High speed detection of broken rails, rail cracks and surface faults
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Title: High speed detection of broken rails, rail cracks and surface faults

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Synopsis:
Despite significant technological advances in the safety of trains and the associated strategies of railway track maintenance, breakages of rails and joint bars still occur frequently around the world, leading to major train derailments. Traditionally, railways around the world employ track circuit based signalling systems for two important safety functions: a primary function of providing basic traffic flow regulations, and a secondary function of avoiding derailments by detecting broken rails, despite their limitations. Thus the track circuitry is regarded as critical infrastructure for public safety, the economy and the environment. In recent times, alternative train control technologies such as Communication-Based Train Control (CBTC) and Positive Train Control (PTC) are emerging as efficient and cost-effective alternatives to the existing track circuit based signalling systems. Unfortunately, these new technologies cannot detect broken rails. Hence, new technologies for detecting broken rails are urgently required in order to adopt these new train control systems and increase the performance and safety of the railway operations, while reducing the potentially disastrous broken rail risks that can have catastrophic consequences. This report contains a comprehensive review of the state of the art of the technologies relevant to the high speed detection of broken rail and other rail defects, including data on major derailments in Australia and other comparable economies. Track-based and cabin-based systems that are being developed are also reviewed; and a recommendation for tapping the expertise available within the Australian rail industry for the development of a safety system that will solely depend on train-based sensors and communication devices that can coexist with CBTC/PTC systems for broken rail detection is provided.

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# TABLE OF CONTENTS

Executive summary ................................................................................................................................................ ii
List of figures ......................................................................................................................................................... iii
Abbreviations and acronyms ................................................................................................................................. iv

1. Introduction .......................................................................................................................................................... 1

2. Theory of broken rails ........................................................................................................................................ 2
   2.1 General ......................................................................................................................................................... 2
   2.2 Damage detection techniques ....................................................................................................................... 4

3. Review of accidents due to broken rails ........................................................................................................... 6
   3.1 Major broken rail incidents ........................................................................................................................ 8
   3.2 Critical factors affecting broken rails ........................................................................................................ 11
   3.3 Past responses to broken rail derailment incidents.................................................................................... 12

4. Track circuit based signalling broken rail detection systems .......................................................................... 15
   4.1 Review of patented systems ........................................................................................................................ 15

5. Broken rail detection systems for CBTC applications .................................................................................... 19
   5.1 Track circuit based signalling systems ........................................................................................................ 19
   5.2 Ultrasonic broken rail detector from RailSonic ............................................................................................ 20
   5.3 High speed rail IDEA projects ................................................................................................................... 21
   5.4 Other high speed rail research projects ...................................................................................................... 22
   5.5 Rail defect management program ............................................................................................................... 23

6. Applied broken rail detection technical research .......................................................................................... 25

7. Concluding remarks ......................................................................................................................................... 26

References ............................................................................................................................................................. 28
EXECUTIVE SUMMARY

This report contains the state of the art of the high speed detection technologies for broken rails, a summary of which is presented below.

- A broken rail represents one of the leading causes of the most expensive and dangerous rail derailments that occur around the world. Considering derailments in general, in the US alone, on average, more than one major derailment occurs for each three-day period, consistently over a decade. The statistics available on the frequency of broken rail derailments in other countries do not help properly understanding the economic, social and environmental impacts.

- Reports on past broken rail derailments show that the ultrasonic rail flaw detection tests conducted just a few weeks prior to major derailment incidents (caused by broken rails) revealed no suspicious rail defects; this limitation in the technology to detect and interpret the defect data provides no clear guidelines to railway operators for averting those incidents in most cases.

- Conventional track circuit based signalling broken rail detection systems, despite extensive research and patents, are not 100 per cent effective in detecting broken rails.

- Communication- Based Train Control (CBTC) and Positive Train Control (PTC) systems alone cannot provide broken rail detection capabilities.

- Risk-based approaches rate fatigue with the highest severity index, and wear with the lowest severity index.

- Field trials of various broken rail detection technologies for high speed lines and for dark territories show no conclusive findings to date. Many of the new systems being developed also suffer from similar limitations of the existing wayside track-circuit equipment based technologies.

- The majority of broken rail detection technology developments reported in the literature are primarily based on the track circuit based signalling and sensor technologies.

- There is a paucity of literature with regard to reliable technologies (except for a few academic research and small-scale prototype studies) for high speed broken rail detection in real-time manner.
LIST OF FIGURES

Figure 1: Typical examples of broken rails and rail damage: (a) subsurface cracks; (b) surface cracks
Figure 2: Common types of rail breaks
Figure 3: Severity plot of railway mainline derailments by cause (US) from 1996–2005
Figure 4: Annual number of rail-caused derailments in US for the period 1998–2008
Figure 5: Statistical summary of rail-defects related train derailments reported on Canadian railways for the period 2000–2009
Figure 6: Canadian Pacific Railway Freight Train 292-16 derailment scene
Figure 7: View of wagons derailed to the side of the railway track
Figure 8: A schematic illustration of high-rail vehicle-based rail inspection system
Figure 9: Venn diagram of inspection and detection, rail breaks and derailment
Figure 10: Percentage of ‘potential rail breaks’ detected by different inspection tools
Figure 11: A block diagram of a basic system of broken rail detection apparatus
Figure 12: A block diagram of a rail break or vehicle detection system
Figure 13: A block diagram of a rail break or vehicle detection system
Figure 14: A block diagram for an active broken rail detection system
Figure 15: Block diagram of the ultrasonic broken rail detector system
Figure 16: Schematic of the acoustic-based broken rail detection concept
### ABBREVIATIONS AND ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AAR</td>
<td>Association of American Railroads</td>
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<td>ATP</td>
<td>Automatic train protection</td>
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<td>CBTC</td>
<td>Communication-Based Train Control</td>
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<td>CN</td>
<td>Canadian National</td>
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<td>COTDR</td>
<td>Coherent optical time-domain reflectometry</td>
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<td>CWRs</td>
<td>Continuously welded rails</td>
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<td>CTC</td>
<td>Centralised traffic control</td>
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<td>FAST</td>
<td>Facility for Accelerated Service Testing</td>
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<td>FRA</td>
<td>Federal Railroad Administration</td>
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<td>IMT</td>
<td>Institute for Maritime Technology</td>
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<td>Insulated rail joints</td>
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<td>Non-destructive testing</td>
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<td>Office of Transport Safety Investigations</td>
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<td>Positive Train Control</td>
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<td>RDM</td>
<td>Rail defect management</td>
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<td>RCF</td>
<td>Rolling contact fatigue</td>
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<td>RDI</td>
<td>Rail Defect Index</td>
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<td>SHM</td>
<td>Structural health monitoring</td>
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<td>TCRP</td>
<td>Transit Cooperative Research Program</td>
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<td>TDMA</td>
<td>Time division multiplexed access form</td>
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<td>Time domain reflectometry</td>
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<td>TRB</td>
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<td>TTCI</td>
<td>Transport Technology Centre, Inc.</td>
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<td>TTI</td>
<td>Texas Transportation Institute</td>
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<td>UBRD</td>
<td>Ultrasonic broken rail detector</td>
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<td>UIC</td>
<td>International Union of Railways</td>
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1. Introduction

Currently, railways around the world employ track circuit based signalling systems that provide two important safety functions: a primary function of providing basic traffic flow regulation, and a secondary function of avoiding derailments by detecting broken rails ahead. Even though the conventional track circuit based techniques have been useful in reducing the risk of broken rail derailments and served the interests of the rail industries well, they are not accurate enough, and do not detect a substantial percentage of rail breaks in which electrical continuities are maintained. Further, there exist dark territory rail lines, where the railway signalling equipment does not exist; in these low traffic sections, track circuitry is solely maintained for broken rail detection, although partial rail breaks that pose extreme severe derailment risks cannot be detected. Furthermore, joint bars in these track circuitries are vulnerable to breakage as much as the continuously welded rails (CWRs). Thus, the track circuitries are regarded as expensive, considering their limited contribution to broken rail detection and their own poor structural integrity, especially under heavy axle loading. In dark territories, manual interventions and restricted traffic control are the primary means of detecting broken rail or joint bars to maintain safety. This operational procedure often affects the overall productivity and performance of railway operations.

In recent times, new alternative traffic control technologies such as Communication-Based Train Control (CBTC) and Positive Train Control (PTC) are emerging. These technologies do not require the existing track circuit based signalling systems; therefore, these are considered as efficient and cost-effective alternatives. Unfortunately, these new technologies cannot detect broken rails. Hence, alternative technologies for detecting broken rail are required to replace the track circuit based signalling train regulation systems so that the CBTC and PTC systems can be adopted. These alternative technologies can improve the performance and safety of the railway operations by significantly reducing the risk of train derailments with potentially catastrophic consequences to public safety, the economy and the environment.

The aim of this report is to review the state of the art of the technologies, with particular reference to broken rail detection. Section 1 provides an introduction to the report. In Section 2, a short introduction to the theories of broken rails in the context of damage identification technologies is presented. Brief critical reviews of the existing ‘traditional’ broken rail detection technologies developed, based on track circuit based signalling, are contained in Section 3. Typical track circuit based signalling ‘earlier’ inventions are reviewed, and the ‘recent’ inventions that incorporate recent advances made to this technology category are presented in Section 4. In Section 5, broken rail detection systems, notwithstanding the success of field adoption relevant to CBTC applications, are reviewed. In Section 6, brief reviews of the application-oriented advanced research and alternative risk analysis based approach are presented. Finally, concluding remarks and a summary are presented in Section 7, followed by some recommendations for the development of reliable and cost-effective technologies.
2. Theory of broken rails

2.1 General

Rails guide trains and are subjected to severe contact stresses at the wheel–railhead interface. Each wheel passage reshapes the railhead profile due to wear; extreme levels of stress concentration also induce surface and subsurface fatigue cracks in railheads (Figure 1). Routine grinding and re-profiling save railheads from the growth of the initiated cracks to critical levels that lead to partial or full breakage of the rail. Proper maintenance of the wheel profile is also essential to keep the railhead stresses within safe levels, as wheel skid flats and wheel out-of-rounds can substantially increase impact loads; in extreme cases, they can break welds or railheads due to ultimate capacity exceedence, rather than fatigue. Where third party operators of unknown levels of repute run trains, it is necessary to measure wheel impacts in order to determine the potential for ultimate capacity exceedence.

![Figure 1: Typical examples of broken rails and rail damage: (a) subsurface cracks; (b) surface cracks](source: Schafer & Barkan 2008a)

Increased axle load and frequency of traffic (throughput) affect the mechanisms of initiation and growth of railhead cracks in a complex manner. Due to the nonlinear nature of the wheel–rail contact, increased axle loads do not always lead to proportional levels of increased stresses. The plasticity of the railhead material also contributes to the significant nonlinearity and complexity of stress levels, and the magnitude and frequency of the axle load. Where the stress levels remain below the shakedown limits of the material, prolonged life of the rails can be achieved. Where the stress levels rise above the shakedown limits, increased metal flow (ratchetting of material) occurs; once the metal flow exceeds a critical threshold, fatigue crack might initiate and lead to the onset of crack growth. Sensors do not always accurately detect the early stages of cracks, as their signature is affected by noises; wavelet analysis of the random signature yields some success, but is computationally expensive. By deploying more powerful multi-processor computers and improved algorithms of signal processing, early detection of cracking of railheads may become a reality.

Metal plasticity is affected by the ambient temperature — particularly when the temperature plunges to freezing levels, and remains in substantial sub-zero territory for prolonged periods of time. In such situations, the ductile steel becomes brittle, and can lead to rail breaks due to capacity exceedence under rail bending. Most North American broken rails occur during severe winter. Australian weather saves the track from such disasters. While cracking of the railhead is very complex, other parts of the rail (e.g. rail web bolt hole) and joint bars are subjected to stress levels within the elastic limit of the material. The life of these components can be estimated from the theory of linear fracture mechanics; a twofold increase in load (and hence stresses) will cause an eighfold reduction in the life of these components. Through proper management of the axle loads, wheel and rail profiles,
and track conditions, the dynamic load factor could be kept at the minimum; this will help keeping the stress levels in rail at optimal level for increased throughput.

### Common Types of Rail Breaks

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**Figure 2: Common types of rail breaks**

*Source: Taylor 2011*

Common types of broken rails are shown in Figure 2. Any breakage that occurs over the joint bars, rails or welds in any shape or form is classified as a broken rail incident; as can be seen, partly damaged, cracked or separated rails are also counted as incidents within the limits of the special track work, as they pose high risks to the safety of trains.

Rails are designed as beams resting on continuous elastic foundation. This theory assumes the beams as continuous; any break in rail changes this assumption, causing severe disruption to the deflections and rotations determined at design stage. Even a breakage far away from a wheel can potentially affect the rail rotations under the wheel that change the contact conditions, leading to undesirable dynamics for the wheel sets. The vibration signature of the rails can be used for the prediction of the damage levels including breakage.

Rails can be analogised as a string in a musical instrument, with the sleepers as their nodal points; any change to sleeper spacing affects the soundwaves generated by the dynamic interaction between the wheel and the railhead. Similar to the vibration signature of the rails, the wheel–rail interaction based soundwaves can also be used to predict the damage levels, including breakage in rails.
Rails resting on low stiffness tracks, characterised by poor ballast stiffness, lack of impervious capping layers and hanging sleepers, dip unfavourably due to the passage of wheels; these dips, coupled with permanent track defects, pose a challenge to maintaining speed levels required for the desired levels of productivity. Rail breaks on such tracks aggravate the undesired dynamic interaction between the wheel and the railhead. Signatures of vibration and soundwaves from these tracks will have added noise levels that make detection of the broken rail component complex, if not impossible.

Although detection of broken rails using the passive approach, based on rail response from the principles of engineering mechanics, is possible, most existing technologies rely on the active method of transmitting and receiving signals; these technologies usually require trackside infrastructure that is expensive to maintain if not install.

In general, the basic premise behind these active methods of structural damage identification is that the defects cause changes in structural physical properties, which will, in turn, alter structural response characteristics such as vibration responses and wave propagation characteristics in structural solids, among others. Hence, by monitoring response signatures through the use of various measurement sensors and data acquisition technologies, the current condition of the structural system concerned can be determined.

Moreover, the broadly accepted paradigm in the damage identification techniques generally involves four levels of identification processes. These included (from lowest level to highest level) (Rytter 1993):

- detection of the existence of any defects
- identification of the location of the defects, if they exist
- determination of the severity of the defects
- determination of the remaining service life of the infrastructure concerned.

### 2.2 Damage detection techniques

In general, there exist three main categories of techniques currently used for damage identification and condition monitoring of structures and solids. These include:

- visual inspections
- non-destructive testing (NDT) technologies such as acoustic emissions or ultrasonic methods, magnetic field methods, radiography, eddy current techniques, thermal field methods, dye penetrant, fibre optic sensors of various kinds
- vibration-based ‘global’ methods.

Both visual and NDT-based methods offer limited capabilities to conduct ‘global’ structural damage condition investigation in common structural systems such as bridges and buildings. The successful implementation of these inspection methods generally requires the regions of the suspected damage to be known as a first step, and be readily accessible for physical inspection. As a result, these methods can be costly, time consuming and ineffective for large and complex structural systems such as the rail track. However, it is important to mention that visual inspection and NDT-based technologies are the primary techniques used for defect identification in structural solids, and are effectively used in specialised disciplines, such as in the railways.

On the other hand, vibration-based ‘global’ structural damage identification methods are based on global vibration response measurements at certain points of a structure, so as to inversely determine its damage condition (Sohn et al. 2004; Bayissa 2007). The theoretical basis for damage identification methods based on vibration response measurements is that structural damage causes changes in structural dynamic properties, which in turn cause changes in the global vibration response characteristics of the structure (such as natural frequencies, mode shapes, modal damping, frequency response functions, spectral strain energy). Consequently, examination of the variations in the vibration response characteristics provides useful information regarding the existence, location and extent of the structural damage, without prior knowledge of the damage condition.
Structural damage identification and condition monitoring methods can also be classified as non-modal-based and modal-based methods. Non-modal-based damage identification methods employ response data obtained separately from the undamaged and the possibly damaged state of the structure, in order to detect and localise damage without involving a detailed analytical model of the structure. On the other hand, modal-based damage identification methods employ updating of an analytical model of the undamaged system along with the response data obtained from various damage condition of the structure concerned to detect, localise and estimate the damage severity. The main difference between the two identification methods lies with the level of damage that can be identified using each of them.

In the context of this chapter, the technologies for high speed detection of broken rails, rail cracks and surface faults should be able to not only detect the existence of rail defects or breaks, but also provide reliable predictive information regarding the location and severity of the rail defects or breaks, so that appropriate real-time safety measures can be implemented by railway managers.

The NDT technologies (Clark 2004; Labropoulos, Moundoulas & Moropoulou 2006; Pau, Leba & Baldi 2008; Magel et al. 2004) are either slow when applied in conjunction with manual inspection, or quite expensive when integrated with special classes of rail vehicles. In general, there is a tremendous need for the development of alternative and improved techniques suitable for monitoring progressive deterioration at early stage to avoid possible undetected sudden failure. In particular, there is an urgent requirement for accurate and more reliable technology for broken rail detection in high speed scenarios.

Finally, high speed broken rail detection requires special attention as it is associated with the safety of critical infrastructure, and any undetected defect could cause train derailments with potentially catastrophic consequences for public safety, the economy and the environment.
3. **Review of accidents due to broken rails**

In recent years, the need for the development of rail defect detection technologies has attracted widespread attention, primarily in response to a series of rail accidents that occurred in various parts of the world (Clark 2004). Typical high profile rail incidents that brought rail safety inspection issues back to the research and development focus included: the Hatfield accident in October 2001 (UK), and the westbound California Zephyr (Amtrak service) accident in 2001 (USA), among others. The causes of these accidents were found to be broken rails, which may have occurred as a result of undetected growth of internal or surface rail defects and rail fatigue cracks due to repeated passage of traffic with increasing axle loads, speed and frequency (Sperry Rail Service 1999; Aglan & Gan 2001; Kim & Kim 2002; da Silva et al. 2003; Fletcher, Hyde & Kapoor 2004; Skyttebol, Josefson & Ringsberg 2005; Smith 2005; Fischer et al. 2006).

Despite significant technological advances made towards the train and railway track infrastructure over the last many decades, rail and joint bar breakages occur frequently around the world, with risk of potentially catastrophic rail derailments. For instance, in the UK, the annual number of broken rails was found to be approximately 770 per year between 1969 and 2000 (Cannon et al. 2003).

In North America, broken rails are the leading cause of reported major derailments. Track‐caused derailments due to broken rails, defects in the track geometry, turnout, etc. are reported to represent up to 40 per cent of all Federal Railroad Administration (FRA) reported derailments (Zarembski 2009). Further, among the track‐caused derailments, derailments due to broken rails present a high potential for injury, death, property damage and accident-caused hazardous materials releases (Barkan, Dick & Anderson 2003).

Figure 3 shows the severity level of railway mainline derailments by cause (USA) from 1996 to 2005 (Schafer & Barkan 2008a). As can be observed from this figure, broken rail derailments (along with joint bar defects) are the main causes of the largest number of accidents, as well as the largest number of cars derailed (with the increased potential for economic losses and environmental disasters). The data shows that, in the USA alone, more than 1200 severe incidents involving average derailment of 10 cars over the decade 1996–2005 occurred due to broken rails and welds; joint bar failure added another 100 severe incidents. On average, such accidents occur at the frequency of just three days! Further, there are several broken rails that are routinely detected and corrective actions taken, preventing accidents. Therefore, rail breakage is regarded as a routine rather than an exceptional event. As broken rail caused derailments are classified among the most expensive and dangerous derailment categories (Cannon et al. 2003), and the risks associated with broken rail for high speed freight and passenger rails are of significant concern, there is a pressing need for reliable and cost-effective technology for the detection and management of defective rails.
FRA statistics shows that 350 to 400 derailments occur a year, with an annual cost to the US railroad industry of more than $140 million. Figure 4 demonstrates that the annual number of rail-caused derailments for the period 1998–2008 shows an insignificant reduction over a 10-year period, despite increased efforts by the railways to develop advanced rail defect detection technologies and adopt improved rail inspections strategies over the years.

From 2003 through 2006, broken rails are reported to have accounted for 335 mainline derailments for Class I railroads in the US; over $176 million of equipment and track damage (approximately $525,000 per incident); and 14 hazardous material release accidents (Schafer & Barkan 2008a).

According to the broken rail events economic impact analysis conducted by Schafer and Barkan (2008a), the following economic costs were obtained:
• Annual direct costs of $83 million were due to broken rail service failures and derailments on US Class I railroads.
• Annual indirect costs exceeded $850 million for broken rail prevention techniques.

Similarly, the statistical data from the Transportation Safety Board (TSB) of Canada for the annual number of train derailments from 2000 to 2009 are presented in the Figure 5, for both the main track and the non-main track train derailments (TSB 2009). From the statistical data provided by the TSB, it can be observed that the rail and turnouts failure related train derailments account for about 16 per cent of all derailments reported on the main track, and for about 10 per cent of all train derailments reported on the non-main track. Approximately 85 train derailment incidents per year over the 10-year period were observed to occur as the result of the rail defect related failures.

![Figure 5: Statistical summary of rail-defects related train derailments reported on Canadian railways for the period 2000–2009](source: TSB 2009)

In the following section, the state-of-the-art review of the broken rail derailment incidents reported around the world is presented. The primary causes for the reported train derailments, and the rail defect inspections conditions prior to the occurrences of these train derailments, are also described.

### 3.1 Major broken rail derailment incidents

#### 3.1.1 North America: USA

- **Derailment of Union Pacific Railroad Train QFPLI-26 at Eunice, Louisiana, 27 May 2000 (National Transportation Safety Board 2002):** The investigations conducted by the National Transportation Safety Board (NTSB) determined that the probable cause of the derailment was the failure of a set of joint bars that had remained in service due to ineffective track inspection procedures and management oversight.

- **Derailment of Canadian Pacific Railway Freight Train 292-16 and subsequent release of anhydrous ammonia, North Dakota, 18 January 2002 (NTSB 2004):** The investigations conducted by the NTSB determined that the derailment was caused by fractured joint bars at the east end of the plug rail under the previous train, or as the train involved in the accident passed over the joint. After the joint bars fractured, the rail itself also fractured and broke away. The aftermath of the derailment accident is shown in Figure 6.
3.1.2 North America: Canada

- **Derailment of 19 cars on Canadian Pacific Railway Train 269-11, 12 October 2003 (TSB n.d.):** The primary cause was found to be the breakage of sections of CWR. High wheel impacts produced by the 15th car behind the lead locomotive were found to be the primary contributor towards rail failure. Interestingly, the last rail flaw detection test was reported to have been conducted just over two months before the derailment (on 30 July 2003); no internal defects were recorded within 16 km of the point of derailment.

- **Derailment of 14 cars on Canadian Pacific Railway Train 863-017, 15 October 2003 (TSB n.d.):** The primary cause was found to be a broken rail (jointed rail) due to a 381 mm vertical split head, and head and web separation. It has been reported that the rail was ultrasonically tested just one week before the accident, in which the defect was detected, but misinterpreted by the operator, with no corrective actions taken.

- **Derailment of 16 cars on Canadian Pacific Railway Train 269-21, 24 October 2003 (TSB n.d.):** The primary cause was the break in high rail within a curved track due to a transverse detail fracture extending from the gauge corner of the high rail. The last ultrasonic test was conducted on the rail a month before the derailment (on 19 September 2003) the derailment with no defects detected in the area.

- **Derailment of 28 loaded grain cars on Canadian National Train A44351-01, 1 January 2004 (TSB n.d.):** The primary cause was found to be a broken rail within a joint on tangent track, possibly due to bolt hole crack.

- **Derailment of 15 cars on Canadian Pacific Railway Train 266-02, 5 January 2004 (TSB n.d.):** The primary cause was a broken high rail within a transition curve, possibly due to transverse defects in the gauge corner of the rail head. The last ultrasonic test conducted on the rail on 3 October 2003 indicated a possible transverse defect near the point of the derailment. However, the significance of the detected defects was not obvious for the ultrasonic operator; unfortunately, for well over three months, no further assessment on fatigue crack growth was made.

- **Derailment of 11 intermodal service cars on Southward Canadian Pacific Railway Train 104-26, 26 January 2004 (TSB n.d.):** The primary cause was the broken rail and joint bars due to well-developed fatigue cracks in the rail and joint bars.
• Derailment of 22 intermodal platforms on Westbound Canadian Pacific Railway Train 10Q11531-19, 22 February 2004 (TSB n.d.): The primary cause was a broken rail due to a vertical split head in a joint near a crossing. No rail defects were detected in the area from the last ultrasonic rail test conducted on 17 June 2003.

• Derailment of 20 cars on Westbound Canadian Pacific Railway Train 575-03, 4 March 2004 (TSB n.d.): The primary cause was broken joint bars on a tangent track due to fatigue fractures. No rail defects were found in the area during the last rail flaw detector test conducted on 13 February 2004, less than a month before the derailment occurred.

3.1.3 Australia
Relatively fewer derailments are reported in Australia, which is a tribute to the Australian technologies and skills of the engineering crew at all levels. The rail sector has hired and groomed engineers and track crew and train drivers over a long period with minimal turnover. In spite of the state-based gauges, vast geography and small population, the country has gained some world-class knowledge over a century, and strived for innovation through excellence by setting up rail specific CRCs in the past decade.

• Rail safety investigation report, derailment of Pacific National’s ore service 4835 Nevertire–Nyngan rail section (Australia), 1 October 2006 (Office of Transport Safety Investigations 2006): The Office of Transport Safety Investigations (OTSI) Australia report concluded that the cause of the derailment was a poorly supported rail joint break under the pressure of the weight of ore cars. The rail-end became exposed when the fishplates that had been used to join two lengths of rail broke. Consequently, the exposed rail end was struck by the wheels of the leading locomotive, causing the derailment of the trailing locomotive and 14 wagons. Figure 7 shows the aftermath of the train derailment.

3.1.4 Inference
It can be inferred that the majority of broken rail derailment incidents occurred within a few weeks or months of the conduct of NDT of the rails. These overwhelming, convincing real-world data demonstrate that there is an urgent need for the development of more effective and accurate rail defect detection technologies, or further improvement of existing technologies.
3.2 Critical factors affecting broken rails

In general, several factors are known to influence the rail degradation process, including (Schafer 2008; Chattopadhyay & Kumar 2009):

- operational conditions (such as the rail-wheel interaction, the throughput in terms of million gross tons, the speed, the traffic type, the track curvature, the characteristics of bogie type and the age of the rail)
- operational environment (such as the temperature and the humidity)
- manufacturing (such as the railhead hardness and the residual stress)
- design (such as the rail-wheel material type, the rail size, the rail welding, and the rail profile)
- maintenance (such as the grinding and lubrication frequency, the ballast tamping and the inspection interval).

Wear and rolling contact fatigue have long been known as the major factors contributing towards rail degradation that subsequently limits the service life of rails (Chattopadhyay & Kumar 2009; Jaiswal 2003). Among various rail defects, broken rail forms the highest stage of the rail degradation process, primarily caused by undetected growth of internal and surface defects (Sperry Rail Service 1999; Aglan & Gan 2001; Kim & Kim 2002; da Silva et al. 2003; Fletcher, Hyde & Kapoor 2004; Skyttebol, Josefson & Ringsberg 2005; Smith 2005; Fischer et al. 2006; Cannon et al. 2003). The rail defects that potentially results in rail breakage included (INNOTRACK 2008):

- rail foot corrosion
- failure at rail ends, including from bolt holes
- failure of welds
- internal defects.

According to the rail break statistical data analysis conducted using Swedish National Rail Administration (Banverket) field data collected from 1997 to 2005, more rail breaks were found during winter than summer (Chattopadhyay & Kumar 2009). These rail breaks were found to concentrate at rail segments having a curve radius of 500–600 m. However, sufficient data and accurate numerical models are required in order to establish the realistic relationships between the rail breakage rates and the critical rail degradation influencing factors with greater confidence.

Schafer and Barkan (2008b) conducted statistical analysis of the factors that influence the occurrence of broken rails, based on broken rail service failure data obtained from US railways. The most important factors related to service failures, including rail weight, rail type, rail age, annual traffic, weight of car, presence of an ultrasonic defect, and presence of a geometric defect among others, were employed to develop a broken rail location prediction model. However, the accuracy level of the model was reported to be only in a range of 65 to 70 per cent, which may not be sufficiently accurate to predict all potential broken rail derailment locations. Moreover, there is a paucity of literature with respect to the identification of the single most important factor with the greatest relative contribution towards the broken rail occurrences.

Canadian National (CN) railway company employs a risk analysis based Rail Defect Index (RDI) for placement of cold weather speed restrictions, replacement of defective rails, and the cascading of used rail based on a severity number (from 1 to 10) assigned to each defect (TSB 2005). The severity numbers are assigned based on the defect type, its rapidity of growth, and the ease of detectability. Consequently, fatigue defects were given the highest severity rating, while wear defects were given the lowest rating.

Therefore, CN’s RDI approach clearly demonstrates that fatigue crack is a critical influencing factor for broken rail problems. Identification of the critical factors influencing broken rails is the most important research task to be accomplished prior to the development of any new broken rail detection technology, with a view to devising the most appropriate mechanism for monitoring critical rail defects and rail degradation processes that ultimately lead to broken rail conditions. This strategy has the potential to contribute to the knowledge-based rail inspection strategies, smart maintenance and replacement programs.
3.3 Past responses to broken rail derailments

As a result of a series of major train derailments, various safety measures were undertaken by railways and rail research organisations around the world. These safety measures included:

- new system development and field trialling of improved NDT technologies for rail defect inspections and broken rail detection
- more frequent, or continuous, rail testing and inspections (using vehicle-based systems or handheld equipment)
- development of rail safety risk management tools.

Figure 8: A schematic illustration of a high-rail vehicle-based rail inspection system

Source: Clark et al. 2003
Some of the main NDT techniques employed by railways included: ultrasonic method, low frequency eddy currents, radiography, electromagnetic acoustic transducers, ground penetrating radar, long range ultrasound, laser generation and reception of ultrasonic waves, alternating current potential drop, alternating current field measurement and impedance spectroscopy (Labropoulos, Moundoulas & Moropoulou 2006). The ultrasonic-based method remains by far the most common inspection technique for broken rail detection and rail defect inspections.

The high-rail vehicle-based rail defect inspection system (US patent) is one of the advanced technologies in existence that can be used for NDT and rail defect inspections (Clark et al. 2003). This system employs a vehicle-based magnetic induction sensor system and an ultrasonic sensor system in a complementary manner to carry out automated rail defect inspections, with some limits applied to the travelling speed of the test vehicle (see Figure 8).

Unfortunately, there are still technological limitations with the rail defect inspection equipment currently employed around the world for all types of rail defect inspections. Manual verifications should often accompany the automated rail defect inspection, which increases the inspection costs and causes significant traffic disruptions. According to the Venn diagram shown in Figure 9, there was significant false detection of defects. It is fair to state that none of the primary rail defect inspection methods were able to comprehensively detect rail defects (Chattopadhyay, Reddy & Larsson-Kråik 2005; Chattopadhyay, Larsson-Kråik & Kumar 2005). This means that more than one technology is required where comprehensive detection is desired; the other alternative is very high levels of track maintenance and very high frequency of track inspection — particularly for fatigue cracks in rails, weld and joint bars.

Other limitations with the existing rail break detection technologies are demonstrated by the redundant rail maintenance strategy employed by Banverket (Larsson, Kumar & Chattopadhyay 2005; Kumar 2006), in which NDT cars, visual inspection, handheld ultrasonic equipment and rail track circuit detection by signals are often used simultaneously or consecutively to inspect possible internal rail defects. Figure 10 demonstrates the percentage of ‘potential rail breaks’ detected using redundant inspection techniques employed on the Swedish iron ore line, in which the track circuit based signalling technique is shown to detect about 4.3 per cent of rail defects. However, Figure 10 does not show the ‘real’ percentage of broken rails detected by various rail defect inspection techniques employed.

The ‘potential rail breaks’ detected are primarily based on the defects detected. In practice, these defects may or may not lead to immediate rail breakage. As a result, it becomes difficult to conclude that track circuit based signalling technique was only able to detect about 4.3 per cent of broken rails, based only on the statistics of the defect detection data presented in Figure 10 (i.e. not based on the ‘real data’ of the broken rails). These data from Banverket are significantly different to the US data presented in Figure 1, which exhibited a very high rate of occurrence of derailment (on average, more than one major derailment for three days). Although the Banverket
data are not the real numbers, through the meagre 0.38 per cent derailment-related rail defect detection, it can be inferred that the Banverket maintains the track and manages the wheel loads better.

![Figure 10: Percentage of ‘potential rail breaks’ detected by Banverket](source)

In summary, there is no conclusive evidence of any one technology being superior to another as far as broken rail detection is concerned. Visual inspection and handheld NDT used for fatigue crack detection are slow methods that are expensive and can potentially close the track during inspection, lowering the opportunity for increased throughput and productivity gains. Therefore, there is a need for further research and improvement in rail defect inspection technologies. High speed detection of the broken rails and real-time condition monitoring of the rails is of paramount importance. This will not only contribute to the safer operations of railways, with minimised risk of catastrophic derailments of trains, but also promote the adoption of cost-effective alternative new technologies such as CBTC and PTC. The timely preventative maintenance of railways will result in increased performance and profitability of the railway transportation industry.
4. Track circuit based signalling broken rail detection systems

One of the drawbacks of the current or voltage signal monitoring based broken rail detection methods (wayside-based or conventional track circuit based) is that some of the broken rails may remain undetected, which necessitates additional manual methods of inspection for the integrity of the rail. For example, when rail is cracked, but not fully separated (see Figure 2), or where alternative electrical paths are present, broken rails cannot always be reliably detected using conventional track circuits. For the conventional track circuits to detect broken rails, two insulated mechanical rail joints are often necessary, which requires additional track maintenance efforts.

In addition, the use of track circuits where electric traction is used for train propulsion adds additional complexity to the detection system (Reiff 2006). The majority of these systems will not be able to comprehensively detect broken rails when there are trains travelling as they cause shunting. The more trains that are running on the track, the less the system can detect broken rails. Hence, the reliability of the traditional rail inspection technologies for the detection of broken rail is somewhat diminished with the increase in traffic.

Some of the typical limitations of the track circuit based signalling systems are (Taylor 2011):

- not all types of rail breaks can be detected; for instance, only the first two types of rail break types shown in Figure 2 are likely to be detected reliably by track circuit based signalling technologies
- when the two sections of the fractured rail connect due to thermal expansion and contraction, the system fails to detect broken rails
- earthing and bonding may provide an alternative path for the track circuit current, effectively bypassing the rail breaks
- limitations on track length for which the traditional method can be used, hence increased frequency for the insulated rail joints and trackside infrastructure
- infrastructure intensive for large track length
- the majority of existing systems require insulated rail joints in general.

4.1 Review of patented systems

A large number of track circuit based signalling patented broken rail detection systems exist, from the basic broken rail detection systems invented in the 1970s, to the latest improved systems patented in the 2000s. Figure 11 shows a block diagram of the basic system of broken rail detection apparatus patented in 1972 and owned by Marquardt Industrial Products Co. (US).

![Figure 11: A block diagram of a basic system of broken rail detection apparatus](source: Risely 1972)
This track circuit based signalling broken rail detector apparatus employs two pairs of insulated rail joints (shown with the reference numerals (1) and (2)), and a transmitter (14) and receiver (16) along a rail block length to detect changes in track characteristics based on coded direct current electrical signal applied to each rail (10) and (12) in the track. This system is also reported to detect train presence within the signal block. However, the system suffers from similar shortcomings to the traditional track circuit based signalling methods that included signal attenuation and the requirement for power sources for repeaters (i.e. receivers and transmitters). The effective length of the track over which this system works is significantly shorter than that of the latest improved systems.

US patented technologies available for broken rail detection, with advances made to the earlier broken rail detection systems over the years (but also with their own various deficiencies and drawbacks), are presented in Stark, Erlich & Guillaumin 1978; Petit & Auer 1988; Gauthier 1997; Peek & Basta 2000; and Holgare 2003. One particular system worth mentioning here is the broken rail detection system invented by Frielinghaus (1989), and owned by General Signal Corp. This apparatus is used for broken rail and rail joint bar detection in dark territory track sections (i.e. track sections that do not have signalling systems), and can be used with or without the existence of communication links between the two ends of the track sections. It is claimed that this invention employs substantially less electrical power and fewer repeater sections than prior inventions, and provides a new and improved device and system to detect broken rails and rail joints in a single block of 16 km track section, where the minimum ballast resistance is 5 ohms per 300 m, or up to 8 km track section when the minimum ballast resistance is 2 ohms per 300 m. Two pairs of insulated rail joints (IRJs) at the two ends of the block of the track section are employed in this invention.

One of the latest systems invented by Anderson (2007), under the ownership of General Electric Company (US), is designed for the detection of rail break or train occupancy in ‘a long-block’ rail section. The system employs a current signal delivered to an isolated block of rail track through two pairs of IRJs (Figure 12). A control unit is adapted to receive input from the voltage sensor and the shunt current sensor, and to monitor the variation of the shunt current with respect to the voltage to detect the rail break or train occupancy. This system covers over 16 km a block of a rail section (as compared to conventional systems, which cover only about 4 km a block). A variety of the above patented system is also available from General Electric (US), and can be used for detection of ‘a long-block multi-zone’ rail break or train occupancy by applying a voltage across the block, having plurality zones through a plurality of voltage sources (Anderson & Welles 2007). Two pairs of IRJs at two ends of a block are used to form a block section of about 16km length of a railway track.

**Figure 12: A block diagram of a rail break or vehicle detection system**  
*Source: Anderson 2007*

**Figure 13: A block diagram of a rail break or vehicle detection system**  
*Source: Anderson, Andarawis & Fries 2010*

An ‘enhanced’ version of the above-mentioned broken rail detection systems was also invented by Anderson, Andarawis and Fries in 2010 for ‘a long-block multi-zone’ broken rail and train detection for a railway track within a block of about 16km. This system employs ‘in-rail’ communication between the plurality of sensors along the block of rail track, sensor IDs that indicate presence/absence of rail break of vehicle using a time division multiplexed access form. This system employs two pairs of IRJs at two ends of the block of length about 16 km (Figure 13).

**Locomotive-based ‘hybrid’ broken rail detection system**

A locomotive-based system patented in 2006 under the ownership of Bombardier Transportation GMBH (Karg 2006) possesses significant advantages over the track circuit based signalling broken rail detection systems. This ‘hybrid’ system employs a current signal or a voltage signal or a low frequency audio signal circulating in the railway track for detecting broken rails. It comprises at least one locomotive and wayside monitoring equipment.
Each locomotive comprises a receiver, a transmitter, and a processing unit that is in communication with the receiver. The track signal can also be introduced into the railway track by a different locomotive, or by track-side equipment/transmitter. The processing unit operates by detecting a characteristic of the track signal, and generating a signal indicative of a potential broken rail in response to a change in the characteristic of the track signal. The monitoring component comprises a receiver for receiving the signal indicative of a potential broken rail, and a processing unit for detecting a broken rail at least in part on the basis of the signal indicative of a potential broken rail from the locomotive.

In addition to detecting the presence of the track signal, this system is also used for detecting the location of the locomotives on the railway track, using either track-side positioning devices or GPS technology. Moreover, in the case where there are no locomotives travelling along the railway track, the monitoring entity reverts to the traditional method to perform broken rail detection tasks, using a transmitter and a receiver that are either connected directly to the monitoring equipment, or connected to wayside equipment that is in turn connected to the monitoring entity.

Some drawbacks of the locomotive-based system are:
- the track conditions may affect its performance by influencing the characteristics of track signals and signal attenuation characteristics
- this method will not identify the exact location of broken rail; hence, either visual or NDT scans may need to supplement this technique. There may not be sufficient warning time to stop/break the train before it reaches the potential rail break location
- where there are no locomotives travelling along the railway track, the traditional method of broken rail detection needs to be used instead, which increases wayside infrastructure costs
- in order for locomotives to survey portions of the railway track, the railway track needs to be divided into sections via shunts
- this apparatus requires significant wayside-based equipment and infrastructure similar to the traditional method.

**Active broken rail detection system and method**

Invented by Davenport, Hoctor and Stralen (2005) and owned by General Electric Company (US), this active system monitors the integrity of the railway track using continuous signal correlation analysis. The system comprises a mechanical signal source and correlation detector (see Figure 14). The mechanical signal source coupled to the railway track generates mechanical signal pulses over the railway track, which comprises bursts of acoustic or ultrasonic carrier signals, having a predetermined pulse repetition interval. The correlation detector monitors the integrity of the railway track by observing the pulses transmitted. If there are no broken rails, then the pulses will travel to the correlation detector and afford the opportunity for repeatable detection.
The system employs a typical ultrasonic signal frequency that ranges from 10 kHz to 50 kHz, pulse duration of 10 milliseconds each, and pulse repetition interval of 25 milliseconds. Moreover, mechanical signal sources that include piezoelectric slack transducers and electro-mechanical hammers; and mechanical signal transducers that include piezoelectric slack transducers and accelerometers that use piezoelectric elements are employed. The numeral references shown in Figure 14 represent the following: 10 (railway track); 12 and 14 (mechanical signal sources); 13 (pulse train generator); 20 (mechanical signal transducer); 26 and 36 (multipliers); 28 and 38 (integrators); 30 and 40 (detection threshold); 24 and 34 (delay blocks); 50 (block diagram of a system); 60 (correlation detector); 70 (a processor).

Even though this system looks simple (it does not require insulated rail joints and track circuit based signalling), track-side infrastructure for generating a continuous source of mechanical signal and trackside communication equipment for receiving and correlation analysis of pulses are required. Moreover, the length of the track section over which this system can be effective is dependent on various track conditions; on poor tracks, the track section can be much shorter.

Finally, since this system works independently of the track circuit based signalling, for continuous rail integrity monitoring, it can be one of the alternative technologies suited to broken rail detection on dark territory rail sections, but will still require wayside infrastructure.
5. Broken rail detection systems for CBTC applications

In general, limited technologies are available for high speed broken rail detection relevant to CBTC and PTC applications.

5.1 Track circuit based signalling systems

Grappone Technologies (2003) is one of the few organisations known to possess patented track circuit based signalling broken rail detection technology that can be used with CBTC and PTC systems. The main attributes of this patented broken rail detection apparatus are:

- it detects completely broken rails in unoccupied sections of railway track by subdividing the track section into current loops
- insulated rail joints are not required
- commercial AC power is applied to near the physical centre of the track section
- rail break is detected from a subsequent decrease in the coil voltage.

The system also possesses various limitations, including:

- the railway track section should be unoccupied
- train detection capability is not included
- new wayside monitoring infrastructure is required and could be costly
- commercial power source is required
- the system is susceptible to the effects of track parameters and environmental factors such as varying ballast impedance, presence of foreign metallic objects and source voltage variation
- the system is used for ‘passive’ broken rail detection application, hence is not particularly suitable for ‘active’ high speed broken rail detection problems.

**Broken rail detection circuit that works in a sleep mode**

A broken rail detection circuit that works in a sleep mode, and is designed for non-signalled railway territory applications, has been tested by the BNSF railway and US&S (Bowden & Franke 2004). The sleep mode system developed is integrated with BNSF’s Electronic Train Management System, and employs Microlok II unit with Microtrax Sleep Mode application to reduce its power consumption when the track status is not required.

The system is solar powered, wakens when requested by data radio, operates long track distances, does not interfere with crossing warning devices, reports broken rail detection status, and is applicable to CBTC and PTC systems. The BNSF railway tested the broken rail detection circuit in the field for testing the effectiveness of the system at four locations, with the circuit installed varying in length (6–8 km). The tests were conducted using hi-rail vehicle as locomotive. The following companies are associated with this system development: BNSF Railway, Union Switch & Signal Inc., and Ansaldo STS.

However, there is not enough information available in the literature with regard to the reliability of the system for potential field deployment. Moreover, the type of track-side infrastructure required, the purpose of IRJs, and the type of signals used for the sleep mode broken rail detection circuits applied to non-circuited railway track are not provided clearly in the literature available.

**MicroLok® II Interlocking Control System**

A multipurpose monitoring and control system for rail and transit wayside interlocking equipment is reported to be in use in Australian rail lines (e.g. Rio Tinto). Its stated functional capabilities are vital interlocking control; and non-vital code system applications, train detection, rail integrity, coded track circuit communication, etc. (Ansaldo n.d.).
The system uses distributed interlocking, and does not have track-side signals, but is based on fixed block principles; it functions as if there are signals present. The technology infrastructure required for this system to operate (including as broken rail detector in dark territory and CBTC applications) includes:

- a series of track mounted transponders
- wayside interlocking equipment
- in-cab signalling system on board the train.

This system is reported to be integrated with Centralised Traffic Control (CTC) and Automatic Train Protection (ATP) systems, and can be used for broken rail detection in dark territory. This system employs a track circuit based signalling solution for broken rail detection, with the following salient features:

- It uses a very low speed transmission rate for the coded track circuit that enables long track sections (up to 9km) thereby minimising trackside equipment and frequency of insulated joints.
- It employs a continuous in-cab signal system that is transmitted from ahead of the train and received on the locomotive allowing immediate detection of broken rails.
- Higher detection rates are reported.

Finally, whether the broken rail detection component can be implemented for railways that employ different CTC and ATP technologies is not clear, in view of the technology adoption costs involved.

### 5.2 Ultrasonic broken rail detector from RailSonic

One of the few automated commercial broken rail inspection solutions available on the market that can be used for CBTC and PTC applications is the Ultrasonic Broken Rail Detector (UBRD) from RailSonic (South Africa).

UBRD is a Spoornet initiated, International Union of Railways (UIC) supported project (part of Joint Research Project No. 2); a joint venture between Spoornet and the Institute for Maritime Technology (IMT) to manufacture UBRD and sell it to railway companies and operators worldwide. UBRD is reported to have the capability to detect a broken rail almost continuously, without human intervention (with over 1.75 km distance between the transmitter and receiver, and can go up to 2.5 km, depending on the track and environmental factors).

The main components of the acoustic rail break detection system are the ultrasonic transducers, the transmitter, the receiver and the digital interface. Rail continuity is established at receivers by monitoring the presence of ultrasonic signals, bi-directionally inserted into both rails via ultrasonic transducers at a programmable interval by the transmit electronics (see Figure 15). Each receiver can monitor a 3.5 km stretch of rails for breaks. A receiver station thus consists of two transmitters on either side of the receiver, installed at a maximum distance of 1.75 km. Signal insertion and monitoring equipment are interleaved on the rail 1.75 km apart, and operate on both rails. The receiver station monitors both rails, and sends the equipment status and alarm conditions to the central monitoring station via a digital interface. Failure to detect a specific signal signifies existence of a broken rail.

![Figure 15: Block diagram of the Ultrasonic Broken Rail Detector System](Source: RailSonic)
The main attributes of the UBRD (RailSonic) system are:

- Detection of clean breaks
- Detection of crown fractures (fracture size ≥ 80% of crown cross section area)
- Notification of train presence
- Notification of abnormal rail activity
- Remote sensing of equipment failures
- On-board storage of detection history, detection diagnostics, and ambient temperature.

**Estimated costs of UBRD system**

The accurate price of UBRD system depends on the lay-out and availability of mains power, type of alarm terminal required, and integration requirements with CTC System. However, a typical solar powered station is estimated to cost in the vicinity of US$12,000, and the spacing of the equipment can be between 1km to 1.5km depending on the rail type and state.

**Some drawbacks of UBRD system**

- No broken rail detection is available while a train is present in the monitored section. UBRD system may not be suitable for “real-time” high speed broken rail detection purposes; instead can be used for “passive” broken rail detection through continuous monitoring of the track condition.
- The ultrasonic transducers, the transmitter, the receiver and the digital interface are attached to the two rails; new trackside UBRD infrastructure are required to be installed on the railway lines – costs could be the issue.
- The effects of the existing IRJs or CWRs on UBRD system are not clear and require further investigation.

5.3 High speed rail IDEA projects

A series of projects has been conducted as part of the FRA’s next-generation high-speed rail technology development program, managed by the Transportation Research Board (TRB).

**Locomotive-mounted TDR-based broken rail detection for CBTC applications**

This study examined the feasibility of a locomotive-mounted broken rail detection system based on the time domain reflectometry (TDR), assuming the track as a two-wire electrical transmission line (Turner 2004). The same electrical pulse/echo technique commonly used to locate breaks and shorts in electrical cables is employed to allow each train to independently test the track ahead for broken rails and track occupation, up to a given detection range. This TDR-based system is designed to work in conjunction with CBTC applications to replace the present wayside signalling based system and eliminate the associated per-mile maintenance costs.

The TDR method was found to have many of the same shortcomings as the track circuit based methods; the significant problems identified were related to the following factors:

- Partial breaks, breaks under compression and breaks on tie plates
- Reduced detection range
- Modification requirements to track-shunting structures such as turnouts and diamond crossings
- Compatibility with the existing track circuits
- Coupling signals to and from the track
- Electrical characteristics of broken rails, bolted and IRJs
- The railway track attenuation rate relative to test pulse frequency
- Safety of train crew and rail workers.

**Buried fibre optic filament to detect trains and broken rails**

The team involved in this High-Speed Rail IDEA Project included: Texas Transportation Institute (TTI), College Station, TX; Burlington Northern Santa Fe Railroad, Transportation Technology Center (TTCI), and Safetran Corporation.
The use of fibre optic filaments buried under the track structure to detect rail breaks and train presence was investigated using a coherent optical time-domain reflectometry (COTDR), advanced signal processing techniques and neural networks (Olson & Roop 2003).

The premise of this investigation is that an optical transmission, through a continuous length of low-loss, telecommunications-grade fibre optics buried within the right-of-way, holds promise for providing an inexpensive, reliable alternative to conventional track circuitry for train presence and broken rail detection applications. The investigated technology concept employs an externally induced energy wave impinging a buried, single fibre transmitting a coherent light beam, which will alter the polarisation angle of the beam where any impingement occurs and subsequently be processed for detection of trains and rail breaks.

However, it was reported that the large amount of environmental noise accumulated along the fibre made the signal of interest undetectable in fibre lengths in excess of 50 metres. As a result, this contract was reported terminated based on the recommendation of the contractor, Texas Transportation Institute.

5.4 Other high speed rail research projects

The Transit Cooperative Research Program (TCRP) is a joint track-related research between the Association of American Railroads/Transportation Technology Center, Inc., and Manacle Point Engineering (UK) (Kalay et al. 2001). Three potential technologies were evaluated at the FRA’s Transportation Technology Center (TTC) in Pueblo, Colorado, as an alternative to track circuits for detection of broken rails in track. These included:

- strain gauge measurement of longitudinal stress
- fibre optic cable bonded to the rail
- traction return ground current monitoring.

The following conclusions were found in the TCRP report:

- For very short distances, in complex track work, the fibre optic technology offers the most flexible and sensitive solution. For distances longer than 300 m, it’s currently not practical to use fibre optics.
- The strain gauge technology has shown excellent performance in CWR sections where repair welds can be installed immediately after a rail break is removed.
- Both the cross-bond differential current and the centre shunt current measuring systems have the potential to detect traction return current imbalance because of a broken rail.

Acoustic rail break detection demonstration at MTA New York City Transit

A demonstration program to investigate an acoustic-based rail-break detection system in the transit environment was conducted under funding by the TCRP Project D-7/Task 10 Reiff 2006).

With the cooperation of Alstom and Railsonic, a prototype acoustic-based rail break detection system similar to the one used by Spoornet (South Africa) was demonstrated at the Facility for Accelerated Service Testing (FAST), TTCI, Pueblo, Colorado. This system employs a remotely located transmitter, and a receiver located up to 1.6 km from the transmitter. The transmitter sends a coded acoustic signal into the rail at adjustable intervals of 15 sec to over 3 minutes. The receiver ‘looks’ for the coded message; if the proper coded message is not received in a prescribed time window, a rail defect or fault is assumed to have happened, and a stop signal is generated. A schematic of the concept is shown in Figure 16.
A prototype was installed in an active mainline over a 0.7 km section of track on the ‘A’ line of the MTA New York City Transit for about 11 months. However, the reliability of the prototype technology was not yet verified as no rails broke during the monitoring period.

Major issues found with this acoustic-based rail-break detection technology included:

- blockage of the detection signal by conventional mechanical rail joints
- potential interference from adjacent sources of vibration
- inability to transmit signals through certain types of special track work.

Finally, this proposed system requires significant trackside infrastructure and monitoring equipment in place prior to its practical implementation; the associated costs could be too high.

5.4 Rail Defect Management program

Research into broken rail detection was one of the main objectives of an international cooperative research program for railway organisations from five continents, organised under the UIC umbrella to develop the Rail Defect Management (RDM) program. It included seven project elements (Kalay et al. 2002):

- benchmarking flaw statistics, current inspection systems, and effectiveness
- inspection technology improvement
- flaw growth rate prediction
- remaining service life/repair potential
- broken rail detection system
- safety aspects and considerations
- defect management strategies.

The project team members included: AAR/TTCI, East Japan Railway Company, India Railways, Queensland Rail (Australia), Spoornet (South Africa), and China Academy of Railway Sciences. Each RDM member organisation conducted particular tasks of the RDM program:

- East Japan Railways have undertaken improved vehicle-borne ultrasonic testing using sliding and rotating wheel probes, enhanced probe guidance, greater probe scanning area, and improved data processing.
- The China Academy of Railway Sciences has targeted vehicle-borne ultrasonic inspection at speeds up to 80 km/h (about double current systems).
- AAR focused on NDT technologies such as low-frequency eddy current, longitudinal guided ultrasonic waves, neural network analysis of ultrasonic signals, and laser generation and reception of ultrasonic signals.
- TTCI has evaluated three prototype systems: fibre optic cable bonded to the rail, strain gauge modules bonded to the rail, and an acoustic broken rail detection system.
- Spoornet and industrial partner IMT developed a solar-powered acoustic rail break detection system that uses acoustic transmitters and receivers clamped to the rails.
- India Railways' RDSO designed a test rig to apply loads to simulate vertical bending caused by passing trains.
wheels, and longitudinal thermal forces caused by rail temperature variation in continuously welded rail.

- Queensland Rail (QR) addressed two RDM matters: the management of a vertical split head defect; and the development of a guide for technical specifications covering NDT testing of rails in track.

In conclusion, the research outcome achieved by this international cooperative RDM program has been significant. Many of the operational broken rail detection systems, such as the UBRD system by RailSonic, have been developed and tested in part through this cooperative research program.
6. Applied broken rail detection technical research

In this section, the ongoing promising research trials relevant to broken rail detection and rail defect identification in general, based on the knowledge of structural mechanics, measurement sensors applications, and advanced statistical modelling approaches, are reviewed.

Some of the ongoing research trials included: high-speed inspection of rails using alternating current field measurement (ACFM) probes (Papaelis et al. 2009); in-service crack detection using infrared method (Green, Yates & Patterson 2007); high-speed RCF detection using analogue balanced bridge sensing device (Nicolas & Hope 2006); non-invasive rail crack detection using microwave sensors Vijayakumar et al. 2009); ultrasonic guided waves and non-contact probing (FRA 2005; Scalea et al. 2005; Rizzo et al. 2010; Zumpano & Meo 2006); and low-frequency-wideband Rayleigh EMAT (Palmer et al. 2005).

Rose and Avioli (2000) conducted broken rail detection ahead of the train, based on elastic guided wave propagation through the rail generated by the wheel–rail contact impact energy. A feasibility demonstration was conducted at the TTCI precision test track for a train travelling at 90 km/hr towards the broken rail, with accelerometers sensors fixed on rail close to the break. The start of the train was about 5.6 km from the accelerometer; the accelerometer was located about 1 km from the broken section of the rail. The result illustrated that the technique was able to detect a broken rail while the train was about 0.5 km from the accelerometer (or about 1.5 km from the broken rail). However, this study didn’t consider the ideal situation, where the receiver itself is on board the train, in which case the reflected signal travel length significantly decreases, potentially undermining the proposed technique.

Bouteiller et al. (2006) conducted a proof of concept laboratory experiment to determine if impedance-based structural health monitoring can be used to detect rail defects and broken rails. The method employed a very low voltage high-frequency wave, induced to a rail using piezoelectric sensors/actuators bonded to the structure so that their electrical impedance can be directly related to the rail’s mechanical impedance, which is further analysed to detect rail defects and broken rails. However, the potential application of such a system under field conditions is yet to be demonstrated.

Research is needed dealing primarily with the risk analysis and preventive predictions of rail defects and broken rails, based on statistical rail failure data analysis in order to prevent the occurrence of broken-rail and broken rail derailments and its catastrophic effects and to improve the rail inspection schedules (Zarembski 2009; Schafer & Barkan 2006; Zarembski 2007; Zarembski & Palese n.d.; Zarembski 2010; Shry & Ben-Akiva 1996; Dick 2001; Dick et al. 2003; Sourget & Riollet 2006).

Zarembski and Palese (n.d.) from ZETA-TECH conducted research on the relationship between rail defects and broken rail derailments, based on rail defect data obtained from several US railroads. Zarembski [72] examined the risks associated with broken rail for high speed passenger rail. The relationship between rail defects and broken rail derailments, and the techniques used to reduce the risk of these broken rail derailments, were investigated. Consequently, guidelines were provided for the range of broken rail risk that has been found on freight and passenger systems in North America and Europe, including improved inspection and maintenance technology for reducing rail service defects and associated derailments.

Therefore, a risk analysis based approach can be used potentially as an alternative and complementary approach to the technology-based high speed broken rail detection, particularly for non-signalled railway tracks and for CBTC and PTC systems, to predict the potential rail break locations. However, such an approach requires sufficient historical data related to high risk rail defect locations and broken rail derailments, as well as an accurate numerical model to develop reliable rail defect development prediction tools. Ideally, site-specific reliable rail risk models are required, and statistical data may not be available to develop such a model for most railways.
7. Concluding remarks

In this report, various broken rail detection systems have been reviewed under the following main categories:

- systems that employ basic track circuit for signalling
- systems that employ track circuit for signalling with various technology advancements added
- ‘non-signalling’ based systems that employ series of track mounted technology infrastructure and wayside communication equipment
- locomotive-based systems that employ series of trackside ‘non-signalling’ technology infrastructure (described in this report as ‘passive’ continuous crack detection systems)
- train or locomotive-mounted systems that employ ‘in-cab’ signalling systems (i.e. for ‘active’ high speed crack detection systems). Unfortunately, systems in this category are still at the early stage of research and testing (Nature n.d.; Railway Track and Structures 2004; Groundprobe n.d.).

The following specific conclusions emerge from this study:

- Broken rails represent one of the leading causes of derailments of high severity.
- There is little information available in the literature regarding the costs incurred as a result of broken rail derailments (except from US railways). Hence, the frequency of broken rail derailment statistics in various countries, and the economic, social and economic impacts, may have been understated due to various factors, which may have significant effect on funding for research and development in this critical area.
- The most common rail break inspection technique for broken rail detection is the ultrasonic-based method.
- On several occasions, rail flaw detection tests (including ultrasonic tests) conducted just a few weeks or months before derailments revealed no suspicious defect that might have alerted the railway operator to the possibility of the broken rail occurrences.
- Conventional track circuit based broken rail detection systems, despite extensive research and patented systems in existence with various improvements made over the years, are not 100 per cent effective in detecting broken rails.
- CBTC and PTC systems alone cannot provide broken rail detection capabilities.
- Very few reliable technologies exist currently including ultrasonic-based continuous scanning method or passive method (also with some significant deficiencies) for high speed broken rail detection, broken rail detection in the dark territories and for CBTC applications, despite the fact that redundant inspection techniques are employed by railway industries around the world. Hence, a new alternative technology is required when it comes to high speed real-time rail break detection.
- There is a paucity of literature with regard to the existence of any reliable technologies (except for a few academic research and small-scale prototype studies) for high speed broken rail detection in ‘real-time’.
- Many railways around the world are reported to have conducted field testing of various broken rail detection technologies for high speed rail lines and for rails in dark territories; no conclusive findings to date have emerged from these trials.
- Many of the new systems being developed for high speed broken rail detection also suffer from similar limitations to the existing wayside track circuit equipment based technologies.
- The majority of the broken rail detection technology developments reported in the literature are primarily based on track circuit based signalling requirements and sensor technology implementation focus.
- Risk management models have been widely used as an alternative to control and reduce the risk of broken rails derailments.
- As per CN’s RDI approach, used for rating critical influencing factors for broken rail problems, fatigue defects were given the highest severity rating, while wear defects were given the lowest rating.

In summary, the current state-of-the-art literature reports show that it is a common understanding among the railway organisations that a new alternative, cost-effective and reliable system for broken rail detection is essential. It would also be correct to state that all technical solutions appear to have limitations. In general, limited technologies are available for high speed broken rail detection relevant to CBTC and PTC applications, as listed below:

- Grappone Technologies (2003) is one of the few organisations known to possess patented track circuit
High speed detection of broken rails, rail cracks and surface faults

Chapter 7 – Concluding remarks

Based signalling broken rail detection technology that can be used with CBTC and PTC systems.

- Broken rail detection circuit that works in a sleep mode and is designed for non-signalled railway territory applications has been tested by the BNSF railway and US&S (Bowden & Franke 2004). The sleep mode system developed is integrated with BNSF’s Electronic Train Management System, and employs Microlok II unit with Microtrax Sleep Mode application to reduce its power consumption when the track status is not required.

- A multipurpose monitoring and control system for rail and transit wayside interlocking equipment is reported to be in use in Australian rail lines (e.g. Rio Tinto). Its stated functional capabilities are vital interlocking control; and non-vital code system applications, train detection, rail integrity and coded track circuit communication (Ansaldo n.d.).

- One of the few automated commercial broken rail inspection solutions available in the market, that can be used for CBTC and PTC applications, is the Ultrasonic Broken Rail Detector (UBRD) from the RailSonic (South Africa).

Some studies are ongoing to examine the feasibility of a locomotive-mounted broken rail detection system based on the TDR, assuming the track as a two-wire electrical transmission line (Turner 2004). The use of fibre optic filaments buried under the track structure to detect rail breaks and train presence was investigated using C-OTDR, advanced signal processing techniques and neural networks (Olson & Roop 2003). For very short distances, in complex track work, the fibre optic technology offers the most flexible and sensitive solution. For distances longer than 300 m, it’s currently not practical to use fibre-optics. The strain gauge technology has shown excellent performance in CWR sections, where repair welds can be installed immediately after a rail break is removed. Both the cross-bond differential current and the centre shunt current measuring systems have the potential to detect traction return current imbalance because of a broken rail.

- A demonstration program to investigate an acoustic-based rail-break detection system in the transit environment was conducted under funding by the TCRP Project D-7/Task 10 (Reiff 2006).

Some ongoing works include:

- East Japan Railways and Tokimec have undertaken improved vehicle-borne ultrasonic testing using sliding and rotating wheel probes, enhanced probe guidance, greater probe scanning area, and improved data processing.

- The China Academy of Railway Sciences have targeted vehicle-borne ultrasonic inspection at speeds up to 80 km/h (about double current systems).

- AAR and FRA have focused on NDT technologies such as low-frequency eddy current, longitudinal guided ultrasonic waves, neural network analysis of ultrasonic signals, and laser generation and reception of ultrasonic signals.

- TTCI has evaluated three prototype systems: fiber optic cable bonded to the rail, strain gauge modules bonded to the rail, and an acoustic broken rail detection system.

- Spoornet and industrial partner IMT have developed a solar powered acoustic rail break detection system that uses acoustic transmitters and receivers clamped to the rails.

- Queensland Rail (QR) has addressed two RDM matters: the management of a vertical split head defect; and the development of a guide for technical specifications covering NDT testing of rails in track.
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