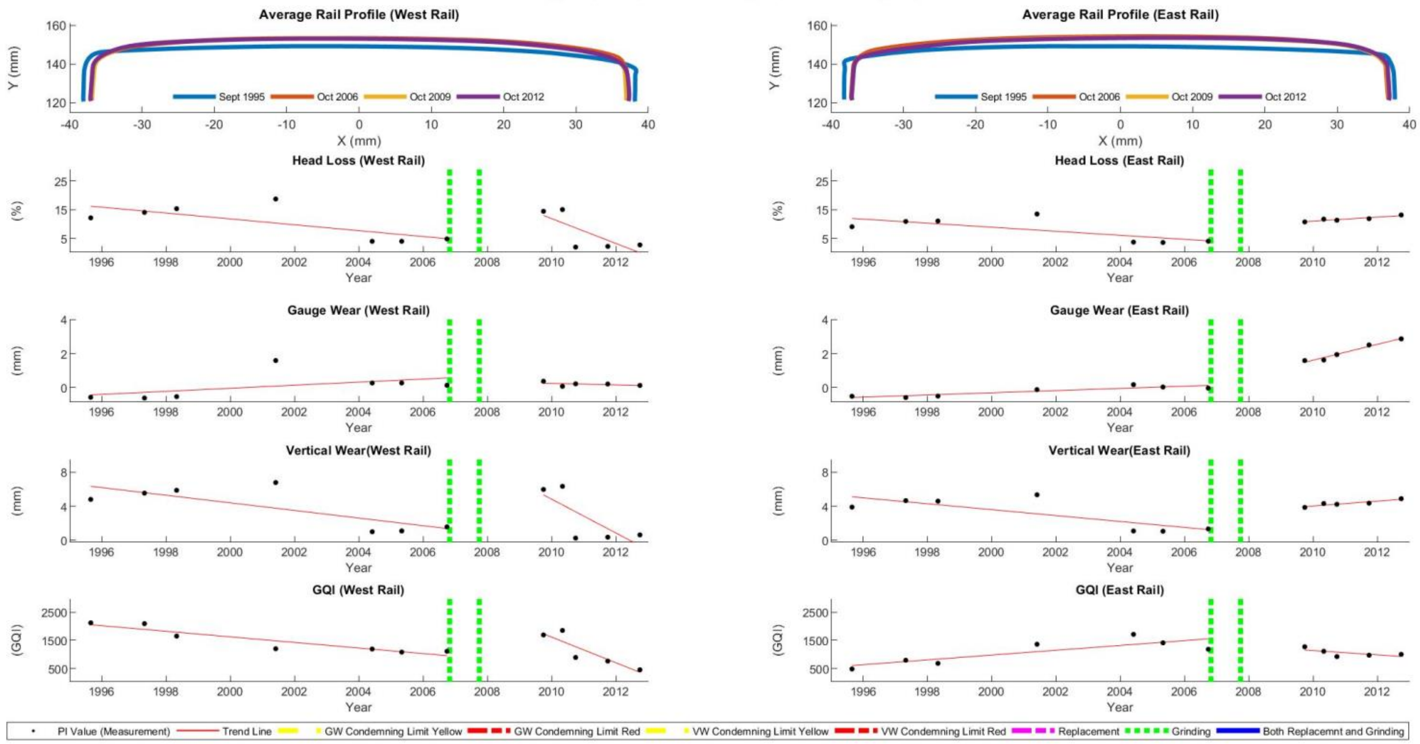
C#085CC (85.707 - 85.906) Degree: 1 (Right)
Rail Type (Both):Both 132 AREA and 136 RE



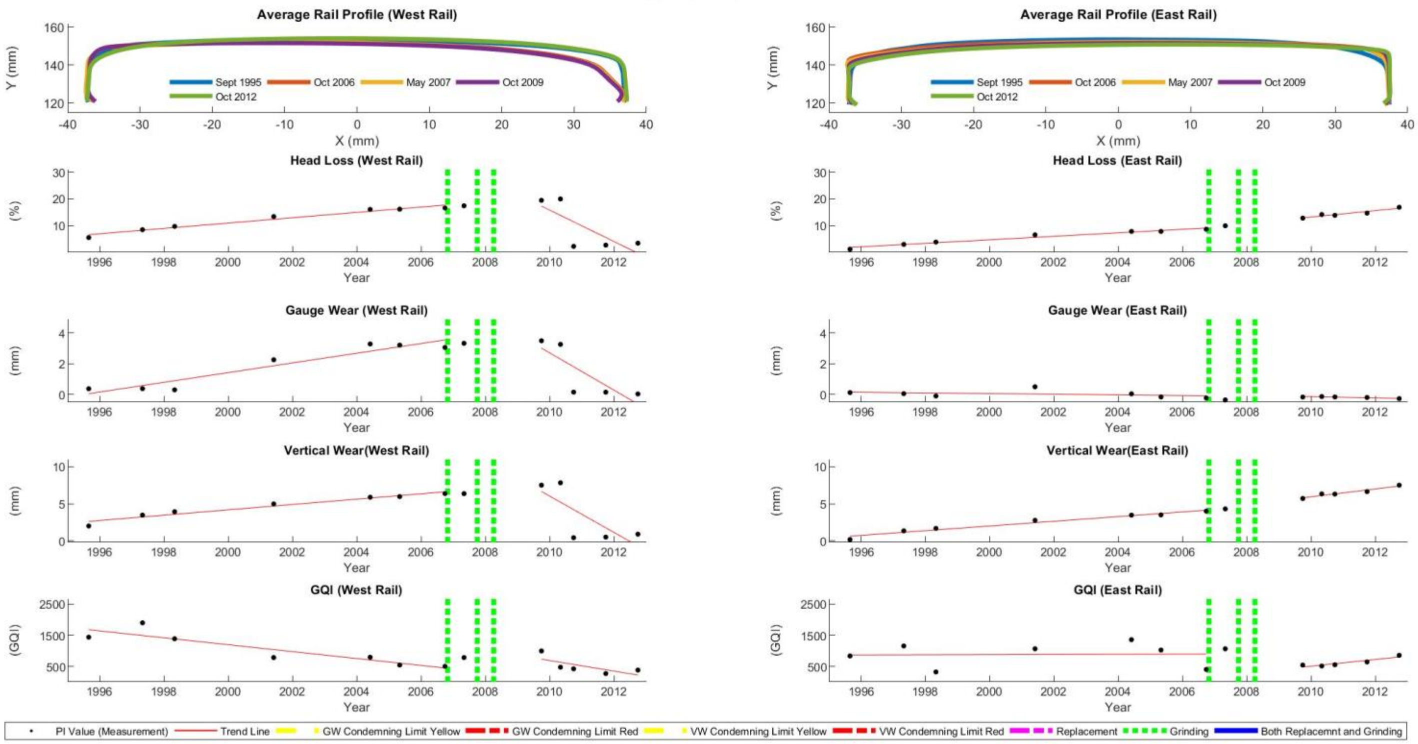
#088T (88.033-88.386)
Rail Type (Both):136 RE



C#090C (89.952 - 90.191) Degree: 0.9 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)

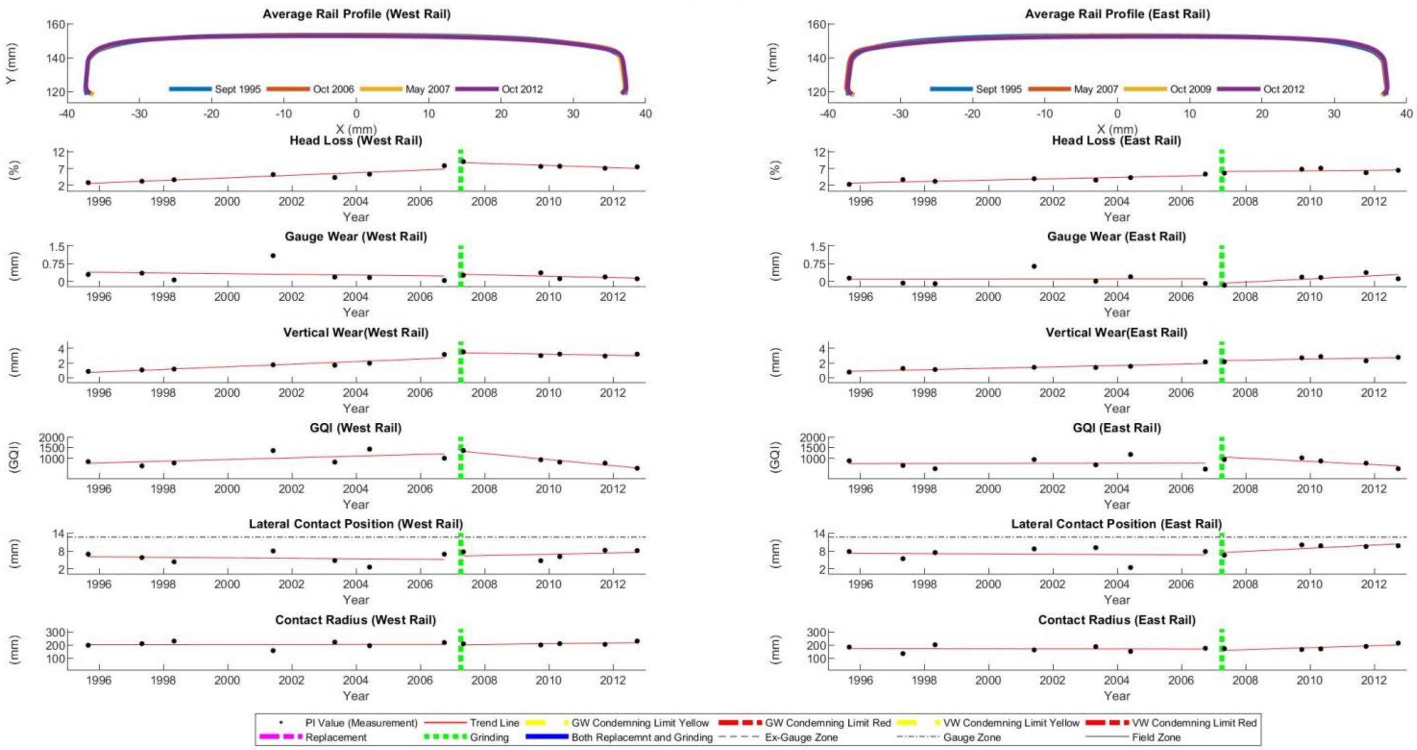


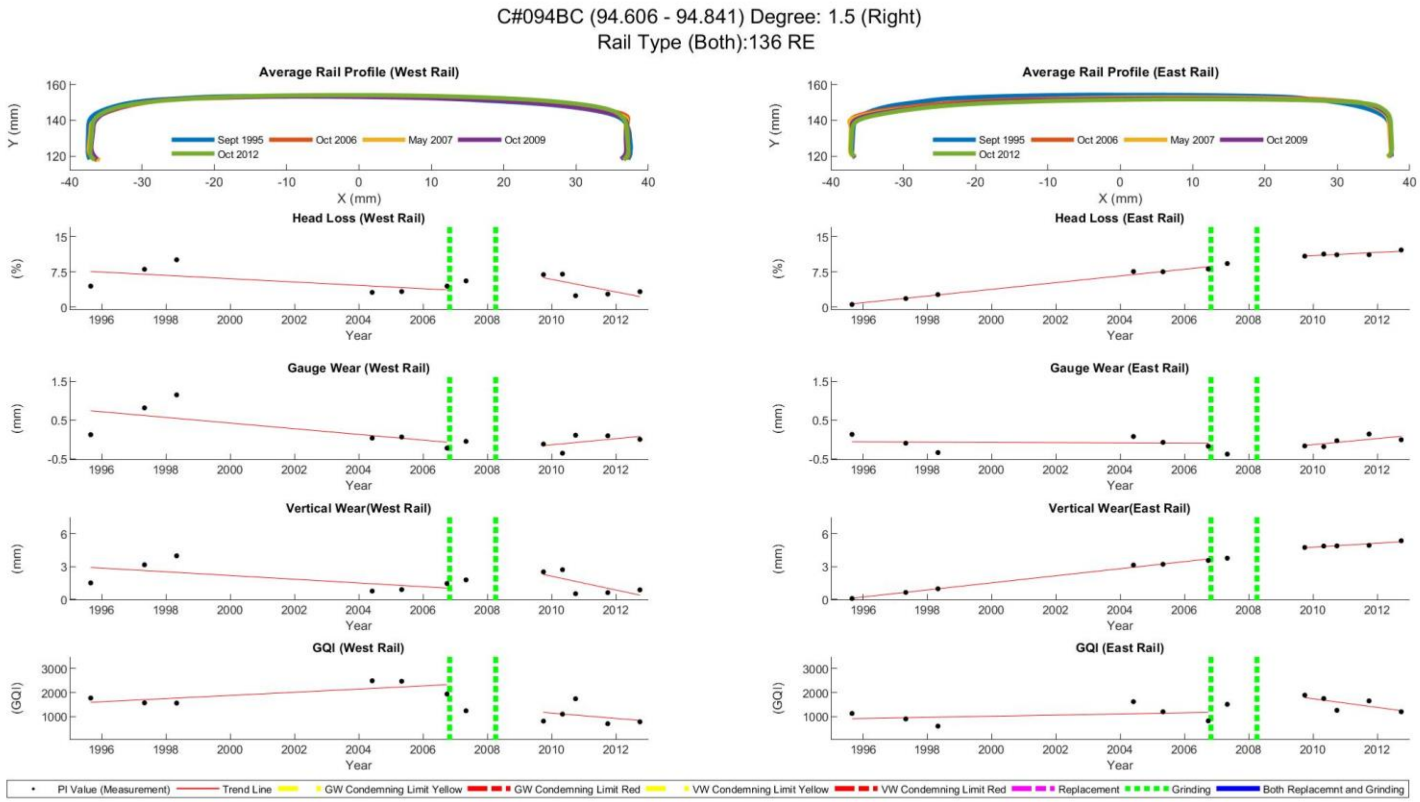
C#093C (92.758 - 93.053) Degree: 2 (Right)
Rail Type (Both):136 RE



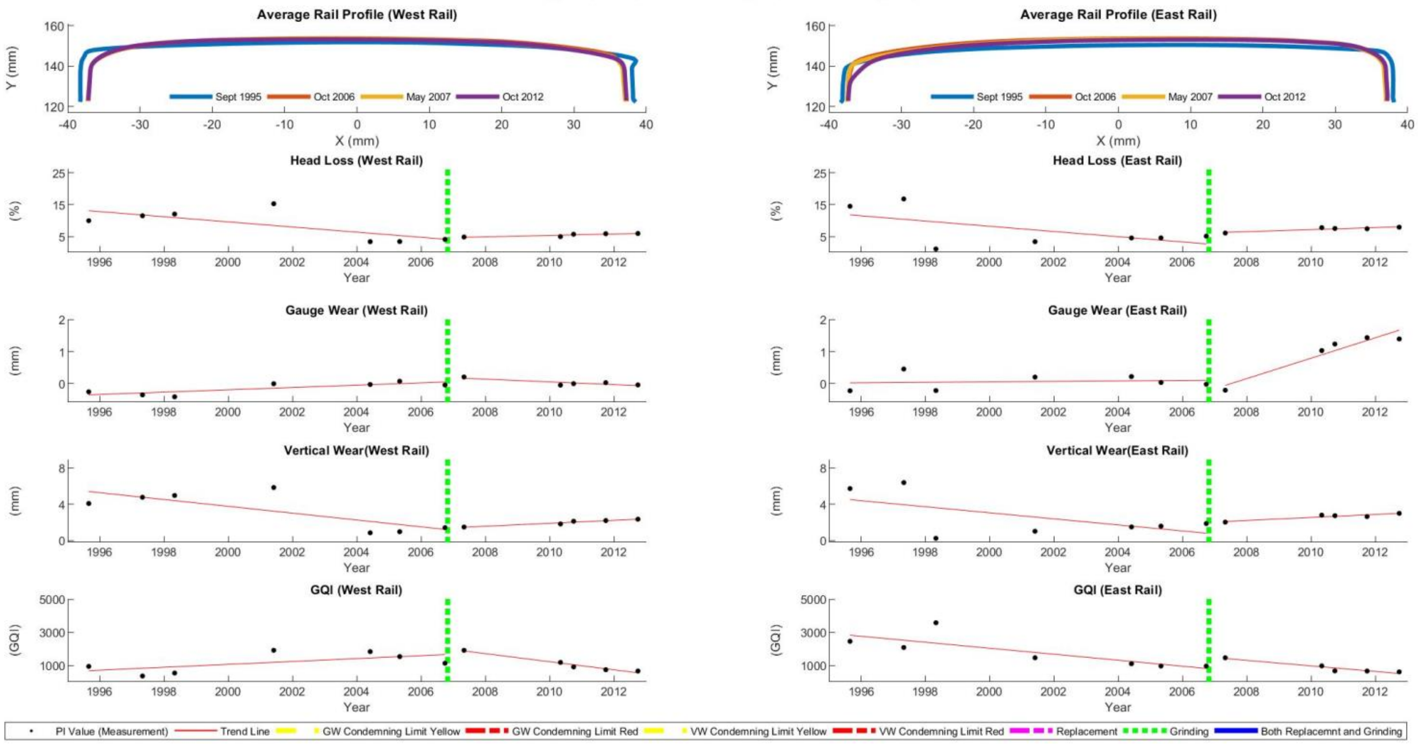
#094AT (94.3-94.628)

Rail Type (Both):136 RE

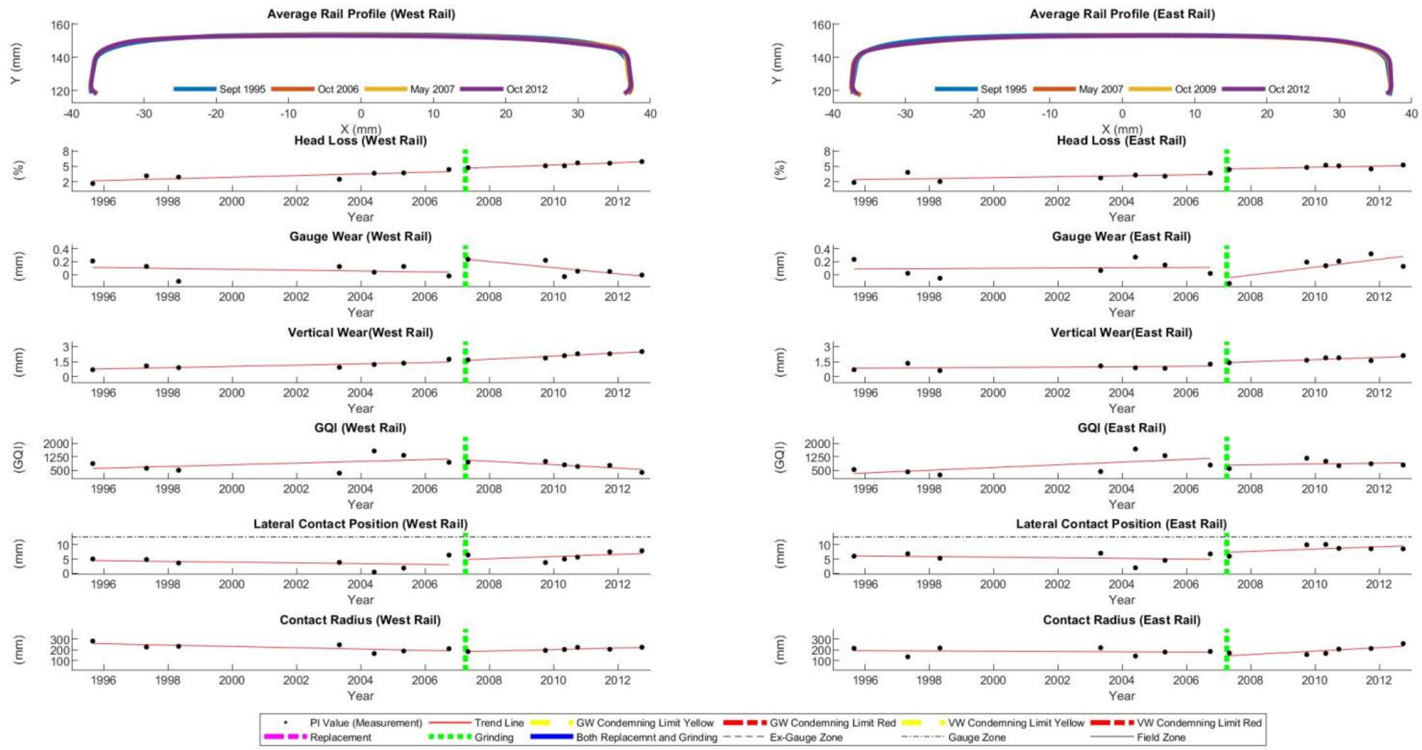



C#094BC (94.606 - 94.841) Degree: 1.5 (Right)
Rail Type (Both):136 RE
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Oct 2006
May 2007
Oct 2009
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

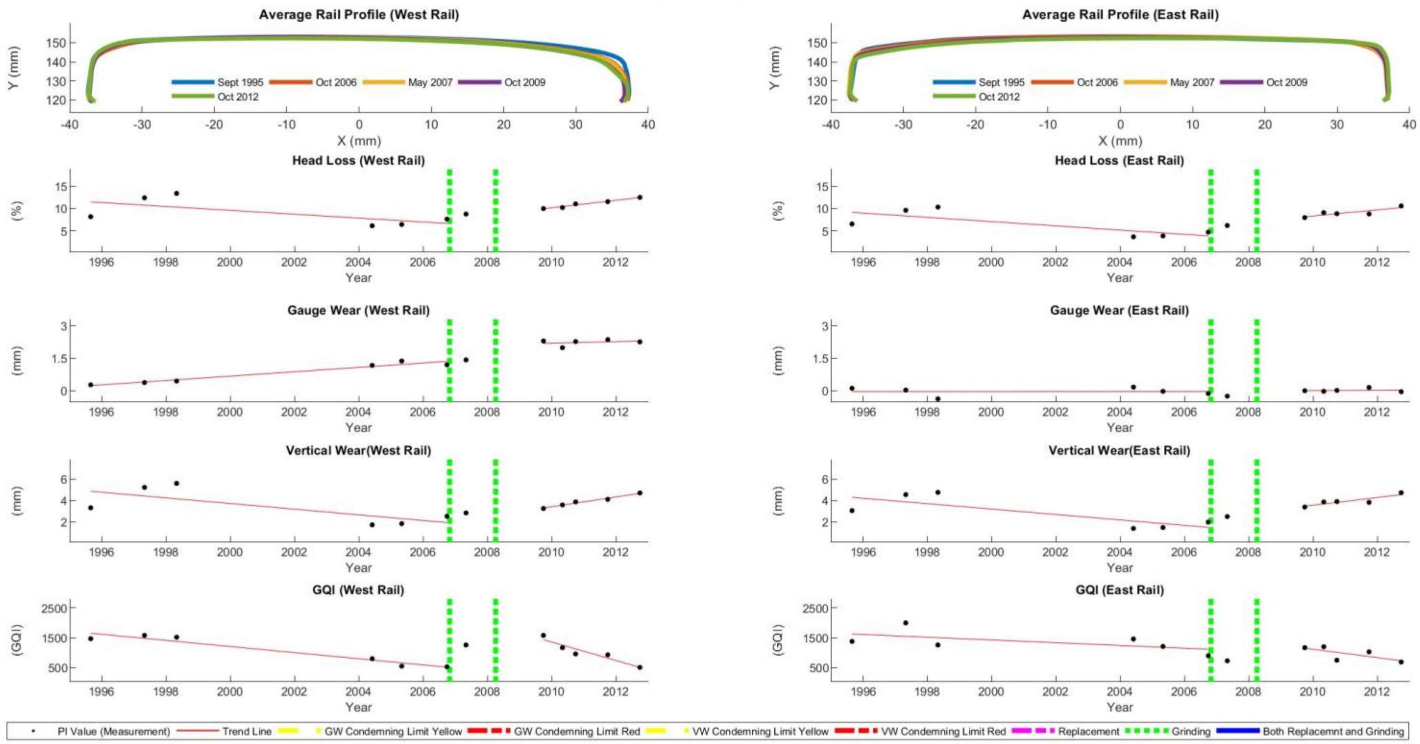
C#096C (96.315 - 96.575) Degree: 1.3 (Left)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)

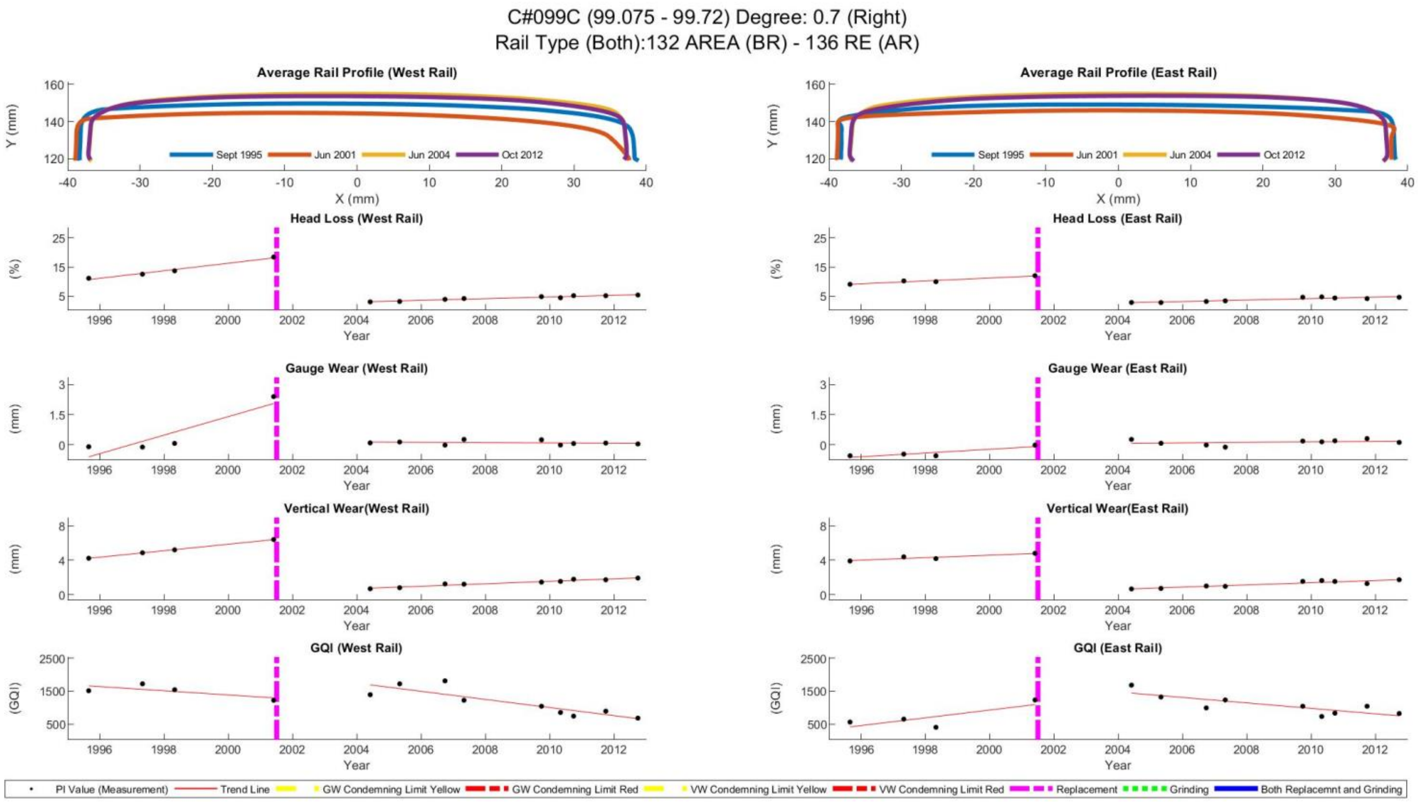


#096T (96.559-96.992)
Rail Type (Both):136 RE



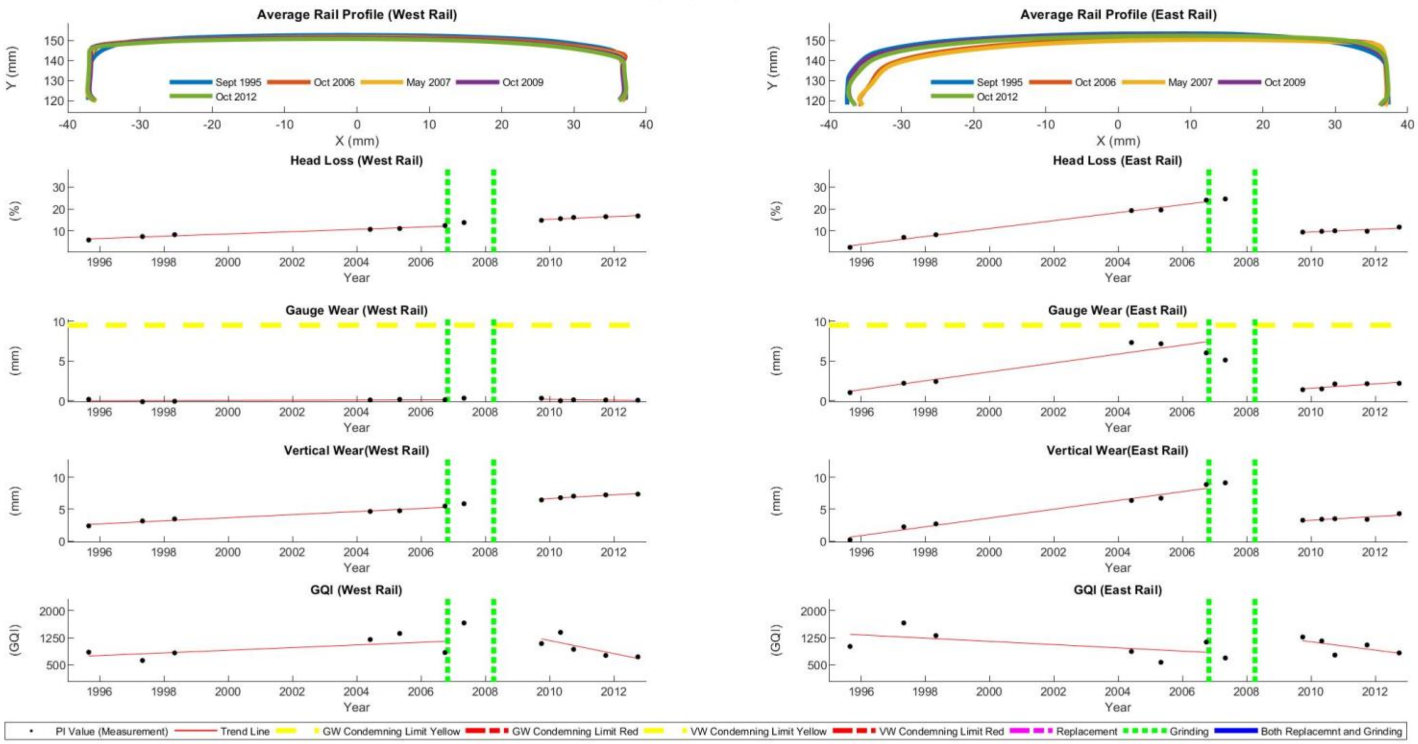
C#097C (96.995 - 97.204) Degree: 2.5 (Right)
Rail Type (Both):136 RE





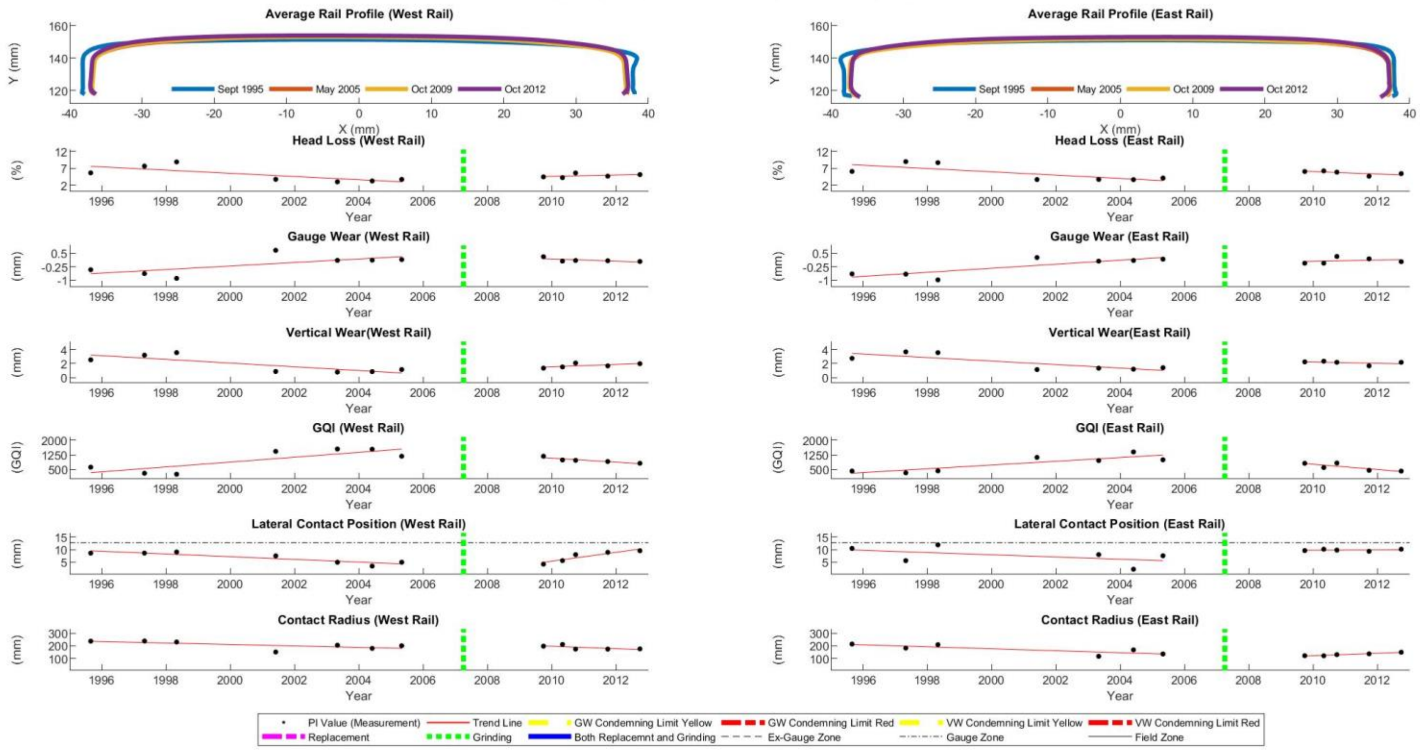
C#099C (99.075 - 99.72) Degree: 0.7 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Jun 2001
Jun 2004
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

C#101C (101.148 - 101.373) Degree: 2.1 (Left)
Rail Type (Both):136 RE

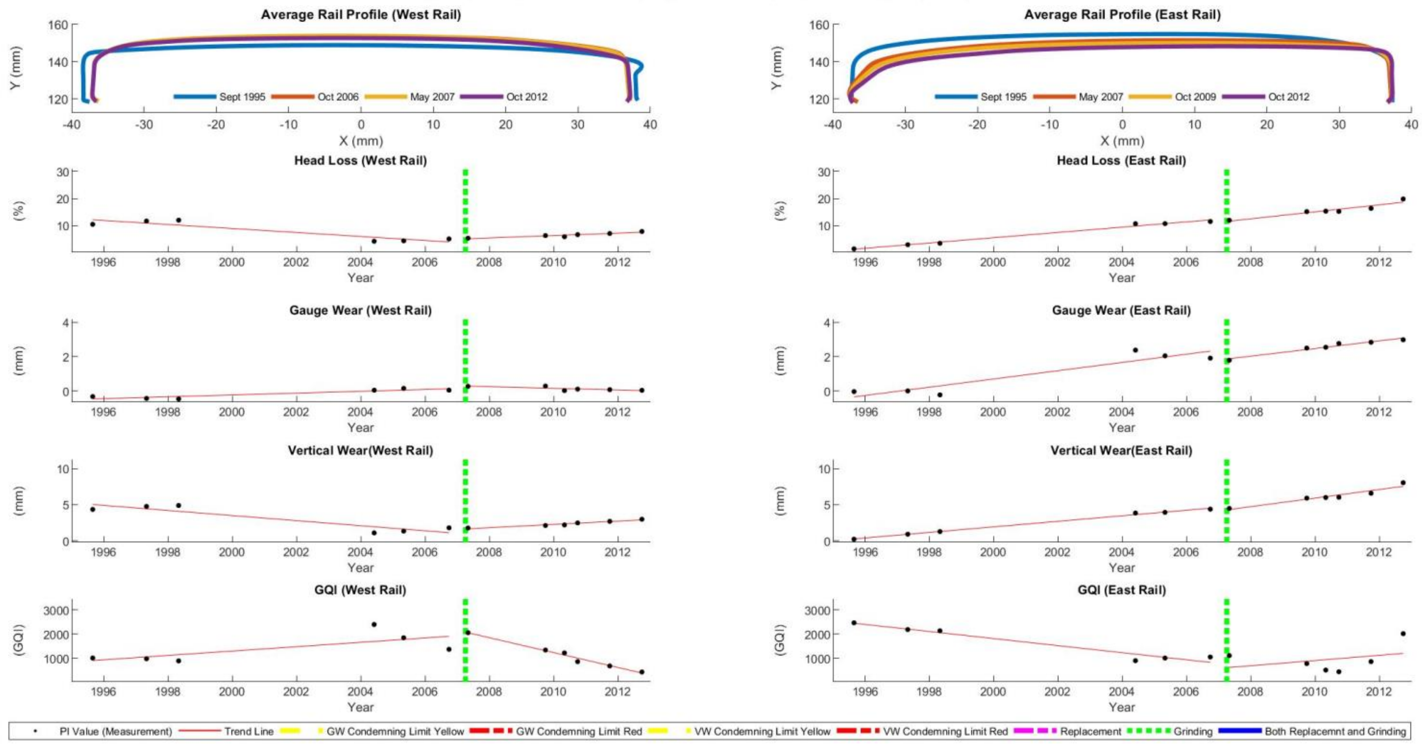


#101T (101.364-101.816)

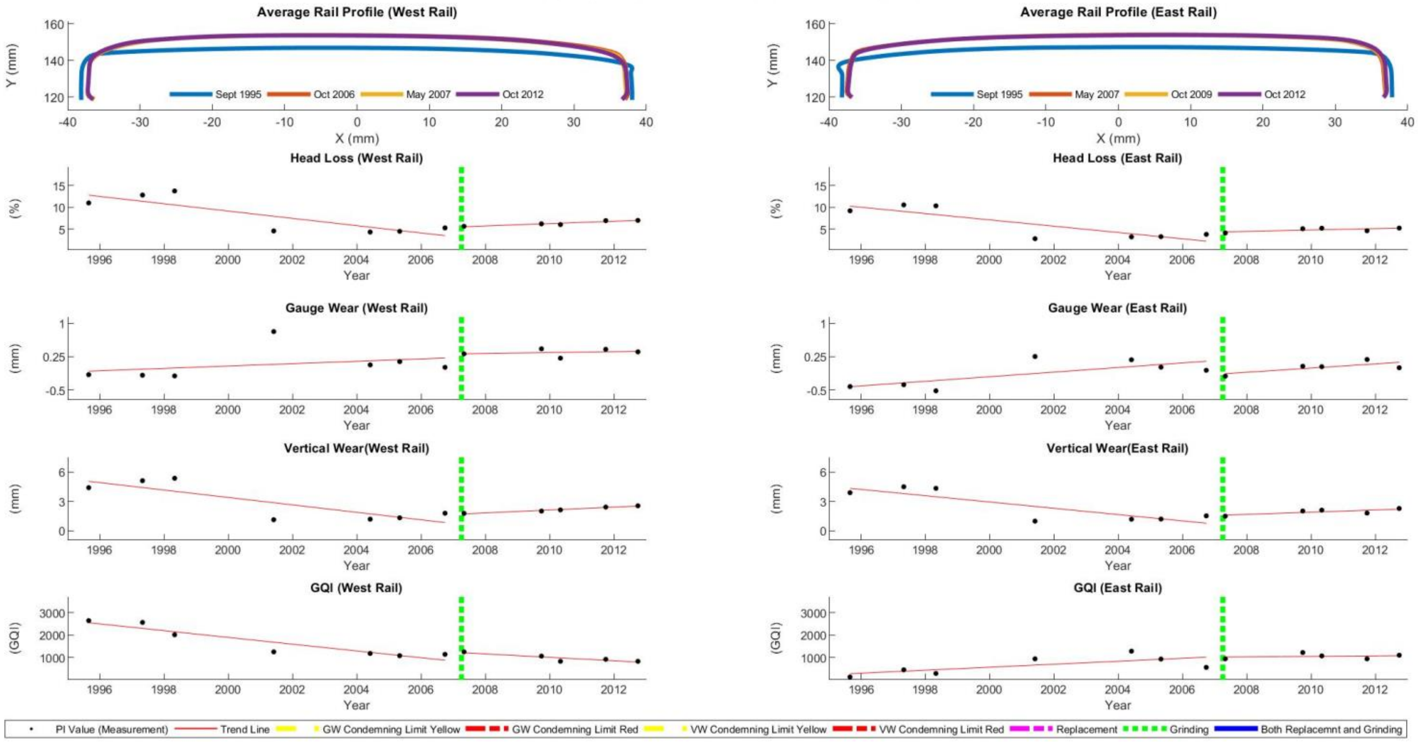
Rail Type (Both):132 ARE (BR) - 136 RE (AR)



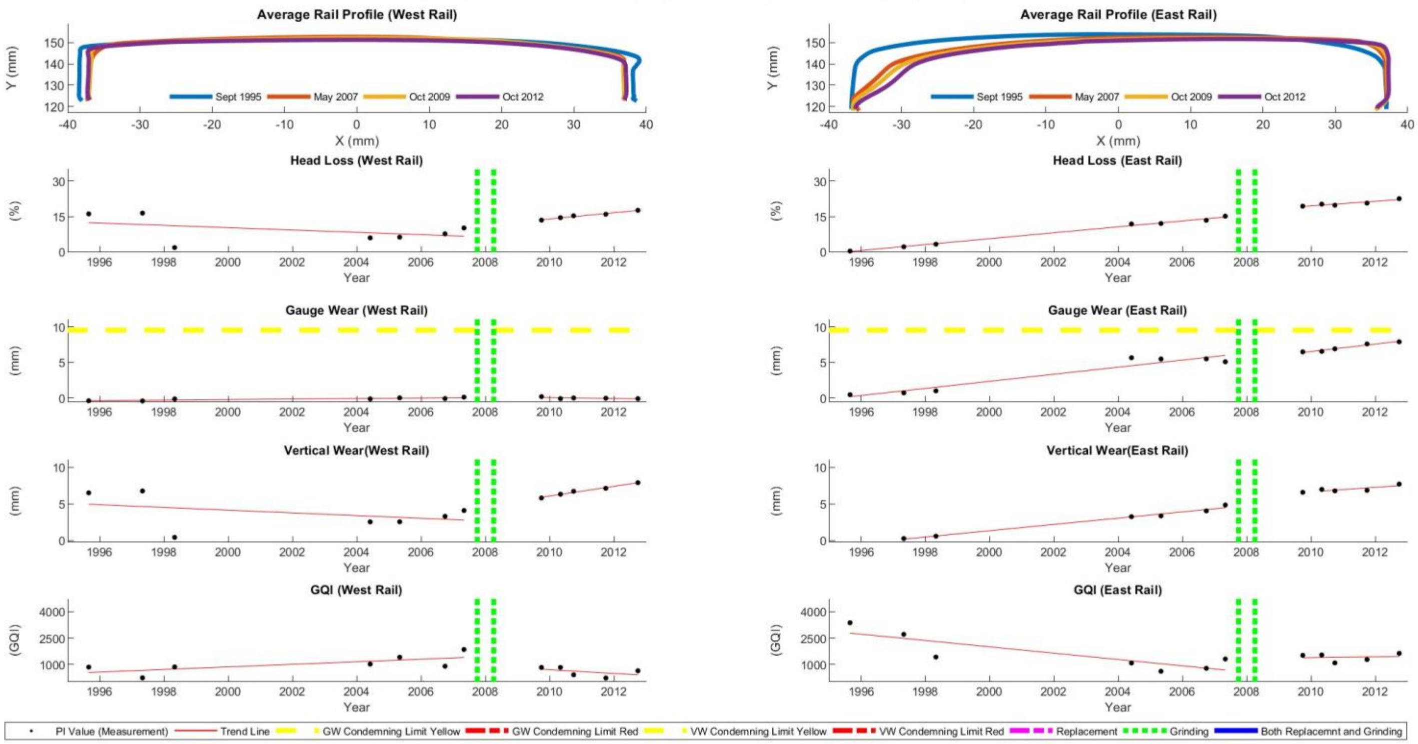
C#102C (101.81 - 102.118) Degree: 1 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE



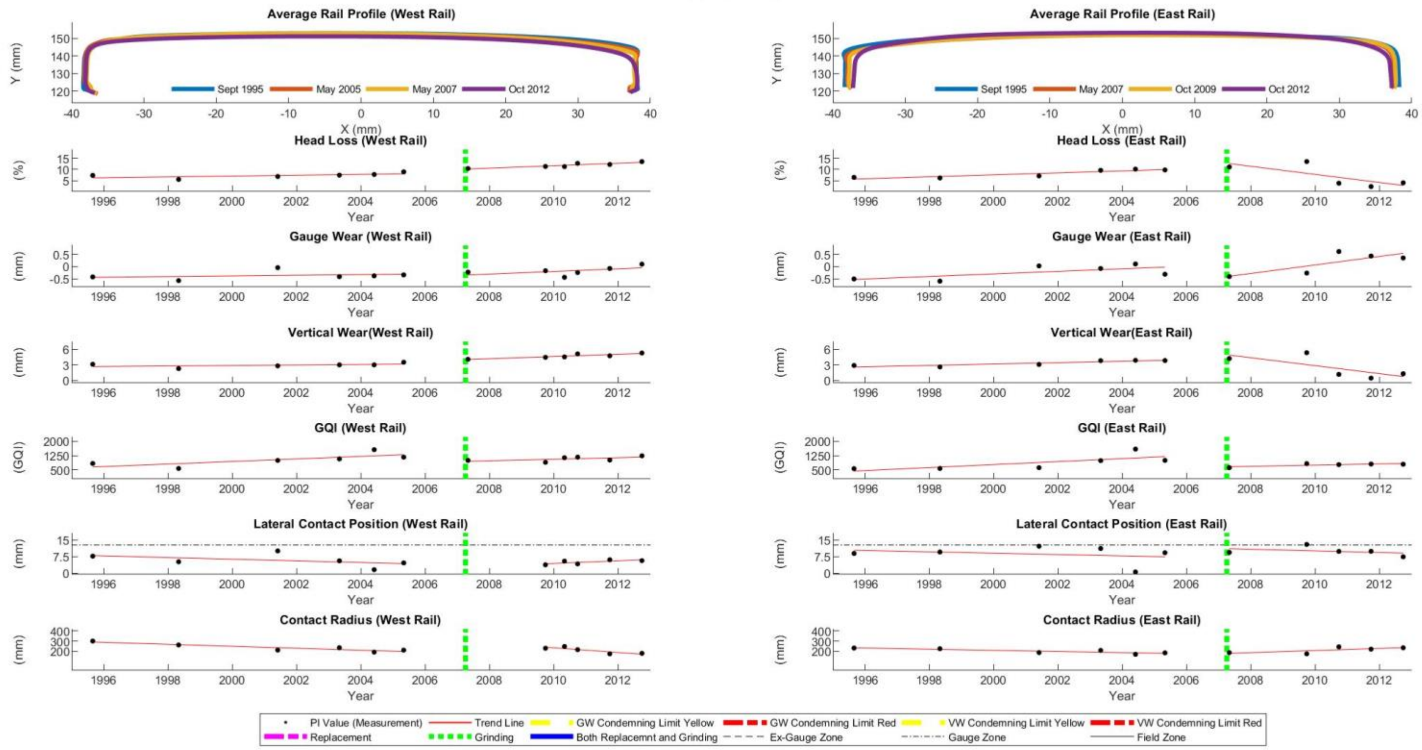
C#103C (103.007 - 103.149) Degree: 0.5 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)



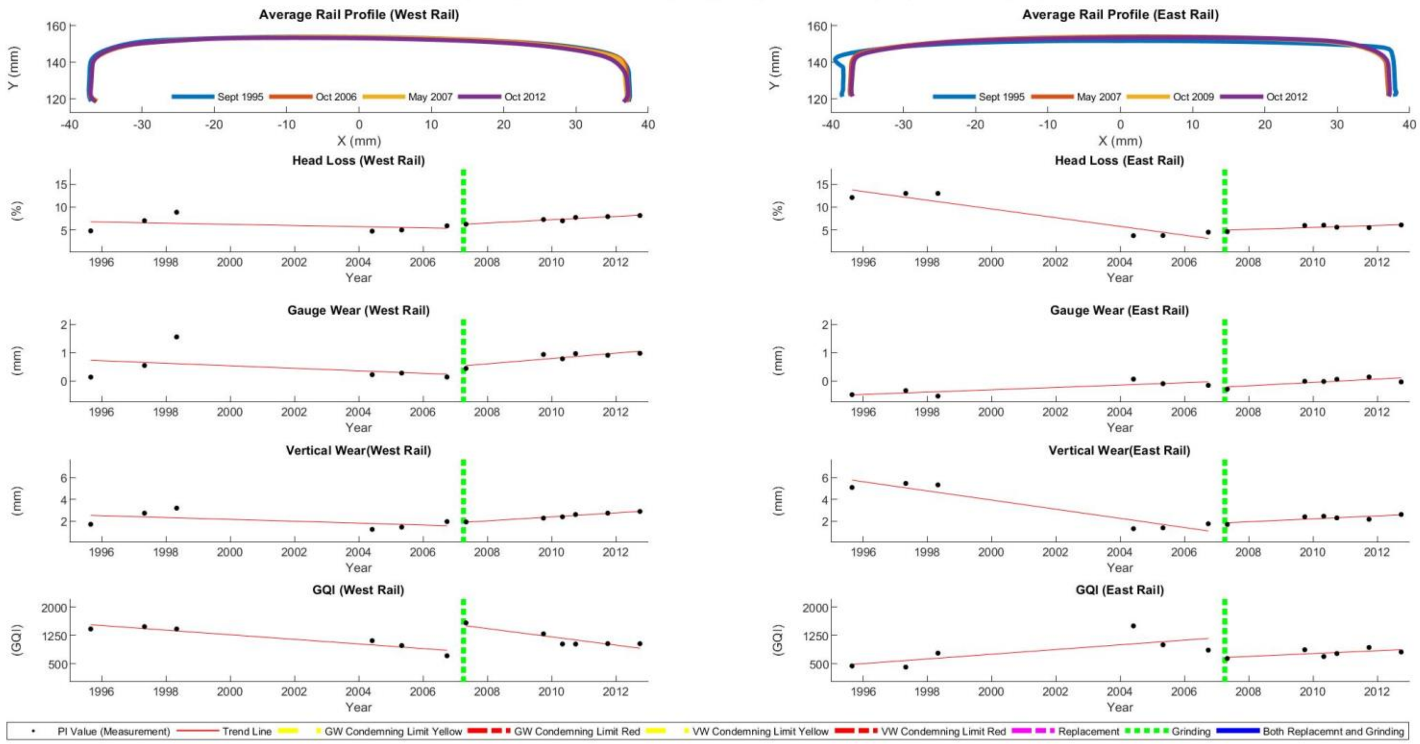
C#104C (104.003 - 104.316) Degree: 3 (Left)
Rail Type (West): 132 AREA (BR) - 136 RE (AR) - Rail Type (East): 136 RE



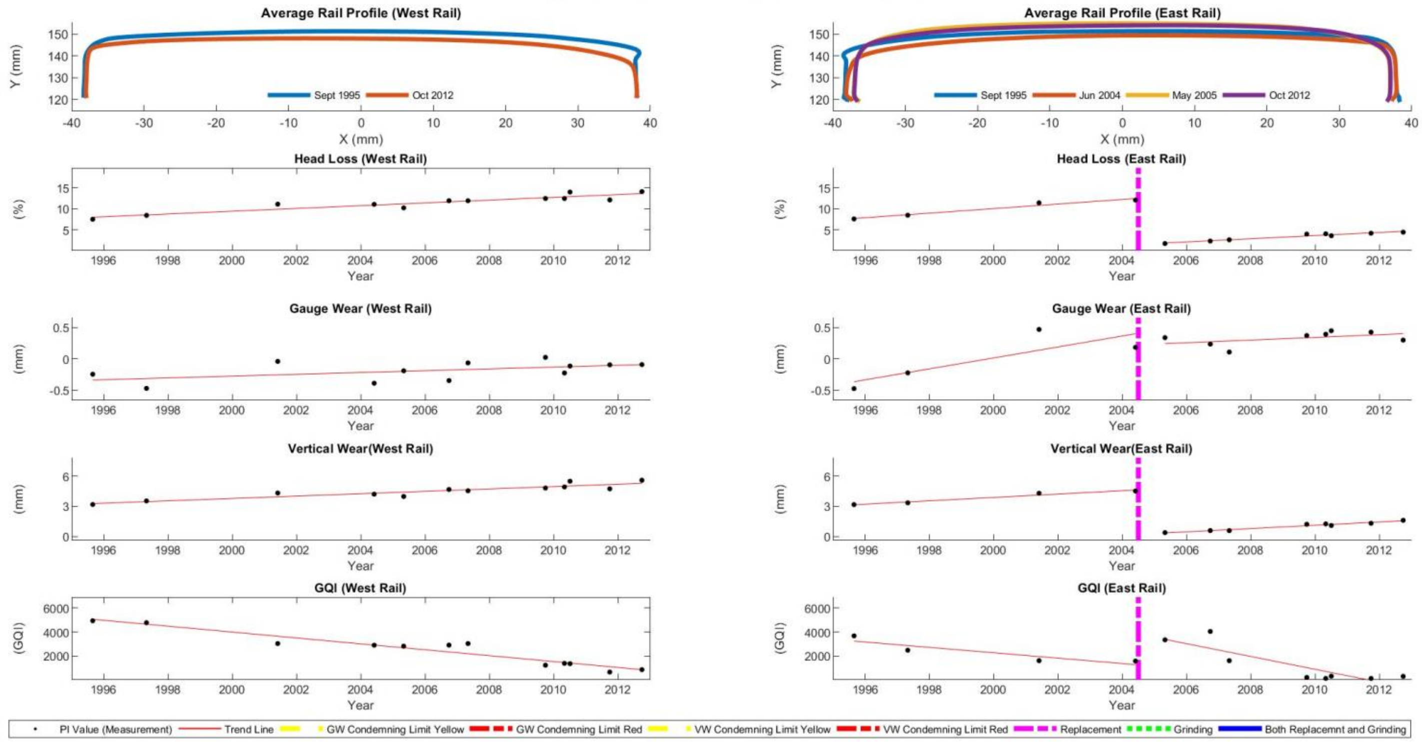
#104T (104.3-104.54)
Rail Type (Both):



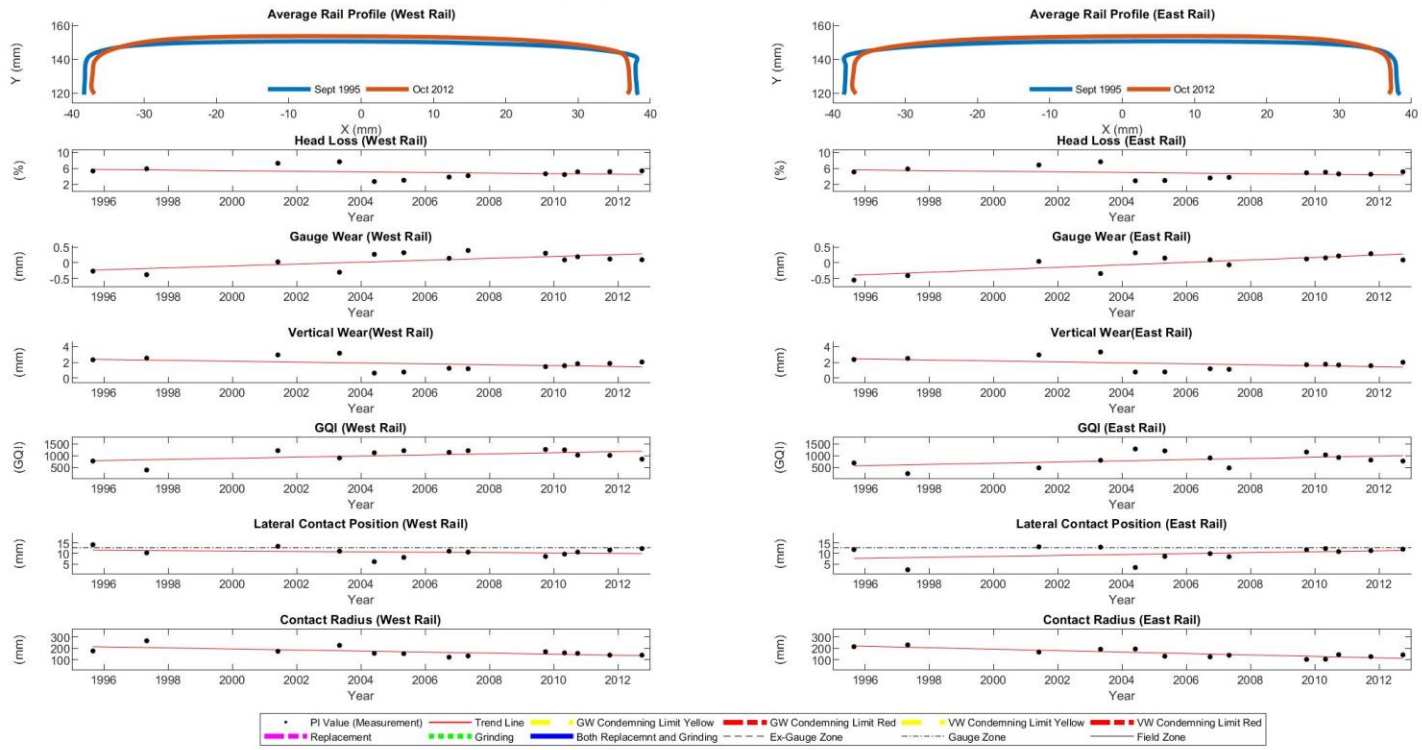
C#104AC (104.558 - 104.911) Degree: 1.2 (Right)
Rail Type (West): 136 RE - Rail Type (East): 132 AREA (BR) - 136 RE (AR)



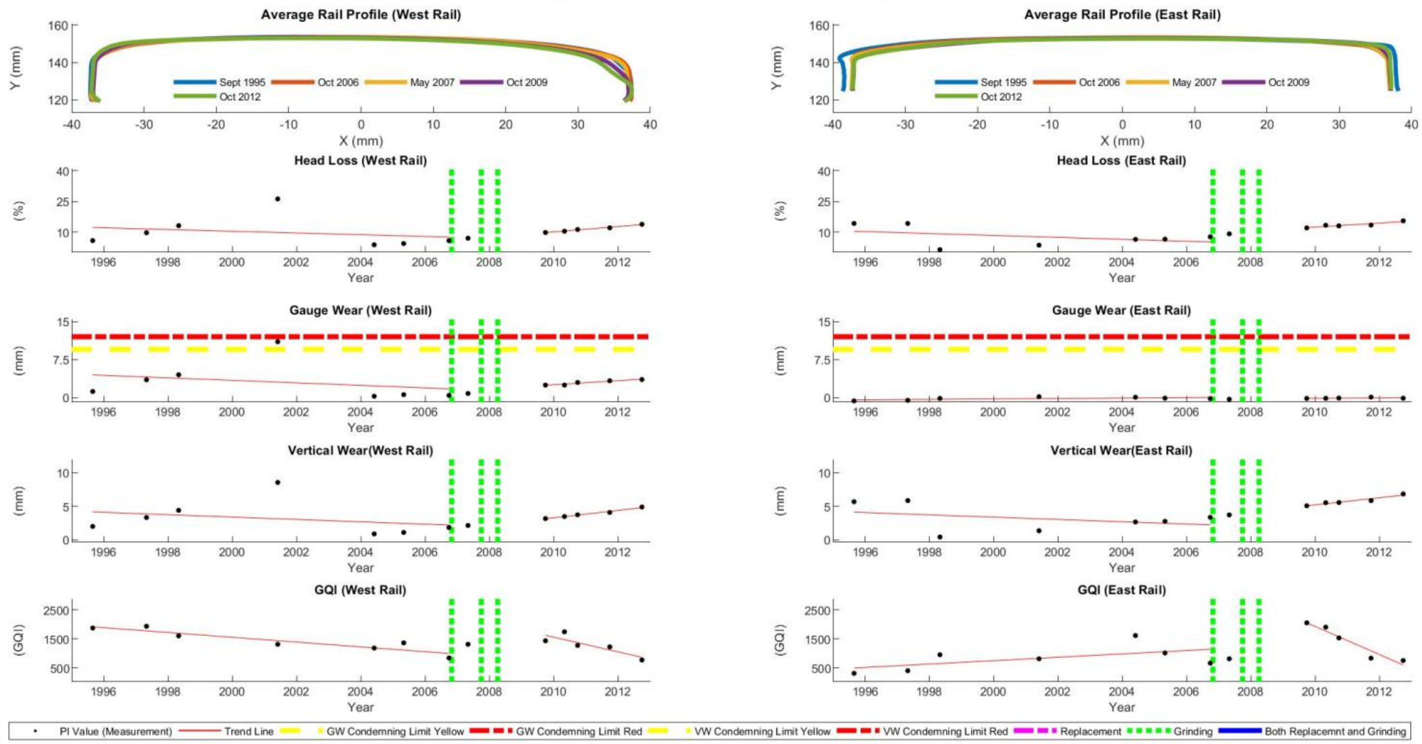
C#105C (105.427 - 105.792) Degree: 0.5 (Left)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)

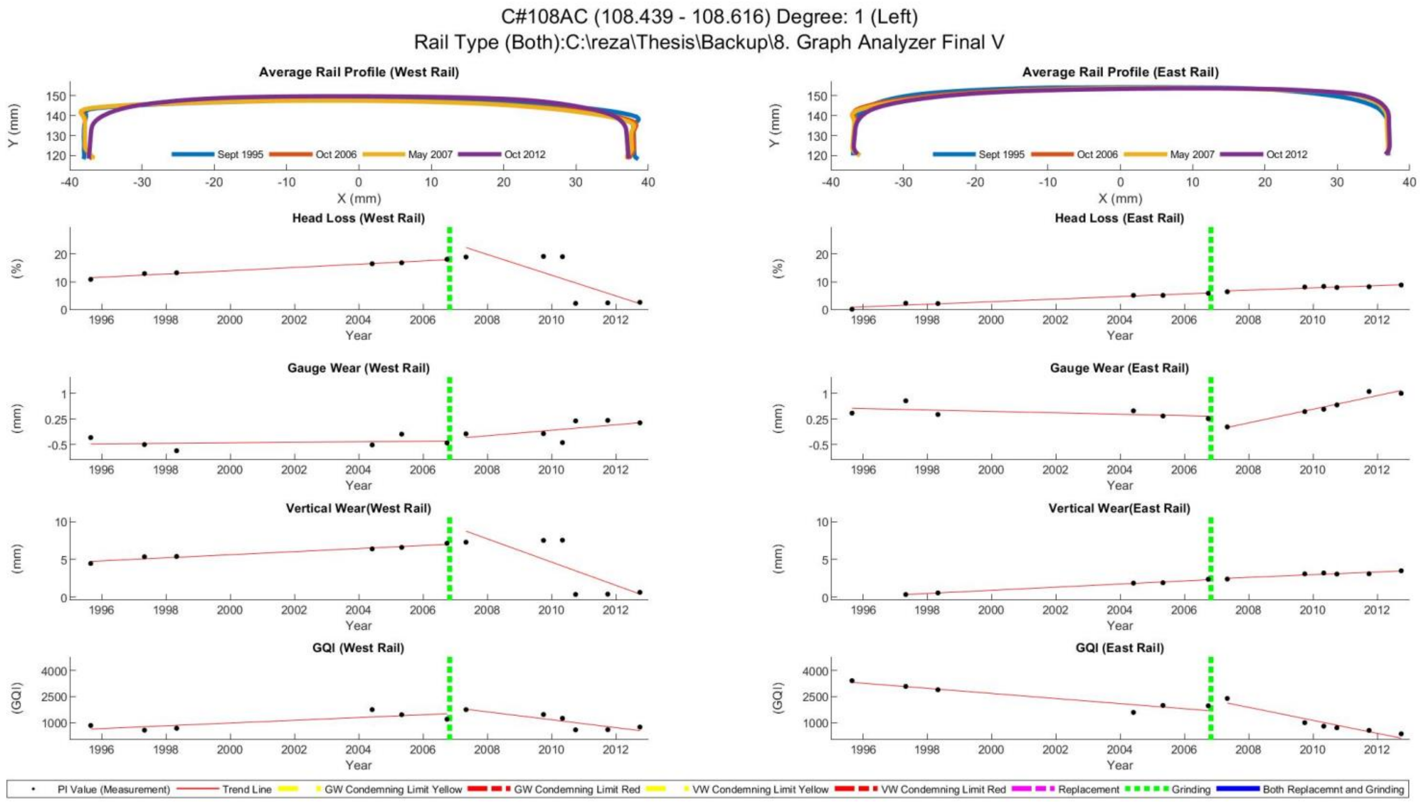


#107T (107.236-107.693)
Rail Type (Both):132 ARE (BR) - 136 RE (AR)



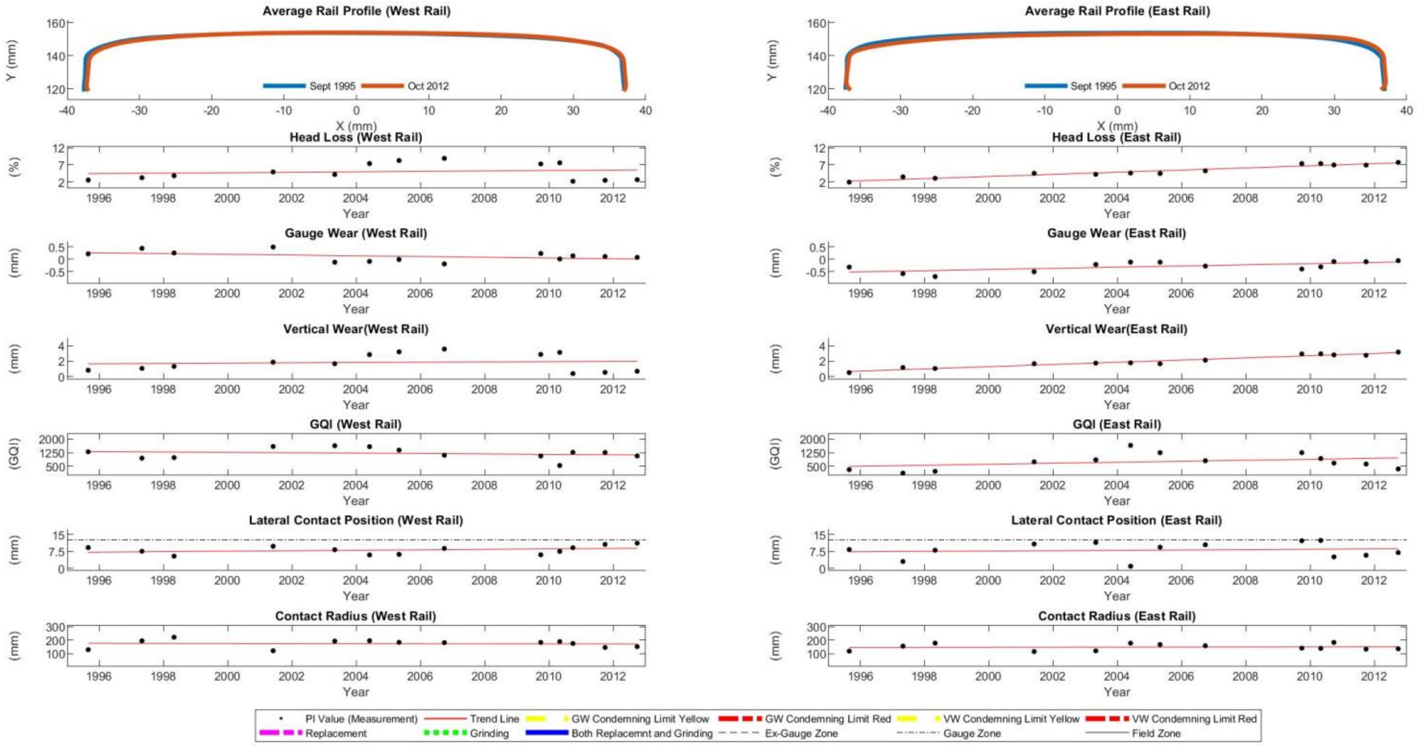
C#108C (108.093 - 108.346) Degree: 2.9 (Right)
Rail Type (Both):132 AREA (BR) - 136 RE (AR)





C#108AC (108.439 - 108.616) Degree: 1 (Left)
Rail Type (Both):C:\reza\Thesis\Backup\8. Graph Analyzer Final V
Average Rail Profile (West Rail)
Average Rail Profile (East Rail)
Sept 1995
Oct 2006
May 2007
Oct 2012
Y (mm)
X (mm)
Head Loss (West Rail)
Head Loss (East Rail)
Gauge Wear (West Rail)
Gauge Wear (East Rail)
Vertical Wear(West Rail)
Vertical Wear(East Rail)
GQI (West Rail)
GQI (East Rail)
Year
(%)
(mm)
(GQI)
PI Value (Measurement)
Trend Line
GW Condemning Limit Yellow
GW Condemning Limit Red
VW Condemning Limit Yellow
VW Condemning Limit Red
Replacement
Grinding
Both Replacemnt and Grinding

#108AT (108.617-108.756)
Rail Type (Both):136 RE



C#109C (108.745 - 109.263) Degree: 2 (Left)
Rail Type (Both):136 RE