Track research: longitudinal rail stress management gap analysis research report (phase 1)
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Track Research: Longitudinal Rail Stress Management Gap Analysis Research Report (Phase 1)

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National Research Council Canada

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.
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ABSTRACT

Rail steel is produced in fixed lengths of between 12 to 120 m. To build track, rails can be joined either mechanically with joint bars and bolts or by welding the sections together as continuously welded rail (CWR). The general industry view is that CWR is preferred for main track construction as it eliminates discontinuities in track support. However, with this type of track construction, the rail steel is fixed in place and not free to expand or contract with changes in temperature. This results in thermally induced stresses in the rail (compressive when hot, and tensile when cold), which can be extremely large and contribute to rail breaks during cold weather conditions, and rail buckles under hot weather conditions. Although North American railways have operated with CWR since the 1950s, there is insufficient information on how rail behaves under stress, how longitudinal stress changes over time, how stress impacts the interaction between track and trains during operations, what exact stress condition(s) would cause broken rail or track buckling, nor how effective are current stress management practices. A literature review of thirty-three technical documents revealed a recurring theme of the difficulty in quantifying the level of stress being experienced by rails in CWR construction. Three potentially game changing technologies for longitudinal rail stress measurement were identified, including frictional strain sensing, X-ray diffraction and fibre optic sensing. These are commercial technologies already used in industries including oil and gas, construction, geotechnical and mining. A way forward is also proposed to test and validate the technologies, and deploy those suitable for the rail operating environment.
Canada is the second largest country in the world. Bordering the United States in the south, Canada’s landmass stretches from the Atlantic Ocean from the east to the Pacific Ocean to the west, and all the way to the Arctic Ocean to the North.

Connecting Canada from east to west are approximately 45,000 route-kilometres of railway tracks [1]. According to the Minister of Transport in Transport Canada’s 2016 annual report [1]:

“Transportation plays a critical role in the Canadian economy by enabling Canadian products, services and people to access key markets, thus creating prosperity and economic opportunities for the middle class. A modern, safe, secure, reliable and environmentally responsible transportation system is essential to our economic wealth...”

The Transportation Safety Board (TSB) indicated the following, as part of their safety recommendation (R14-02) following the investigation into the Lac-Mégantic rail accident,

“United States Federal Railroad Administration (FRA) accident data segregated by cause show that broken rail is the factor most likely to pose the greatest risk to train operations because accidents due to broken rails are more frequent and more severe than average... Consequently, a reduction in broken rails is essential to any strategy to improve the safety of dangerous goods transportation by rail.” [2]

Rail steel is produced in fixed lengths of between 12 to 120 m. To build track, rails can be joined either mechanically with joint bars and bolts or by welding the sections together as continuously welded rail (CWR).

CWR is preferred for main track construction in Canada. The main advantages of CWR include improved ride quality, a longer rail life due to the elimination of joint wear and batter, reduced wheel wear due to a smoother, quieter running surface, and reduced maintenance costs due to reduced dynamic loadings.

Despite the advantages offered by CWR, with this type of track construction, the rail steel is fixed in place and not free to expand or contract with changes in temperature. This results in thermally induced stresses in the rail (compressive when hot, and tensile when cold), which can be extremely large and contribute to the generation of rail breaks during cold weather conditions, or rail buckles that occur under hot weather conditions.

Although North American railways have operated with CWR since the 1950s, there is insufficient information on how rail behaves under stress, how longitudinal stress changes over time, how stress impacts the interaction between track and trains during operations, what exact stress condition(s) would cause broken rail or track buckling, nor how effective are current stress management practices.

A literature review of thirty-three technical documents revealed a recurring theme of the difficulty in quantifying the level of stress being experienced by rails in CWR construction.

A previous study completed by NRC in 2012 noted that “Technologies to measure rail neutral temperature (RNT) exist, but are in various stages of development. Still today, railways are trying to manage something they have great difficulty measuring.” [3]
Recent NRC consultations with railway stakeholders in Canada concluded that there is a need to improve longitudinal rail stress measurement, and such improvements have the potential of advancing rail transportation safety, as well as significantly reducing track-related expenditures.

Three potentially game changing technologies for longitudinal rail stress measurement were identified, including frictional strain sensing, X-ray diffraction and fibre optic sensing. These are commercial technologies already used in industries including oil and gas, construction, geotechnical and mining.

Recommended next steps:

1. An important next step would be to test the three technologies in controlled laboratory settings to determine their accuracy and suitability for rail applications.
2. If the results from the controlled laboratory testing show promise, it is recommended that the technologies be deployed in the field to gather data in order to gain better insights into rail longitudinal stress in-situ.

Ultimately, it is unlikely that it would be practical nor necessary for rail companies to implement system wide monitoring. The ultimate goal of this research is to generate critical information and guidelines to help railways:

- Maintain better records of rail longitudinal stress related issues, such as buckles, breaks and related maintenance. [4]
- Better understand rail asset life and performance over time, and how it impacts safety and cost [5], as well as information that could improve the rail steel fracture toughness. [6]
- Identify more appropriate rail neutral temperatures (RNT) for track construction for the geographical region.
- Identify more practical tools and technologies to use for rail stress monitoring.
- Identify critical track locations that need better monitoring.
- Identify effective track maintenance strategies to maintain the RNT and track resistance.
- Improve CWR track construction methods to mitigate the impacts of rail longitudinal stress due to climatic changes. [6]

Considering the fact that assets are expensive, and for rail transportation, track infrastructure is vast (45,000 km), there is a need to better monitor assets to improve safety, proactively detect issues, and prolong asset life. Since technological innovations appear on the market on a regular basis, NRC recommends that a scan of technologies to advance the monitoring of infrastructure health be performed on a regular basis.
GLOSSARY

BOTDA  Brillouin Optical Time Domain Analysis
BOTDR  Brillouin Optical Time Domain Reflectometer
CN     Canadian National Railway
CP     Canadian Pacific Railway Limited
CWR    Continuously Welded Rail
FBG    Fibre-Bragg Gratings
FRA    United States Federal Railroad Administration
NRC    National Research Council Canada
RNT    Rail Neutral Temperature
Stress \[ \frac{\text{Force (or load)}}{\text{area}} \]
TSB    Transportation Safety Board
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1 RAIL TRANSPORTATION IN CANADA

Canada is the second largest country in the world. Bordering the United States in the south, Canada’s landmass stretches from the Atlantic Ocean from the east to the Pacific Ocean to the west, and all the way to the Arctic Ocean to the north.

Canada is sparsely populated, with 3.7 persons per square kilometer according to the 2011 Statistics Canada census [7]. Approximately 70% [8] of Canadians reside in major metropolitan areas across the country (some are shown in Figure 1).

![Canadian Railway Network](image1.jpg)

1.1 The Context of Rail Transportation in Canada

Connecting Canada from east to west are approximately 45,000 route-kilometres of railway tracks [1] (Figure 1). According to the Minister of Transport in Transport Canada’s 2016 annual report [1]:

“Transportation plays a critical role in the Canadian economy by enabling Canadian products, services and people to access key markets, thus creating prosperity and economic opportunities for the middle class. A modern, safe, secure, reliable and environmentally responsible transportation system is essential to our economic wealth... Over 60 railways operate in Canada. About half of them operated under the
federal jurisdiction in 2016. In December 2016, 26 federal railway companies held a valid certificate of fitness (with 5 cancelled and 1 suspended licenses), down from 34 in 2007.”

The Canadian rail network consists primarily of two types of operations:

- freight operations
- passenger operations

Freight rail operations, specializing in the movement of large volume goods, is by far the dominating rail operation type in Canada. As noted by Transport Canada, in 2016 the freight rail sector carried 297 million tonnes of freight [1]. Many freight railway mainline routes can accommodate cars weighing up to 130 tonnes (286,000 lbs) and train lengths up to 4 km [9]. In addition, the vast majority of the Canadian rail network is owned by freight railway companies, with Canadian National Railway (CN) and Canadian Pacific Railway Limited (CP) owning a combined 75% of the total track infrastructure in Canada. [1]

Passenger rail operations are much smaller in comparison and consist of VIA Rail Canada, a crown corporation providing national intercity service, along with a handful of local authorities providing commuter, transit and tourist services.

1.2 Examination of Rail Safety in Canada

The Transportation Safety Board of Canada (TSB) collects data on rail occurrences in Canada as per requirements set out by the Transportation Safety Board Regulations, SOR/2014-37. In general, the Rail Occurrence Database relies on self-reporting by federally regulated railways, as only a small percentage of reported occurrences are officially investigated.

According to official figures from the TSB, as shown in Figure 2, the number of rail accidents reported in Canada has been declining. 1,035 rail accidents were reported in 2016, the lowest number in 10 years. [10]

![Figure 2: TSB Statistical Summary](image)
References reviewed as part of this project indicate that in general, the safety trend for rail transportation in Canada has been positive, with the most significant improvements to have taken place in the 1980s from key technological innovations such as the wide implementation of continuously welded rail (CWR), improvements in rail metallurgy and flaw detection, as well as “the automation of track geometry measurements”. These improvements led to the yearly derailments decreasing from 3.8 - 3.2 per million train miles to 1.5 - 1.4 per million train miles. [9]

The vast majority of the reported occurrences were non-main track accidents, as shown in Figure 3 [10]. Within the category of main track occurrences, as shown in Figure 4, main track derailment occurs much more frequently compared to main track collisions. In addition, the general trend for the number of main track derailments has been declining since 2007.

![Figure 3: TSB Statistical Breakdown of Accident Type [10]](image1)

![Figure 4: TSB Statistical Summary for Main Track Accidents [10]](image2)
According to the “Canadian Main Track Derailment Trends, 2001 to 2014”, as shown in Figure 5, while the percentage of main track derailments attributed to each of the main cause groups appear to be similar, the severity of the derailment in terms of the number of cars derailed appears to be higher, when the cause is attributed to track, roadbed and structures (Figure 6). [9]

In addition, as shown in Table 1, the top three main causes for main track occurrences are related to track, roadbed and structures, in the form of “rail, joint bar and rail anchoring”, “track geometry”, and “environmental conditions”. These results are similar to the trends found in the United States. [9]
Table 1: Top 10 Incident Causes of Train Derailments for Main Track by Number of Derailments between 2001 and 2014 in Canada [9]

<table>
<thead>
<tr>
<th>Rank</th>
<th>Main Track Cause</th>
<th>%</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Rail, joint bar and rail anchoring</td>
<td>10.8</td>
</tr>
<tr>
<td>2</td>
<td>Track geometry</td>
<td>9.7</td>
</tr>
<tr>
<td>3</td>
<td>Environmental condition</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>Wheels</td>
<td>6.8</td>
</tr>
<tr>
<td>5</td>
<td>Train handling/ train make-up</td>
<td>6.6</td>
</tr>
<tr>
<td>6</td>
<td>Other miscellaneous</td>
<td>6.2</td>
</tr>
<tr>
<td>7</td>
<td>Axles and journal bearings</td>
<td>5.3</td>
</tr>
<tr>
<td>8</td>
<td>General switching rules</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Switches</td>
<td>4.8</td>
</tr>
<tr>
<td>10</td>
<td>Brakes</td>
<td>3.9</td>
</tr>
</tbody>
</table>

1.3 Safety Recommendations from the Transportation Safety Board of Canada

Canada’s worst rail disaster took place on July 6, 2013 in the town of Lac-Mégantic, Quebec, where a freight train operated by Montreal, Maine & Atlantic Railway derailed near the centre of the town. The TSB indicated the following, as part of their safety recommendation (R14-02) following the investigation into the Lac-Mégantic rail accident:

“United States Federal Railroad Administration (FRA) accident data (as shown in Table 2) segregated by cause show that broken rail is the factor most likely to pose the greatest risk to train operations because accidents due to broken rails are more frequent and more severe than average... Consequently, a reduction in broken rails is essential to any strategy to improve the safety of dangerous goods transportation by rail.” [2]
## Table 2: Top 10 Causes of Train Derailments for Main Track in the United States [11]

<table>
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<th>Main</th>
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<td>1</td>
<td>Broken rails or welds</td>
<td>22.7</td>
</tr>
<tr>
<td>2</td>
<td>Track geometry (excluding wide gauge)</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>Buckled track</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>Obstructions</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>Bearing failure (car)</td>
<td>4.6</td>
</tr>
<tr>
<td>6</td>
<td>Wide gauge</td>
<td>4.6</td>
</tr>
<tr>
<td>7</td>
<td>Train handling (excluding brakes)</td>
<td>4.1</td>
</tr>
<tr>
<td>8</td>
<td>Broken wheels (car)</td>
<td>3.9</td>
</tr>
<tr>
<td>9</td>
<td>Other axle or journal defects (car)</td>
<td>3.1</td>
</tr>
<tr>
<td>10</td>
<td>Other rail and joint defects</td>
<td>3.0</td>
</tr>
</tbody>
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2 TECHNICAL THEORIES AND FUNDAMENTALS

2.1 Broken Rail Causes

As illustrated by the partial fault tree diagram (Figure 7) presented by FRA at the 2016 Joint Rail Conference, there are many factors that contribute to the development of broken rails in service. These factors can be broadly classified as critical rail defects and high rail stress.

![Broken Rail Fault Tree Diagram](attachment:figure7.png)

Figure 7: Partial Broken Rail Fault Tree Diagram [12]

A critical rail defect refers to a flaw in the rail that has grown to a size that is not able to withstand the forces during rail operations. There are a number of different types of rail defects including flaws in the rail steel, defects in rail welds, rolling contact fatigue defects, etc.

Since stresses in the rails can drive rail defects of sub-critical size to develop into critical rail defects [13], the following sections examine rail stresses in more detail.

2.2 Types of Rail Stress

During static and dynamic railway operations, the track structure experiences many different loading conditions that generate stress in different parts of the rail, as partially illustrated in Figure 8.
Figure 8: Example Rail Loads and Stresses [13]

Stress can be in the vertical plane, transverse plane or horizontal/longitudinal plane, as shown in Figure 9.
The main types of stress experienced by rails include:

- **Residual stress**
  - During the rail manufacturing process, the rail steel is subjected to a number of different actions, such as casting, forming, hardening, straightening, flexing and cooling. As a result, rail steel retains what is referred to as residual stress.
  - During the rail welding process, residual stress can also develop, due to the different rates of expansion and contraction of the rail steel and welding materials.
  - Residual stress, can exist in different directions and planes.

- **Bending stress**
  - Rail experiences bending stress during static and dynamic train operations. As shown in Figure 8 (top), the vertical load from railway rollingstock causes the rail to bend, resulting in stresses in the longitudinal and vertical directions.
  - Torsional stress, as shown in Figure 8 (bottom), occurs when the wheel load is not applied at the rail centerline, or when there is a lateral load present (for example, when negotiating a curve).

- **Longitudinal stress**
  - Stress in the longitudinal direction, as shown in Figure 9, can be generated from train actions, such as the forces exerted during acceleration and braking; as a result of rail movement (for example at fixed points such as road crossings and bridges); and as a
result of changes in the temperature of the rail for CWR track, also known as rail thermal stress.

- **Contact stress**
  - The small elliptical contact area between the wheel and the rail, as shown in Figure 10, is approximately the size of a dime. This region supports the entire wheel load of railway rollingstocks and can experience very high stress levels. Contact stress is shear in nature [13], in that it is parallel to the loading direction. Contact stress depends on the magnitude of the vertical load, as well as the shape of the wheel and rail.

![Figure 10: Contact Patch between the Wheel and Rail [13]](image)

### 2.3 Track Construction Methods

Rail steel is produced in fixed lengths of between 12 to 120 m long. To build track, rails can be joined either mechanically with joint bars and bolts or by welding the sections together as CWR.

CWR is the preferred method for main track construction in Canada. The main advantages of CWR include improved ride quality, a longer rail life due to the elimination of joint wear and batter, reduced wheel wear due to a smoother, quieter running surface, and reduced maintenance costs due to reduced dynamic loadings.

### 2.4 The Prevalence of Thermal Stress as a Root Cause of Broken Rails

Despite the advantages offered by CWR, with this type of track construction, the rail steel is fixed in place and not free to expand or contract with changes in temperature. This results in thermally induced stresses in the rail (compressive when hot, and tensile when cold), which can be extremely large and contribute to the generation of rail breaks during cold weather conditions, or rail buckles that occur under hot weather conditions.
2.5 The Role of Rail Neutral Temperature

Rail neutral temperature (RNT) is one of the most critical factors in CWR track design, installation and maintenance. It refers to the temperature where the rail experiences no thermally induced stress, as shown in Figure 11.

![Figure 11: Rail Neutral Temperature](image)

CWR rails are generally pre-stressed to a RNT of 90°F (32°C) in Canada and 80°F (26.7°C) in the United Kingdom. According to “In-Situ Longitudinal Rail Stress Measurement Technology Validation” by Ian Mackenzie and Ray Barton (2012), the reason for the preference for higher RNT’s is that rail breaks tend to be less operationally problematic for railways, as train wheels can roll over small breaks, while rail buckles typically result in derailments [3]. The other significant factor, according to CN, is that the centralized traffic control centre signal system provides detection for broken rails but not track buckles. It should also be noted that rail temperature is not always the same as the ambient temperature. This will be further explained in Section 3.

The preference for higher RNT combined with the colder climate in Canada is one of the reasons that broken rails has been singled out by the TSB as a major cause of concern for the safety of rail transportation.

To complicate matters, RNT does not stay constant throughout the life of the CWR installation, nor is it constant along the track. RNT is heavily affected by train action (braking and acceleration), track settlement, track lateral resistance, location on track (proximity to fixed structures such as bridges and switches), and maintenance activities.
Thirty-three technical documents, including technical manuals and journal/conference papers, were reviewed on rail stress management’s state of practice around the world.

The following is a summary of the most relevant information to rail stress management,

- The track system consists of rails anchored by fasteners onto railway ties (track superstructure) supported by a system of ballast, sub-ballast and subgrade (track substructure). An example of the track’s surface portion is shown in Figure 12.
- Track that is well constrained resists movement in the longitudinal direction and lateral direction induced by thermal forces and train load [4], thus reducing the potential for broken rail and track buckling.
- The track system is complex, extremely dynamic and constantly changing, with interactions between different track components affecting the condition of each portion of rail.
- Track resistance can be weakened over time due to train traffic, wear and tear of the track fastening mechanism and components, track geometry misalignment, track maintenance activities leading to a lack of ballast consolidation, ballast degradation and subgrade conditions. According to TSB, ballast disturbance during maintenance could result in more than 50 percent reduction in lateral track stability. [14]
- For every 1°C that the rail changes temperature from its RNT, a stress of 2.4 MPa is created. [3]
- Rail breaks and rail buckles have a tendency to initiate at weak points, such as rail defects and bad welds (for rail breaks) and areas where the lateral strength of track has been disturbed (for buckles).
- Studies have found that three factors play a crucial role in the potential for track buckling, including the RNT (low RNT value), the rail temperature (high ambient temperature leading to high rail temperature) and track resistance (it can be determined by methods such as the single-push-tie-test) [15]. There are also indications that certain locations are more vulnerable, including near fixed structures (such as bridges), locations of descending grade and heavy braking locations. Interestingly, while curves are more vulnerable to track buckles, tangent track can cause more damage to trains due to the sudden movement and change in direction. [4]
- Table 3 outlines the empirical relationship used (in some parts of the world) to determine rail temperature based on ambient temperature. However, in reality, the temperature of the rail can vary greatly along a segment of rail due to other factors including position of the sun, season, duration of direct sun exposure, wind conditions, shade and topography. In fact, past studies have noted up to 16°F (8.9°C) difference in rail temperature between measurement points that are 4 m apart, within a half hour time span [3].

---

1 According to Track Stability Management – Part 1: Literature Review: Theories and Practices, “rail temperature will generally be higher in a deep cutting than in open country or an embankment”. [13]
Table 3: Relationship between Rail Temperature and Air Temperature [4]

<table>
<thead>
<tr>
<th>Rail Company</th>
<th>Country</th>
<th>Rail Temperature (°C)</th>
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<td></td>
<td></td>
<td>Cold weather: $T_r = T_a$</td>
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<td>$T_r = 1.64T_a - 8$</td>
</tr>
<tr>
<td>Transnet Freight</td>
<td>South Africa</td>
<td></td>
</tr>
</tbody>
</table>

### 3.1 Current Railway Stress Management Practice

According to 2014 figures, Canada’s freight rail sector earned $13.3 billion in revenues while the passenger rail sector earned $1.85 billion. However, the rail industry is a capital and operating intensive industry. In 2014, $1.3 billion was utilized for track related expenditures, including building/replacing track, rail grinding, track surfacing, and replacing ties and ballast. [16]

CP has raised the need to improve rail stress management with National Research Council Canada (NRC) a number of times over the past few years. CP’s observations indicate that the first train of the day during a period of sudden and large temperature drop will typically cause a broken rail. There are theories proposed of uneven stress build-up concentrated in certain locations along the track. However, there is insufficient information on how rail behaves under stress, how longitudinal stress changes over time, how stress impacts the interaction between track and trains during operations, what exact stress condition(s) would cause broken rail or track buckling, nor how effective are current stress management practices.
The following is a summary of the most relevant information on current railway stress management practices:

- **Rail de-stressing** – This is a preventative measure against rail buckling, where the rail is cut at predetermined locations to relieve compressive longitudinal stress, with the excessive steel materials removed. The amount of rail removed depends on the operational practice of each railway, but is generally based on the installed rail’s thermal coefficient and the desired RNT for the locale. [4]

- **Rail re-stressing** – This is a preventative measure against rail buckling, where the length of the rails are adjusted using heaters, coolers and/or tensors to re-establish the desired RNT. According to a study from Australia, this is an expensive and intensive process, and “usually requires 12-16 railway track operation people, heavy hydraulic tensioning or thermal equipment and welding equipment.” [4]

- **Broken rail repair** – This is a reactive measure against rail breaks, where additional rail steels are added (plug rail) to a rail section to either repair rail breaks or to reduce the risk of rail pull-apart. [4]

- **Speed restriction** – This is a rail operational practice to increase safety during periods of severe climatic conditions, such as sudden and large changes in ambient temperature. It is important to note that the longitudinal stress experienced by rails is due to the differences between RNT and actual rail temperature, therefore while ambient temperature can be a good measure for enhanced inspections and speed reductions, it is not sufficient for predicting track related failures. Speed restrictions are also imposed after “track disturbing work”, such as tamping, since these types of work can reduce the track resistance and introduce stress by correcting rail alignment defects. [4] [3]

- **Track inspection** – This is a rail operational practice to proactively increase safety. According to the TSB, railways rely on visual inspections to identify risks of rail buckling and this method has been successful for years, however, “the track must be inspected at the right time of the day, and the employee must identify the physical signs of a tight rail condition. Employees normally have no tools readily available in the field to quantify their assessment” [14]. With respect to reducing risks related to rail breaks, railways increase track inspections (both visually and utilizing ultrasonic flaw detection methods) in the late fall to identify rail defects that might progress into initiating rail breaks. Railways also carry out rail grinding activities to remove small surface defects to curtail the growth of surface and sub-surface defects.
4 GAP ANALYSIS

During the literature review, a recurring theme was the difficulty in quantifying the level of stress being experienced by rails in CWR construction.

A previous study completed by NRC in 2012 noted that “Technologies to measure RNT exist, but are in various stages of development. Still today, railways are trying to manage something they have great difficulty measuring.” [3]

A study from Australia indicated that “installing sensors over the whole network to get information is not cost effective. To avoid the cost of installation of sensors and disturbance of traffic, railway companies usually employ visual inspections…” [4]

According to a Swedish study, the method used in Sweden to determine RNT is a rail cutting and lifting method, which is destructive and labour intensive. As a result, RNT is known for only a small portion of the 9,335 km of CWR track. “The same type of information is lacking in other parts of Europe as well... Information is especially lacking in tracks, which were built in the 80s and earlier and which were put into position with older measurement techniques.” [6]

In Canada, according to TSB, “existing inspection methods largely rely on employees to inspect the track structure... To a knowledgeable employee, signs such as spike lift, or rail creep, can indicate the possible existence of a rail that has excessive compressive stress... Employees normally have no tools readily available in the field to quantify their assessment... Because there is no easy method readily available to track maintenance employees to identify and assess the amount of stress in a rail... there is a risk that stressed rail may go undetected and later cause an unsafe track condition.” [14]

CN has invested $3 million into the development of rail stress monitoring technologies in the past [3]. CP has indicated to NRC that a large portion of their maintenance budget is utilized for managing rail stresses, including rail de-stressing, pre-stressing rails, inspections, etc... however, in absence of reliable and practical stress measurement solutions, it is difficult to quantify the effectiveness of the various approaches.

Recent NRC consultations with VIA Rail Canada, Quebec North Shore & Labrador, ArcelorMittal Infrastructure Canada and Genesee & Wyoming Canada Inc., also concluded that there is a need to improve longitudinal rail stress measurement, and such improvements have the potential of advancing rail transportation safety, as well as significantly reduce track-related expenditures.

Key information on rail stress/RNT enables railways to deploy stress management strategies more effectively. Some examples are listed below: [6]

- Strategies for managing longitudinal rail stress that result in buckling:
  - Identifying a more applicable RNT for the geographical region, better monitoring of RNT and performing more effective track maintenance to maintain the RNT. [6]
  - Providing cooling to critical sections of rail during hot weather conditions, either by cooling the air surrounding the rail, or through the transfer of cooler temperature from the ground below the rail. [6]
  - Reducing energy transfer from radiation to critical sections of rail, such as coating or painting the rail to minimize heat absorption. [6]
- Improving track quality in critical sections of rail, through the use of longer ties, appropriate ballast shoulder, higher quality anchors, thus increasing the resistance of the track to buckling. [6]

- Strategies for managing longitudinal rail stress that result in rail breaks:
  - Identifying a more applicable RNT for the geographical region, better monitoring of RNT and performing more effective track maintenance to maintain the RNT. [6]
  - Providing heating to critical sections of rail during cold weather conditions, either by heating the air surrounding the rail, or directly heating the rail itself.
  - Improving track support in critical sections of rail, through the use of longer ties, appropriate ballast shoulder, higher quality anchors, thus increasing the resistance of the track to breaks. [6]

The following sections examine the fundamentals of rail stress measurement and current available technologies.

### 4.1 Fundamentals of Rail Stress Measurement

Stress refers to the amount of force over an area, it is expressed mathematically as:

\[
\sigma = \frac{\text{Force}}{\text{Area}}
\]

#### 4.1.1 Direct Stress Measurement Methods

The following are examples of methods (with commercial products) to measure stress directly:

- **Magnetic methods** - this is a non-destructive method, portable, and more commonly used in Europe on passenger railways. In theory, when a magnetic field is applied to a ferromagnetic material, a magnetic induction will take place and a Barkhausen noise is generated. The level of noise can be used to determine the stress. The relationship between the level of Barkhausen noise and the associated stress needs to be determined (calibration) against materials of similar nature\(^2\). A European company, Goldschmidt Thermit Group offers the TrackSafeRelease (based on the Barkhausen noise method) as a service. In order to calculate RNT, two measurements are needed at two different temperatures (with 7 to 10°C minimum difference between the temperatures). RNT accuracy is reported to be ±3°C. Apparently, this method is only useful at stresses between ±280 MPa in steels, since larger stresses generate flat curves of Barkhausen noise vs. stress. [6]

- **X-ray diffraction methods** - this is a non-destructive method and is not currently being used in the railway industry. The principle is based on the measurement of diffractions of X-ray beams along the crystal lattice of the material according to Bragg’s Law \((2D\sin\theta = n\lambda)\). Stress results in a change in the distance between lattice planes, which can be measured, from which strain can be determined. As noted by the Swedish study, crystal grains in rail steels are not all oriented in the same manner, thus the measurements are obtained only through the grains that are

---

\(^2\) This method is a challenge for older rail constructions, where technical data and calibration rails are often not available.
oriented “favourably” to the X-ray and those closer to the surface of the measurement. The measurement is an average over a small area, rather than over an entire cross section. A clean measurement surface is needed. Some of the advantages of this technology are that the measurement time is comparatively short (10 to 15 minutes), the method is well understood, and it has been used in many industries. [6] American Stress Technologies makes two portable diffractometers (Xstress 3000 G2/G2R, Xstress Mini) which are available commercially.

- There are other proposed rail stress measurement techniques including ultrasonic methods and rail vibration methods. At the time of this research there were no commercial products/methods using these techniques, thus they were not explored further as part of this work.

4.1.2 The RNT Method

Despite the fact that two techniques have been described in the previous section, stress is difficult to measure directly and longitudinal force in CWR is difficult to measure directly.

Stress can also be determined by the following methods using rail temperature and RNT.

$$\sigma = E\alpha (T_{\text{RNT}} - T_{\text{Rail}}) \ [4]$$

Where:

- $E =$ Modulus of elasticity of rail steel (207 GPa [15] or $30 \times 10^6$ PSI)
- $\alpha =$ Coefficient of thermal expansion of rail steel ($11.7 \times 10^{-6}$/°C [15] or $6.5 \times 10^{-6}$/°F)
- $T_{\text{RNT}} =$ Rail neutral temperature (°C or °F)
- $T_{\text{Rail}} =$ Actual rail temperature (°C or °F)

According to a presentation from FRA in 2005, there is a need for RNT measurement accuracy to be ±2°F (±1°C), while a presentation from a past Heavy Haul Seminar indicated that RNT measurement accuracy of ±5°F (±2.8°C) is more achievable. [3]

The following are examples of methods to measure stress from RNT and temperature:

- Rail lifting method – This is a semi-destructive method and is currently considered the industry standard. The method involves unclipping a 30 m long section of rail (from the ties). A vertical lift force is applied to the unclipped rail section, and RNT is calculated from the resulting vertical displacement, along with data including rail temperature. This is a labour intensive method, where each measurement can take anywhere between 30 minutes to one hour. The measurements must be done when the rail temperature is below RNT. The accuracy of this method is reported to be ±3.5°C. While it is not suitable for measurement of rail stress in curves, this technique is often used to calibrate other measurement methods. Vortok International’s Verse system is based on this measurement technique. [6]

- Rail creep measurement method - One of the papers reviewed as part of this work described a method to determine changes in RNT through measurements of rail creep [15]. In track engineering terms, creep refers to the longitudinal displacement of rail track, which can be a result of train action (acceleration, braking) or thermal stresses. Creep is more often found in
locations such as near fixed structures (bridges, switches, etc...), at the bottom of hills, and at locations prone to track buckles.

\[
\sigma = E\alpha (T_{RNT0} - \frac{\Delta L}{L}\alpha - T_{Rail}) \quad [4] \quad [15]
\]

Where:
- \(E\) = Modulus of elasticity of rail steel (207 GPa [15] or 30 x 10^6 PSI)
- \(\alpha\) = Coefficient of thermal expansion of rail steel (11.7 x 10^-6 /°C [15] or 6.5 x 10^-6 /°F)
- \(\Delta L\) = measured rail creep or rail displacement (mm or in)
- \(L\) = length of rail segment (mm or in)
- \(T_{RNT0}\) = Rail neutral temperature when rail was constructed (°C or °F)
- \(T_{Rail}\) = Actual rail temperature (°C or °F)

- The rail cutting method – This is a destructive method outlined in the Swedish paper. In warm weather conditions, a rail is cut at two locations approximately 100 mm apart. After the rail anchor removal on a predefined length of rail, the rail temperature is calculated based on the average temperature of the rail within 50 m on each side of the measurement location, if the ends of the rail are pushing together, a segment \(L_f\) is cut away and the distance between the ends \(L_e\) is measured. RNT can be determined using \(e = L_e - L_f\) and Table 4. In cold temperature conditions, the rail is cut in one location only. After the rail anchor removal on a predefined length of rail, the gap \(L_e\) is measured between both ends of rail. RNT can be determined using \(e = L_e - L_f\) and Table 4. The measurement accuracy of the RNT is ±2°C. This is a labour intensive method that requires long measurement times.

<table>
<thead>
<tr>
<th>(e) (mm)</th>
<th>(T_{RNT-TRail}) (°C)</th>
<th>(e) (mm)</th>
<th>(T_{RNT-TRail}) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.5</td>
<td>-10</td>
<td>-0.6</td>
<td>0</td>
</tr>
<tr>
<td>-4.9</td>
<td>-9</td>
<td>-0.1</td>
<td>1</td>
</tr>
<tr>
<td>-4.4</td>
<td>-8</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>-3.8</td>
<td>-7</td>
<td>0.7</td>
<td>3</td>
</tr>
<tr>
<td>-3.3</td>
<td>-6</td>
<td>1.2</td>
<td>4</td>
</tr>
<tr>
<td>-2.8</td>
<td>-5</td>
<td>1.6</td>
<td>5</td>
</tr>
<tr>
<td>-2.3</td>
<td>-4</td>
<td>2.0</td>
<td>6</td>
</tr>
<tr>
<td>-1.9</td>
<td>-3</td>
<td>2.5</td>
<td>7</td>
</tr>
<tr>
<td>-1.4</td>
<td>-2</td>
<td>3.0</td>
<td>8</td>
</tr>
<tr>
<td>-1.0</td>
<td>-1</td>
<td>3.5</td>
<td>9</td>
</tr>
</tbody>
</table>

### 4.1.3 The Strain Measurement Method

Strain refers to the deformation an object experiences when a load or force is applied. The relationship between stress and strain can be generally described by Hooke’s law. [17]

\[
\varepsilon_x = \frac{\sigma_x}{E} - \nu \left( \frac{\sigma_y}{E} + \frac{\sigma_z}{E} \right)
\]

\[
\varepsilon_y = -\nu \frac{\sigma_x}{E} + \frac{\sigma_y}{E} - \nu \frac{\sigma_z}{E}
\]
\[ \varepsilon_z = -\nu \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} + \frac{\sigma_z}{E} \]

Where:
\( \varepsilon_{x,y,z} \) refers to strains in the longitudinal, lateral and vertical directions
\( \sigma_{x,y,z} \) refers to stress in the longitudinal, lateral and vertical directions
\( \nu \) refers to Poisson’s ratio (0.3 for rail steel [15])

It is clear from Hooke’s law that a strain can be measured in a direction, even if there was no direct load applied in that direction.

In absence of lateral and vertical load, longitudinal stress can be calculated via the following equation:
\[ \sigma_x = \varepsilon_x E \]

In absence of lateral load, longitudinal stress can be calculated via the following equation:
\[ \sigma_x = \frac{E}{1 - \nu^2} (\varepsilon_x + \nu \varepsilon_z) \]

Strains can be measured by using strain gauges, which are readily commercially available. There are many types of strain gauges available, including foil strain gauges, vibrating wire strain gauges, etc. Strain gauges are generally bonded, spot-welded or arc-welded into place. The instruments are relatively inexpensive, and depending on the type of data logging and collection equipment used, the data sampling rate can be extremely high.

Strain gauges are only able to measure the change in strain from the time they are installed, therefore it is necessary to calibrate the measurements with another instrument, or install them when the rail is at its stress free state. It is interesting to note that one research paper indicated since movement in the rail would be constrained by the track support system, therefore, in theory, while stress would develop in the rails, strains would not be measured. [5]

4.2 Measurement Technologies Review

NRC performed an in-depth scan of in-situ longitudinal rail stress measurement technologies in 2012. The work was funded by Transport Canada and the motivation for the work was to determine how the SFTPro S70, developed by a Canadian company, compared with other commercial technologies/prototypes available at that time for stress measurement.

The scan grouped the products into two primary categories, permanently installed technologies (as shown in Table 5) and portable measurement technologies (as shown in Table 6).
<table>
<thead>
<tr>
<th>Name</th>
<th>TrackLoad</th>
<th>Rail Multisensor</th>
<th>SafeTrak</th>
<th>RailStress Module</th>
<th>SFTPro S70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Rail Technology Ltd / Enco</td>
<td>Vortek International, UK</td>
<td>DataTraks, USA</td>
<td>Salient Systems (LB Foster), USA</td>
<td>Iders, Canada</td>
</tr>
<tr>
<td>Installation Method on Rail</td>
<td>Precision hole drilled in web, interference fit</td>
<td>Precision hole drilled in web, interference fit</td>
<td>Spot welded onto web using two 005in welds</td>
<td>High-strength adhesive (epoxy)</td>
<td>Two holes drilled in web, bolted attachment</td>
</tr>
<tr>
<td>Interrogation Method</td>
<td>Wired sensors connect to data loggers or to a wireless box, which communicates up to 400m to a wireless gateway for internet connection.</td>
<td>Up to four wired sensors connected to the SmartDean data logger, which transmitted wirelessly by Wi-Fi, email, or SMS.</td>
<td>Each wireless mesh network of sensors sends data to a self-powered communication base station, which transmits using wired or wireless moderns.</td>
<td>Sensors are interrogated individually using wireless handheld, truck mounted, or wayside readers. Many stored readings can be downloaded at once.</td>
<td>Sensors are interrogated wirelessly using handheld or truck mounted reader. New readings are taken only during interrogation.</td>
</tr>
<tr>
<td>Interrogation Range - Handheld</td>
<td>n/a</td>
<td>n/a</td>
<td>Possible with PDA or laptop, 150m</td>
<td>8 m</td>
<td>15 cm</td>
</tr>
<tr>
<td>Interrogation Speed - Moving</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0 km/h, 33m range</td>
<td>32 km/h</td>
</tr>
<tr>
<td>Transmission Frequency/ Data Values Stored</td>
<td>5 – 30 minutes</td>
<td>30 seconds – 24 hours</td>
<td>Up to 15 minutes, 1 hour default setting</td>
<td>10 minutes / 32,768 values stored</td>
<td>2,000 values stored</td>
</tr>
<tr>
<td>RNT Monitoring During Installation or Repair?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approximate Cost per sensor, Wired (C$)</td>
<td>$500 per sensor, $700 with data logger and modem, $1100 for remote locations</td>
<td>$400-450 per sensor, $1625 per sensor including data logger for remote locations</td>
<td>$400-450 per sensor plus communications</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Approximate cost per sensor, Wireless (C$)</td>
<td>n/a</td>
<td>n/a</td>
<td>$650 per sensor plus $300-1000 per network for base station.</td>
<td>$2000 per sensor plus $5000 for handheld or wayside readers.</td>
<td>$500 per sensor plus $10,000 handheld receiver or $30,000 hi-rail receiver.</td>
</tr>
<tr>
<td>Zero Calibration</td>
<td>By VERSE, remote calibration using &gt;10°C difference, or rail cutting.</td>
<td>By VERSE or cutting rail</td>
<td>By VERSE or cutting rail</td>
<td>By VERSE or cutting rail</td>
<td>By VERSE or cutting rail</td>
</tr>
<tr>
<td>RNT Accuracy</td>
<td>± 1.8°F if rail cut, ± 3.6°F by VERSE</td>
<td>Strain ± 1%, limited only by temperature accuracy</td>
<td>± 1 microstrain, limited only by temperature accuracy</td>
<td>Very accurate strain reading, limited by temperature</td>
<td>± 5 to 7°F</td>
</tr>
<tr>
<td>Operating Range</td>
<td>-50 to +100°C</td>
<td>-40 to +85°C</td>
<td>-40 to +80°C</td>
<td>-40 to + 70°C</td>
<td>-40 to +70°C</td>
</tr>
<tr>
<td>Sensor Maintenance</td>
<td>6-month inspections recommended</td>
<td>None if SmartDean used, battery charging by sun and vibration</td>
<td>Battery changes every 5 years in 'average climate'</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Limitations</td>
<td>Wireless sensors must be within 150m of each other</td>
<td></td>
<td></td>
<td>Maximum 10 year product life due to battery</td>
<td></td>
</tr>
</tbody>
</table>
Table 6: Summary of Commercially Available Portable Rail Stress/RNT Measurement Technologies in 2012 [3]

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>D'strese Technique</th>
<th>Stressing Gauge</th>
<th>CWR-Adjust</th>
<th>MAPS-SFT</th>
<th>Tracksafe Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERSE</td>
<td>Vortok International, United Kingdom</td>
<td>n/a</td>
<td>Vortok International, United Kingdom</td>
<td>n/a</td>
<td>TTCI, USA</td>
<td>Goldschmidt-Thermit, Japan</td>
</tr>
<tr>
<td>D'strese</td>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technique</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


| Measurement Method       | 30m of rail must be unfastened. The rail is then lifted and a deflection measurement taken | Dynamic shaker is clamped on rail. Resonance of rail under dynamic load is measured | Stressing Gauge clamps onto the rail. Changes in RNT are then displayed in real time | Computer software estimates RNT and how much to adjust it based on data that is entered | Electronic measurement device clamps onto rail for measurement | Portable device pushed along rail by operator takes stationary measurements |

| Measurement Time per RNT value | 20-30 minutes | n/a | Displays change of RNT in real time | n/a | 32 minutes | 30 minutes |

| RNT Measurement With Rail Monitoring During | ✔ | ✗ | ✗ | ✗ | ✔ | ✔ |
| RNT Measurement When Cutting | ✗ | ✔ | ✗ | ✗ | ✗ | ✗ |

| Cost (C$) | $85,000 | n/a | n/a | None for AAR railroads | n/a | Available as service only |

| User Calibration | None, calibration performed by manufacturer | Multiple readings must be taken at the same location at different temperatures | None | n/a | Calibration required for each rail grade and manufacturer | Calibration required. Rail must be at zero stress or accurately known stress |

| RNT/SFT Accuracy | Mean ± 2.5°F, Max ± 3.5°F (TTCI) | ± 10°F | ± 1.8°F | unknown | ± 8°F | ± 5.4°F |

| Limitations | Works only when rail is in tension. Ambient temperature must be lower than RNT when measuring. Proximity to certain structures not permitted. Corrections required for sharp curves. | Rail tension or compression must be independently established by operator. | Can determine neutral temperature if rail is cut, otherwise only tracks changes during maintenance operations or installation. | Provides estimates only, not a measurement tool. | Multiple readings required for single RNT value calculation. Operating range -10 to 60°C |

In 2017, only four of the eleven products are still commercially available,
- TrackLoad from Rail Technology Ltd., United Kingdom (Table 5)
• Rail Multisensor (renamed as Wheel Flat Detector System) from Vortok International, United Kingdom (Table 5)
• VERSE from Vortok International, United Kingdom (Table 6)
• Tracksafe Release from Elektro-Thermit GmbH & Co. KG, Germany (Table 6)

All other products were either still in the developmental stage, not accepting new orders, or no information could be obtained on them.

4.3 Measurement Technologies Hurdle

Judging from the drastic reduction of the number of commercially available technologies for rail stress/RNT measurement over the past few years, achieving accurate measurement in a practical and cost effective manner within the Canadian rail operating environment is clearly a difficult challenge.

NRC’s 2012 technology scan further identified the following unique challenges for the Canadian operating circumstance [3]:

• Track environment – The railway operating environment can be extreme in Canada. In addition, routes often traverse through remote regions. Sensing equipment must be able to withstand extreme temperature fluctuations (at least between -40°C to +40°C), severe weather conditions (i.e. freezing rain, heavy wind, frost, rain and snow fall), strong vibrations, potential damage from maintenance activities (i.e. tamping), as well as vandalism from trespassers and damage from wild animals.

• Installation related concerns – Experience from companies such as Iders indicated that Canadian railway companies are often not in favor of installation techniques that require welding or drilling onto the rail itself. This does not appear to be an issue elsewhere, as Koda Australia Pty Ltd. has utilized spot weldable gauges for its rail stress monitoring work in Australia.

• Calibration requirements – Since many of the most common technologies measure change (i.e. strain gauges measure the change in strain from the time they are installed), it is important to have a method of establishing the initial stress state (absolute stress) in order to calibrate the measured values.

• Lack of consensus on data collection frequency – Most of the railway personnel interviewed by NRC during the 2012 technology scan indicated that there is no need for real time data, as most would use the data for maintenance planning purposes (about two to three times per week) rather than operational decision making. A few railway personnel indicated that real time information would be useful for work crew during installation and maintenance activities. Most expressed the need for non-destructive measurement methods.

• Lack of consensus on permanent versus portable solutions – Interviews with railway personnel indicated that there is interest from railways to monitor their entire network, though 60%

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3 The TrackLoad system (Table 5) and Rail Multisensor system (Table 5) require drilling into the rail.
4 The Verse System (Table 6) is considered to be a semi-destructive method.
5 The Tracksafe Release System (Table 6) is available only as a service and is not necessarily available on demand for Canadian railways.
interviewed preferred portable technologies, which provide greater flexibility for taking measurements where needed.

- **Cost** – Due to the vastness of Canada’s rail infrastructure, the cost for wide implementation of measurement technologies is a key consideration and challenge. The estimated cost in 2012 on the effort required to implement permanent sensors on a national level is shown in Table 7.

<table>
<thead>
<tr>
<th>Country</th>
<th>Rail Network Length</th>
<th>Sensors to Monitor 50% of Track Every 150 m</th>
<th>Price to Monitor 50% of Track at $500 / Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>United Kingdom</td>
<td>16,454 km</td>
<td>109,693</td>
<td>$ 55 M</td>
</tr>
<tr>
<td>Canada</td>
<td>48,000 km</td>
<td>320,000</td>
<td>$ 160 M</td>
</tr>
<tr>
<td>United States</td>
<td>224,792 km</td>
<td>1,498,613</td>
<td>$ 749 M</td>
</tr>
</tbody>
</table>

### 4.4 Potential New Technologies

While it is preferable to utilize products designed specifically for rail applications, due to the limited number of commercial options available for the Canadian circumstance, a review of technologies was expanded to industries with similar operational environments, including oil and gas, construction, geotechnical and mining.

Three technologies were identified that could be adapted for longitudinal rail stress measurement, including frictional strain sensing, X-ray diffraction and fibre optic sensing.

#### 4.4.1 Frictional Strain Gauges

As discussed in Section 4.1.3, strain gauges are inexpensive and proven methods to collect data in-situ. However, bonded and welded strain gauges require extensive surface preparation such that it can take up to a few hours to install each sensor in the field, making them impractical for the purpose of collecting measurements from long sections of track.

TML Tokyo Sokki Kenkyujo Co., Ltd., manufactures a type of foil strain gauge that attaches using magnets, as shown in Figure 13.

![Figure 13: Frictional Strain Checker [18]](image-url)

The advantage of this type of strain checker, according to the manufacturer, is the ease of installation. It does not require bonding or welding, and likely requires much less surface preparation than other types.
of strain gauges, such as grinding, degreasing and polishing. The strain checker can be used in small and hard to access areas, such as near a weld, and also can be removed and reused, thus enabling the refinement of measurement locations without sacrificing sensors. The FGMH-3A is also able to measure strain in multiple axis (0°/45°/90°), thus able to provide more information for research purposes.

The frictional strain checker is one of the most expensive strain gauges examined as part of this research project, at between $772 and $1,300 CAD. The operating temperature of the strain checker is rated at between 0 to 60°C, which is a cause for concern over its ability to operate in cold weather conditions. In addition, the manufacturer indicated that measurements might not be accurate if the strain checker is located near the vicinity of strong vibrations. Since train operations can generate strong vibrations through the rail, propagating at the wheel-rail interface, it remains to be seen whether this type of strain gauge is suitable for the rail operating environment.

The potential use of frictional strain gauges include applications at new field sites to assist in refining permanent strain monitoring locations, warmer climates, and possibly on replacement plug rails. CN also suggested using this technology to monitor the effect of maintenance activities on rail stress and RNT.

4.4.2 **X-Ray Diffraction**

As discussed in Section 4.1.1, X-ray diffraction is a non-destructive, direct stress measurement method. This method has not been tested for rail applications. According to American Stress Technologies Inc., a manufacturer of this type of equipment, this technology has been utilized in manufacturing and civil engineering applications for many years.

American Stress Technologies Inc., makes a number of different portable models, including the Xstress 3000 G2/G2R and the Xstress Mini. The Xstress 3000 G2/G2R model consists of a main unit (25 kg/55 lbs, Figure 14, left) and a goniometer (10-16 kg/22-35 lbs, Figure 14, centre). The Xstress Mini (Figure 14, right) weighs 6.5 kg/14.3 lbs.

![Figure 14: Example X-Ray Diffraction Equipment, Xstress 3000 G2/G2R (Main Unit – Left, Goniometer - Centre [19]), Xstress Mini (Right [20])]  

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6 As with other strain gauge sensors, a data collection solution is needed to be used in conjunction with the frictional strain checker.
The advantages of this type of technology include the potential to determine absolute stress in a non-destructive manner, and more rapid setup and measurement (potentially 10 to 15 minutes per measurement) compared to the Verse system. This system has the potential to provide the initial reference point to calibrate systems that measure relative stress, such as strain gauges.

Both XSTRESS 3000 G2/G2R, and XSTRESS Mini require a power source. In the field, a generator is likely needed. All the necessary equipment can easily fit and be transported in normal hi-rail trucks.

Since the technology has not been tested for rail applications, there are a few unanswered questions about its suitability for longitudinal rail stress measurement in the field. The minimum operating temperature of the system is rated at 5°C which is a cause for concern over its ability to operate in cold weather conditions, during which the majority of rail breaks occur. In addition, the technology performs a surface measurement, to a depth of 5 to 7 µm, therefore the questions of whether absolute stress of the entire rail section can be accurately determined from such a measurement and whether near-surface damage will interfere with the accuracy of the measurement remain to be answered. It is also important to note that it is unclear if surface preparation is needed. Finally, as x-rays are used to perform the measurement, appropriate safety precautions for personnel handling the equipment must be considered.

4.4.3 Fibre Optic Sensing

To make real progress in advancing the understanding of rail longitudinal stress, an accurate, practical and affordable method to instrument long segments of track is needed. Fibre optic sensing presents a potential solution.

Fibre optic sensing is a relatively generic term used to describe many different methods that are used for different types of measurements. In general, fibre optic sensing requires two elements, the fibre optic cable (the sensing element) and an analyzer.

Fibre optic sensing can be broadly categorized into “fully distributed” or “quasi-distributed” systems. Fully distributed systems make measurements along the whole length of the fibre cable\(^7\), while quasi-distributed systems make measurements at specific points only\(^8\).

Table 8 provides a quick overview of some commercially available fibre optic analyzer methods that could be adapted for rail applications.

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\(^7\) The fiber optic cables used for fully distributed systems are selected based on the sensing purpose and operating environment, but are generally mass produced with a comparatively lower cost.

\(^8\) The locations of measurement on the fibre cable are referred to as gratings, which are made by multiplexing (exposing the fibre to intense ultraviolet light). Gratings usually have a length of approximately 10 mm. Fibre optic cables used for quasi-distributed systems are comparatively higher cost.
### Table 8: Summary of Commercially Available Fibre Optic Analyzer Methods Reviewed for Rail Applications

<table>
<thead>
<tr>
<th>Fibre Optic Analyzer Method</th>
<th>Key Principles</th>
<th>Sensing Information</th>
<th>Pros</th>
<th>Cons</th>
<th>Known/Potential Applications</th>
</tr>
</thead>
</table>
| Rayleigh scattering         | A pulse of light is sent down the length of the fibre. Imperfections in the fibre scatter some of the light back. When the fibre is subjected to strain, the light that is back scattered changes in frequency. The frequency change (or spectral shift) can be determined, and is linearly related to the change in strain. | - Fully distributed sensing  
- Can be configured to measure strain  
- Can be configured to measure acoustics and vibrations | Commercial products using this method have comparatively the highest spatial resolution.  
|                                                                           |                                                                                                  |                                                          | The sensing length is comparatively short (50 to 70 m).               | The method is also not able to differentiate strains caused by different loading mechanisms (i.e. when both mechanical and thermal loading is present). | Queen’s University has been using systems configured for strain measurements on rail infrastructure research.  
|                                                                           |                                                                                                  |                                                          |                                                                      |                                                                      | Systems configured for strain measurements with high frequency data collection may be well suited for the monitoring of dynamic rail forces.  
|                                                                           |                                                                                                  |                                                          |                                                                      |                                                                      | Systems configured for acoustic and vibration measurements are commonly used in oil and gas industries.  
|                                                                           |                                                                                                  |                                                          |                                                                      |                                                                      | Systems configured for acoustic and vibration measurements may be well suited for railway trespasser and intrusion detection applications. |

9 Spatial resolution refers to the smallest sensor spacing placement.
<table>
<thead>
<tr>
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<th>Pros</th>
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</tr>
</thead>
</table>
| Brillouin scattering        | Brillouin scattering occurs from acoustic vibrations stimulated in the optical fibre, which produce a counter-propagating wave (Brillouin scattering wave) which weakens the forward moving light pulse. To satisfy the requirement of energy conservation, there is a frequency shift between the Brillouin scattering wave and the original light pulse frequency. This frequency varies for different temperature and longitudinal strain conditions, making it possible to measure strain and temperature distribution. | - Fully distributed sensing  
- Measures strain when tightly bonded to material under test  
- Measures temperature when loosely bonded to material under test | Commercial products using this method have comparatively the longest sensing length (150-200 km).  
Depending on the broadband pulse generator, the broadband photodetector, and high speed digitizer used, a spatial resolution as small as 2 cm is possible with long sensing lengths. | Compared to Rayleigh scattering systems, this technology has a lower spatial resolution. | University of Ottawa has been using fiber optic sensing systems based on this method for pipeline, civil and structural monitoring.  
Commercially available systems based on this method may be well suited for long term measurement and monitoring of longitudinal stress and temperature. |
<table>
<thead>
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| Raman scattering           | A high intensity light signal is sent down the length of the fibre. Two frequency-shifted components called Raman Stokes and Raman anti-Stokes appear in the back-scattered light spectrum. The relative intensity of these two components depends on the local temperature of the fibre. If a light signal is pulsed and this back-scattered intensity is recorded as a function of the round-trip time, it becomes possible to obtain a temperature profile along the fibre. | - Fully distributed sensing  
- Measures temperature | Commercial products using this method can have long sensing length. | For this method, there is a tradeoff between sensing length and spatial resolution. (For example, a sensing length of 37 km has a spatial resolution of 17 m. A sensing length of 1 km, can have a spatial resolution of 1 cm). | Fire detection, temperature measurements of structures such as tunnels. |
| Fibre-Bragg gratings (FBG) | A light is sent along the length of the fibre (with Bragg gratings). The wavelength corresponding to the grating period will be reflected, while all other wavelengths will pass through the grating undisturbed. Since the grating period is strain and temperature dependent, it becomes possible to measure these two parameters by analyzing the spectrum of the reflected light. | - Quasi-distributed sensing (Other quasi-distributed systems include Long Period gratings, Tilted Fibre Bragg gratings)  
- Measures strain  
- Measures temperature  
- Measures displacement (Note: when both strain and temperature need to be measured simultaneously, it is necessary to use a free reference grating that measures the temperature only to calibrate the strain measurements) | Precision can be in the order of 1 με and 0.1°C with the use of the best demodulators | The reliability of simultaneous measurement of strain and temperature have yet to be proven in the field.  
Typically, 4 to 16 gratings can be measured on a single fibre line. There is a trade-off between the number of grating and the dynamic range of the measurements on each of them. | This method is widely used commercially on a variety of applications. |
In North America, railways have operated with CWR since the 1950’s. However, there is insufficient information on how rail behaves under stress, how longitudinal stress changes over time, how stress impacts the interaction between track and trains during operations, what exact stress condition(s) would cause broken rail or track buckling, nor how effective are current stress management practices.

A literature review of thirty-three technical documents revealed a recurring theme of the difficulty in quantifying the level of stress being experienced by rails in CWR construction.

A previous study completed by NRC in 2012 noted that “Technologies to measure RNT exist, but are in various stages of development. Still today, railways are trying to manage something they have great difficulty measuring.” [3]

Recent NRC consultations with railway stakeholders in Canada concluded that there is a need to improve rail longitudinal stress measurement, and such improvements have the potential of advancing rail transportation safety, as well as significantly reducing track-related expenditures.

Three potentially game changing technologies for longitudinal rail stress measurement were identified, including frictional strain sensing, X-ray diffraction and Brillouin scattering fibre optic sensing. These are commercial technologies already used in industries including oil and gas, construction, geotechnical and mining.

Recommended next steps:

1. An important next step would be to test the three technologies in controlled laboratory settings to determine their accuracy and suitability for rail applications. Three tests are recommended: a compression-tension test to determine the accuracy and precision of the instruments compared to a known applied load, a climatic test to determine field durability of the instruments under a thermal load, and a field test under the operation of rollingstock to determine their behavior in more realistic settings (including coping with vibrations).

2. If the results from the controlled laboratory testing show promise, it is recommended that the technologies be deployed in the field to gather data in order to gain better insights into rail stress in-situ. The first step would be to deploy X-ray diffraction with the Verse system to compare the two systems and to establish baseline measurements. A brillouin scattering fibre optic sensing system could be permanently deployed at sites across Canada, containing different climatic zones and different track features, including tangent track, bridge transitions, different track stiffness, curved track, different speed zones, and hills. A number of potential research sites have been identified including VIA Rail’s Smith Falls Subdivision, Chemin de fer QNS&L’s Wacouna Subdivision, Genesee and Wyoming’s North Bay Subdivision and ArcelorMittal’s Cartier Subdivision.

Ultimately, it is unlikely to be practical nor necessary for rail companies to implement system-wide monitoring. The ultimate goal of this research is to generate critical information and guidelines to help railways:
• Maintain better records of rail longitudinal stress related issues, such as buckles, breaks and related maintenance. [4]
• Better understand rail asset life and performance over time, and how it impacts safety and cost [5], as well as information that could improve the rail steel fracture toughness. [6]
• Identify more applicable RNTs for track construction for the geographical region.
• Identify more practical tools and technologies to use for rail longitudinal stress monitoring.
• Identify critical track locations that need better monitoring.
• Identify effective track maintenance strategies to maintain the RNT and track resistance.
• Improve CWR track construction methods to mitigate the impact of rail stress due to climatic changes. [6]

Considering the fact that assets are expensive, and for rail transportation, track infrastructure is vast (45,000 km), there is a need to better monitor assets to improve safety, proactively detect issues, and prolong asset life. Since technological innovations appear on the market on a regular basis, NRC recommends that a scan of technologies to advance the monitoring of infrastructure health be performed on a regular basis.
6 REFERENCES


