#### THE LUBRICATION OF HIGH SPEED CURVES

J Rastall Interfleet Technology Interfleet House Pride Parkway Derby DE24 8HX UK rastall.j@interfleet.co.uk

KEYWORDS: Rail; lubrication; rolling contact fatigue; RCF; remote condition monitoring; RCM.

#### ABSTRACT

After the incident at Hatfield in October 2000, Railtrack (now Network Rail) set up a programme to examine and develop a number of initiatives. The increased use of rail lubricators to improve the friction characteristics on curves was identified as an important way to manage and reduce the incidence of Rolling Contact Fatigue on higher speed curves.

At the end of 2001, Network Rail purchased forty electric track lubricators from three manufacturers to be used in a trial to judge their effectiveness and efficiency. Interfleet Technology Ltd assisted Network Rail in the assessment of these units by on-site monitoring and analysis of the data obtained.

For more than a year, Interfleet has monitored the performance of the lubricators installed under different configurations for the trial. The effectiveness of the deposition of grease onto the gauge corner of the rail has been assessed under different route and traffic conditions and five types of lubricant have been included.

An important benefit from the study has been the identification of the feasibility of significantly reducing the number of conventional lubricators in use on the railway network whilst improving the effectiveness of curve lubrication. Although the capital costs of the electric lubricators are significantly higher, they can replace a number of traditional devices in certain circumstances and show a positive financial benefit within one or two years. Added to this benefit is their improved reliability and the ease with which they can be maintained and adjusted.

#### INTRODUCTION

After the derailment incident at Hatfield in October 2000, Railtrack (now Network Rail) set up a programme to examine and develop a number of initiatives. These were intended to identify the causes and reduce the incidence of rolling contact fatigue (RCF).

One of those initiatives was to review the efficiency of the existing types of lubricators and investigate any improvements that have been made since the currently used types were selected. Many of the lubricators currently in use are of very old designs and demand a high level of maintenance effort to achieve optimum performance. Newer designs of pumps, reservoirs and grease distribution units promise improved reliability, less frequent adjustment, more uniform distribution of grease on wheel flanges and can be used in a wider range of locations.

#### DEVELOPMENT OF TRIAL BRIEF

At the end of 2001, Network Rail purchased forty electric track lubricators from three manufacturers to be used in a trial to judge their effectiveness and efficiency. Interfleet Technology Ltd assisted Network Rail in the assessment of these units by on-site monitoring and analysis of the data obtained.

# DEMONSTRATION OF THE TRAINSAFE RESEARCH CLUSTER MECHANISM IN THE CONTEXT OF "ADHESION MANAGEMENT" WITHIN THE "SAFE INFRASTRUCTURE" RESEARCH CLUSTER

### ISSUE HIGHLIGHTED IN THE STATE OF THE ART REPORT

This resulted in the topic of "adhesion management" being included in the agenda for the "Safe Infrastructure" workshop.

The following is the relevant extract from the State of the Art Report.

#### 4.2.1.3. The Wheel-Rail Interface: Adhesion Management

In order to minimise emergency braking distances, it is important to maintain good adhesion between the wheel and the rail. The organic residues associated with autumn leaf fall have been found to accumulate on rails and have the effect of lowering the coefficient of friction/adhesion at the wheel-rail interface to the extent that train braking and acceleration efficiency is seriously impaired. Some 2000 track miles (4000 miles of rail) are affected in the UK alone and the problem is known to affect many other European countries. In the worst affected areas of the UK, there is a risk that the reduced level of adhesion can compromise passenger safety and consequently remedial measures are taken through the application of 'Sandite' (a gelatinous suspension of sand) or grinding<sup>9</sup> to ensure satisfactory wheel-rail adhesion. Alternative methods include applying chemical or organic treatments that breakdown the residue, although the implementation of such methods is very limited. The organic residues range from 'heavy leaf mulch' to nano-thick layers and both their fundamental nature and their behavioural characteristics with respect to friction changes are not clearly understood. It is therefore necessary to undertake a programme of fundamental investigations to develop suitable methods that can predict or measure adhesion in order that a warning message can be communicated to the train driver. This will allow the driver to take appropriate actions and mitigate the risks of signals passed at danger (SPADS) or in the worst-case scenario, train collision. Furthermore, the resulting increased understanding will also assist in the development of effective preventative solutions.

One example of such technology has been developed by AEA Technology Rail BV. A low adhesion warning system was delivered to the Dutch Railways in October 2003. It consists of 15 trains that send low adhesion warnings to a central computer by GSM. These warnings are then converted to SMS messages and sent to drivers, who can adjust their braking accordingly. It is anticipated that this system will improve both safety (reduced SPADs) and train availability (reduced wheelflats).

#### 4.2.1.4. Line Side Equipment

In the event of a derailment, the design of line side equipment can play a significant role in determining the ultimate severity of the incident. There is currently an ongoing debate with respect to the most effective safety role for line side items such as electrification pylons. On the one hand, if such pylons were made to be very strong they could help to contain a derailed train and save it from further risk (water, bridges, buildings, etc.). The argument against this is that if the pylons were designed to fail at a predetermined force level, they could act as energy absorbing devices to control the deceleration of the vehicle. This would also reduce damage to parts of the train not designed for impact (sides and roofs). For example, as described in Section 4.1, one of the carriages in the Hatfield crash suffered extensive damage due collisions with line side pylons.

Further investigation is needed in this area.

#### 4.2.1.5. Collision Protectors

Collision protectors can be used to protect line side constructions (e.g. bridge columns) from being damaged by a derailed train. Rigid ground constructions are often unsuitable for absorbing large amounts of energy. Therefore, solutions such as the one shown in Figure 4.12 have been developed. This consists of a block of steel or concrete that is attached to the ground with anchors. In the event of a collision, the anchors are pulled out of the ground at a predetermined force level to decelerate the vehicle.

# DISCUSSION PRESENTATION FROM AN ADHESION MANAGEMENT EXPERT

A brief five minute presentation to introduce the topic to the workshop delegates. This defined the topic's scope and highlighted the key specific issues to be addressed.







# RESULTS OF FACILITATED DISCUSSION AT THE SAFE INFRASTRUCTURE WORKHSOP

The output from a two hour session, which was then presented to the other workshop delegates for comment.









# FINAL CHAPTER FOR CLUSTER REPORT

Describing the problem, its magnitude, the limitations of existing solutions, and the business implications. Making recommendations for new standards, technical solutions and future research activity.

N.B. Current document is still in draft form.

# ADHESION MANAGEMENT

Prepared by the Advanced Railway Research Centre and the Rail Safety & Standards Board (RSSB)

#### Introduction

Adhesion management relates to the control of the coefficient of friction,  $\mu$ , at the railhead. The challenge is to consistently maintain a value of  $\mu$  between approximately 0.15 and 0.40, although the exact boundaries of the desired range are open to debate

Low adhesion (µ less than approximately 0.15) can lead to extended braking distances and failure to stop at signals. Indeed, in the UK, incidents have occurred in which sliding trains have over-run signals by up to a mile. A recent study by AEA Technology found that in a five year period between June 1997 and June 2002, there were 140 adhesion related SPAD\* incidents in the UK. Annually, the breakdown of these SPADS was as follows:

Category	Severity	Average Annual Occurence
1	0-25 yd over-run	12.4
2	25-200 yd over-run	10.0
3	200 yd+ over-run	5.0
4-8	Damage to people / equipment	0.8

Analysis of UK SPADS, June 1997 – June 2002

As well as being a safety issue, low adhesion can also impact upon the availability of rolling stock. This is because sliding generates wheel flats, leading to the withdrawal of vehicles from service for repair.

The most common causes of low adhesion are leaf films, oil spillages, and rust<sup>†</sup>. Moisture generally exacerbates the

\* "Signal passed a danger" – an incident in which a train passes a stop signal without authority to do so. situation. Wet leaves can result in values of  $\mu$  as low as 0.01. Consequently, chronic low adhesion is both a regional and a seasonal problem. The worst affected areas are the UK and similar latitudes in Northern Europe, during periods of autumnal leaf fall.

High adhesion ( $\mu$  greater than approximately 0.4) can lead to high creep forces and the initiation of rolling contact fatigue. Again, it is predominantly a regional issue, particularly in climates with high temperatures and low humidity. In the US,  $\mu$  values as high as 0.7 have been recorded.

# Current Technical Issues Relating to Adhesion Management

Current approaches to managing low adhesion tend to involve one of the following:

- Cleaning the rail (e.g. using high pressure water spray or grinding).
- Adding substances to the track to raise the coefficient of friction (e.g. sand).
- Vegetation management (e.g. clearing trackside foliage so that leaf-fall is no longer an issue).

The problem with the former two approaches is that they are only short term solutions. In extreme circumstances, their effectiveness can diminish within a matter of hours. The addition of sand can also interfere with track circuits and initiate wear.

The main drawback of clearing trees and other trackside vegetation (aside from the environmental implications) is that it can lead to the destabilisation of embankments. Trackside foliage can also act as an effective noise barrier.

To a certain extent, drivers can also modify their driving style to accommodate low adhesion (e.g. through the use of earlier braking). However, drivers obviously need to be aware of the existence of low adhesion conditions for this approach to be effective. High adhesion is usually treated through lubrication.

# Current Issues Relating to Standards and Adhesion Management

There are currently no mandatory legal standards relating to adhesion management. A UIC product acceptance standard for wheel-slide protection does exist (Leaflet 541-05), and this is based on a water / soap solution test. However experience shows that this test is not particularly useful. Therefore:

The TRAINSAFE consortium recommends that a new standard for adhesion measurement should be developed. For European interoperability, this should be through a TSI.

However, before such a regulation could be introduced, it would first be necessary to develop standardised approaches to the measurement of  $\mu$  and the management of this data. Consequently:

The TRAINSAFE consortium recommends that a standardised system for the measurement of  $\mu$  should be developed.

The TRAINSAFE consortium recommends that standardised systems for the management of adhesion information should be devised and implemented.

Further consideration needs to be given to both of the above recommendations. For example, should µ be measured on a continuous or discrete basis? Should any measurement system be train-based or track-based? Is more than one measurement system required? (e.g. a highly accurate scientific measurement

 $<sup>^{\</sup>dagger}$  A particular problem when a section of track has been out of service for a period of time

system for calibration and research purposes and a more robust, less refined, cost-effective system for in-service use).

# Solutions for Improved Adhesion Management

Any new solutions for adhesion management should clearly aim to overcome the limitations of existing approaches. Therefore, they should:

- Be long-term or ongoing solutions.
- Not interfere with track circuits or other systems.
- Not have detrimental side effects (e.g. the initiation of wear).
- Be able to accommodate existing trackside vegetation.

In terms of low adhesion, one approach might be to employ new, cost-effective, noncontact rail cleaning devices that could be fitted to all in-service rolling stock. Potential technologies might include:

- Laser treatment (e.g. Laserthor).
- Microwave or ultrasonic devices.
- Aerodynamic devices that deflect air so as to clear fallen leaves from the track.

Alternative, or complimentary, approaches to the problem of low adhesion might involve technologies that don't rely on modifying  $\mu$ directly. For example, non-adhesion dependant braking devices (e.g. air brakes). Or the use of modified rail head profiles to increase contact pressures.

As low adhesion is a transient problem, it might also be worthwhile to develop improved techniques for forecasting its onset, perhaps using local climatic condition monitoring / prediction tools. Contingencies for dealing with low adhesion could then be implemented in advance. For high adhesion, the following solutions could be considered:

- The use of modified rail materials, e.g. nickel coatings.
- The use of modified rail profiles to reduce contact pressures.
- In-service misting systems.

# The Business Benefits of the Proposed Solutions

It has been estimated that the total annual cost of low adhesion in the UK is some £20 -40 million (approximately €30 - 60 million). This represents the revenue lost due to "leaves on the line" service disruption, the revenue loss / repair cost of wheel flats, and the cost of accidents caused by SPADS (although the latter are fortunately extremely rare).

Clearly, when the Europe-wide situation is considered, together with the additional costs associated with track damage due to high adhesion, the total cost of adhesionrelated issues to the European rail industry is likely to be into the hundreds of millions of Euros per year. Consequently, any technologies that can help to address the problems surrounding adhesion have the potential to yield significant cost savings.

#### Recommended Priorities for Future Research into Adhesion Management

In order to facilitate the proposed solutions, the following primary recommendations are proposed:

The TRAINSAFE consortium recommends that the following programmes of research into adhesion management should be prioritised:

- The development of reliable adhesion measurement technologies.
- Improved fundamental understanding of leaf films in terms of their chemical, mechanical and electrical properties.
- The development of track cleaning technologies that can be implemented within existing inservice rolling stock.
- For high adhesion, a study of optimum rail metallurgy, coatings and profiles.

Other, secondary, research priorities that would also usefully contribute to the knowledge base include:

- The definition and development standard surfaces, with calibrated levels of adhesion, as a tool for research.
- Cost-effective, train-based, low adhesion warning systems.
- The evaluation of braking systems that don't rely on adhesion.
- Tools for the forecasting and prediction of adhesion.
- Accurate definition of threshold levels for "low adhesion" and "high adhesion".
- The chemical development of solid lubricants to counteract high adhesion

The brief for the trial was developed as understanding of the nature and extent of RCF emerged. Interfleet worked closely with Network Rail and Arup-TTCI during that time and a good general agreement emerged on the aims of the trial and the methods to be employed.

#### SELECTION OF SITES

So as to gather as much data as possible, a matrix was drawn up to give a representative mix of line speeds, curve radii, topography and traffic patterns for the different types of grease and lubricator. All Network Rail Zones were invited to identify and submit sites suitable for the trials. The size of the trial was inevitably limited by available funding but four Zones were eventually included in the trials.

#### DESCRIPTION OF TRIAL

The site investigation work included a number of measurements and observations intended to identify the longer term performance and efficiency of the lubricators.

The examinations of the curves concentrated on the high rails although profiles of both were routinely monitored. The measuring equipment used on site consisted of a Miniprof to check the rail transverse profiles and a Goop gauge to assess the amount of grease present on the rail around the curve to determine the effectiveness of the grease distribution at each site. Battery voltages were checked with a multimeter and visual assessments and photographs were taken to record the general conditions. The data collected was then collated for analysis.

A complete inspection undertaken at the first and last visit to each site included all the above observations at the defined points. A few sample readings were taken with the Miniprof at intermediate visits for verification and for checking trends. The rail profiles as measured by the Miniprof were compared over the period of the trial as an indication of the rate of wear.



The Miniprof, shown in action, left, is used to measure the transverse profile of a rail to within 0.1mm or better. It is a small handheld device connected to a standard laptop computer which measures the rail head profile in-situ, together with the location and other identifying information. Subsequent measurements at the same location can calculate the amount of rail wear that has taken place.



The Goop Gauge, shown left, is a simple template which is calibrated to assess the level of grease on the rail. The calibration is nominal and based on zero at the mid-point of the gauge corner radius. It has been surprisingly useful in quantifying the rate of propagation of the grease around the curves.

#### DESCRIPTION OF EQUIPMENT

The three different types of electric lubricator all had certain features in common. They had non-contact triggers, electric pumps which were battery powered and delivered grease to the rail gauge face through GDUs not dissimilar to traditional practice.

#### Electric operation

The big innovation was the introduction of electric pumps triggered by inductive or other non-contact detectors clamped to the rail. This eliminated the most wear-prone component, the grease plunger. The plunger essential to mechanical and hydraulic lubricators has a very hard life and needs constant adjustment to maintain effective lubrication of the curve. With an electric pump and control box, the amount of grease delivered per train or per wheel can be adjusted in discrete steps and this will not drift with time.

#### <u>GDUs</u>

Each manufacturer used their own GDUs and we experienced mixed success. The difficulties experienced by some were exacerbated by the tendency of some of the greases to separate out within the lines. This led to rapid blockage of the GDUs. One type of GDU supplied was based on European LRT systems and was quickly replaced after it became apparent that the assembly was not robust enough for UK main line use.

#### Location on transition and straight

The Arup-TTCI report recommended dual-rail applications following North American practice. This was contrary to conventional UK practice but, for the trials, some of the lubricators were installed on straight track. The majority were installed on transitions following traditional practice.

#### DUAL RAIL GREASE COLLECTION ON STRAIGHT TRACK

Received wisdom on the behaviour of coned steel wheels running on steel rails is that they will self-centre on straight track and will steer themselves around curves. This is true up to the limit of the flange clearance which is normally reached on curves sharper than about 1000 metres. Thereafter, flange contact is inevitable.

In practice, wheelsets do not operate alone. They are mounted in bogies (4-wheel or 6-wheel) and in rigid wagons. In such situations, the wheelsets are unable to align themselves radially with the curve and the leading wheelset of each bogie or wagon will tend to attack the high rail. Three-piece or steering bogies are an attempt to overcome this effect but they can be unstable at higher speeds and have not found favour outside heavy haul railways. The result is that some flange contact may occur on curves as flat as 2000 metres. In general, the higher the speed and the greater the cant deficiency, the flatter will be the curve when flange contact commences.

This is further complicated in that it is not possible to build a perfect bogie or wagon frame, so the axles will not be perfectly parallel. The result of this is that the bogie or wagon will tend to steer to one side or the other, the degree of steering will depend on the inaccuracy in the construction and assembly of the vehicle. This is a random phenomenon and, statistically, 50% of wheelsets will incline towards each rail on straight track.

If this can be relied upon, then we have the opportunity to radically alter the way rail lubrication is attained. No longer will the blades have to be located at exactly the right point on the transition of each and every curve, they can be located on straight track before the start of the transition. And when curves are found in groups, as is prevalent in many parts of the network, then the possibility presents itself for a dual-rail grease application at one point on straight track before a succession of curves. Evidence has been found during the trials to suggest that this phenomenon is quite prevalent, pickup has been obtained reliably and consistently from all of the dual-rail GDU installations on straight track during the trial.

It is important to remember that flange contact is not required to achieve pick up of the grease. Indeed, there is evidence from other trials to suggest that hard contact may reduce the effectiveness.

#### DISCUSSION OF RESULTS

Initial observation results of the lubricators have been encouraging. It is apparent that the long GDU sets fitted to both rails on straight track before the first of a series of curves are able to dispense grease to both wheels at the one location. This is carried forward and reapplied to the following curves – and there is firm evidence to show that this can be reliably achieved over several curves for 2 to 3 miles or even more. Even using a conventional set up of a pair of short GDUs on the high rail, coverage of two successive curves for a total distance of  $1\frac{1}{2}$  miles separated by half a mile of straight has been achieved in this trial using the better quality grease.

#### Grease clogging

The greases used in this trial were composite formulations designed to give a better performance than traditional greases. It became apparent that the properties required for successful delivery through an electric lubricator system are different to those normally successful in a mechanical or hydraulic system. Traditional lubricators induce high impulse loads into the grease lines which do not occur with the electric pumps. The result has been that the composite greases were inclined to segregate and congeal, the hydraulic shock loads induced by the non-electric lubricators seem more able to overcome these tendencies.

Two types of grease emerged as particularly successful in these trials, both manufactured by Clare. These were the Hi-Load, a black molybdenum-based grease, and the B-1099 biodegradable grease. Network Rail now prefers the use of biodegradable greases wherever possible so the later trials concentrated on this type.

Subsequently, Shell and other manufacturers have also become keen to supply greases suitable for these devices.

#### GDU length

Lubricators have traditionally used blades (grease distribution units, GDUs) approximately 400 mm long in pairs, separated by two sleeper beds or about 1.4 metres. Modern rolling stock has fairly consistent wheel diameters in the range of 750 mm to 950 mm (or up to 1150 mm for locomotives) which gives circumferences of 2.3 m to 3.0 m (3.6 m for locomotives). This often leads to spotting of the grease deposits around the curve at regular intervals corresponding to two spots per average wheel circumference. If the grease delivery rate to these short blade pairs is increased then the consequent splashing will spread the grease further around the wheels which may improve the evenness of the distribution around the curve. But this is at the expense of using large quantities of grease, much of which is deposited on the rail head and the ballast.

One of the lubricators used in this trial used blades 1200 mm long in pairs with a very small gap between. This resulted in almost complete coverage of a wheel circumference which resulted in an even coverage of grease around the following curves. Other lubricator designs



used four standard 400 mm long blades, spaced over four or five sleepers. This also resulted in a very even distribution of grease around the following curves.

#### **GDU** location tactics

The most significant finding from these trials has been the ability to reliably dispense grease from long GDU arrays placed on straight track. This is a complete break in tradition from the usual location at a

point between one quarter and one third of the way up the transition. The implication of this finding is that, on curvaceous routes, lubricators can be sited on straight track with dual-rail installations to feed a series of curves. Even for a single curve where only one rail is to be lubricated, there could be a benefit from using the same tactic. Thus the lubricator's location can be chosen as much for accessibility and safe working as for the route's topography.

#### Power supply

Clearly, for the majority of lubricators, there will be no convenient shore supply available and the devices must rely on self-generated power. The lubricators included in these trials have used solar panels and wind turbines, alone or in combination, with a battery to maintain power whilst the prime source of energy is unavailable. One site depended on battery alone due to it being sheltered in a deep cutting.

There will be a cost and reliability trade-off between a combined solar panel and wind turbine and a larger solar panel alone but this will only become apparent after a much longer period of operation.

Some apprehension was expressed at the start of the trial over the vulnerability of the solar panels to vandalism and theft. However, apart from two incidents, one in 2001 and one in 2003, no trouble has been experienced. It is worth noting that there is now a growing population of solar and wind turbine powered equipment on and around the railway network. However, it would be prudent to consider the vulnerability of the units along with all the other usual considerations when siting.

#### Ease of adjustment with electronic controls

The lubricators in these trials have been fitted with electronic controls which govern the running times of the electric pumps. This has the benefit of making adjustment predictable and has removed much of the trial and error which is a feature of the mechanical and hydraulic devices.

#### COMPARISON WITH HERITAGE LUBRICATORS



Traditionally, lubricators have been maintained by dedicated individuals who have needed to develop an affinity with the devices. The mechanical parts wear rapidly and need frequent adjustment to maintain optimum performance. But their successful maintenance depends on a great deal of enthusiasm and diligence by the individuals. Such qualities are increasingly difficult to find and attract and

retain in today's labour market conditions, certainly in the numbers required to maintain the numbers of lubricators installed across the network. The electronic devices used in these trials have shown themselves to be easily and reliably adjustable and can be expected to maintain their adjustment indefinitely.

#### RELATIONSHIP BETWEEN LUBRICATION AND RCF

Many conclusions on the causes of RCF are still subject to debate. But laboratory tests by others have shown that RCF cracks in rail steel are formed by initial running without fluid lubricants followed by additional running with fluid lubricants. This suggests that initial dry running is required to damage the rail head surface and to initiate RCF cracks. These cracks can then grow by fluid entrapment within the embryonic cracks.

The surface of new rails has a decarburised layer 0.1 to 0.2 mm thick which is relatively soft and in which RCF cracks can more easily develop. The finished surface is also quite rough and this is initially more aggressive to passing wheels. This may lead to higher than normal rates of wheel flange wear in certain circumstances.

It is therefore vitally important that lubricators are installed and commissioned as soon as possible after rerailing to avoid or reduce the onset of possible RCF cracking and claims for accelerated wheel flange wear. Network Rail have recognised this and have specified that new rail at RCF sites should be ground shortly after installation and that lubricators should be fitted immediately after the initial grinding.

#### CONCLUSIONS

Network Rail is now considering their long term strategic plan for future lubrication tactics. They are aware that decisions made now and equipment bought now will affect costs and liabilities for the next decade or more.

- 1. Future lubrication policy will include an increasing number of electric lubricators similar to the types found to be successful in these trials.
- 2. Pairs of longer GDUs or arrays of standard GDUs will be employed to improve the efficiency of applying grease.
- 3. Wherever possible, groups of curves will be identified and the dual rail, straight track installation tactics be employed.
- 4. The importance of reinstalling and recommissioning lubricators as soon as possible after rerailing and/or grinding has been recognised.

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### A SYSTEMS APPROACH TO MONITORING ASSET RELIABILITY

#### Dr C.R.Bell

#### CDSRail 1570 Parkway Solent Business Park Fareham, Hampshire PO15 7AG

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#### ABSTRACT

Any system obtaining useful information on the state of remote assets needs to perform the following functions:

- Collecting the relevant data.
- Collating data from many different, and often geographically separated, sources.
- Reducing the data to useful information.
- Transmitting this information to where it can be used.
- Displaying the right information to the right people.

This paper outlines some of the issues involved in taking a whole system approach to produce successful asset monitoring systems for the rail environment.

Monitoring systems are not signalling systems, and many of the safety requirements for vital signalling equipment apply, but equally many do not, making safety approval challenging. Monitoring systems can produce vast quantities of data in remote outside locations where conventional IT equipment cannot be used for data reduction. This problem is compounded by the low bandwidth communications links generally available.

Information about an asset is frequently of interest to different parts of the organisation. Monitoring S&C can provide information about physical movement, interlocking with the signalling system and heating in cold weather. System design and operation must cover the differing requirements of all these interest groups.

#### **INTRODUCTION**

Since remote asset monitoring began in the time of British Rail there has always been a lingering perception that the costs outweigh the actual benefits. Fragmentation of the rail industry has aggravated the situation, but there are signs that efforts are now being made to identify the underlying reasons behind the problems and to formulate a better approach to overcome them.

A recent initiative at Network Rail HQ was to hold a Remote Asset Condition Monitoring Systems Strategy Workshop, using an external facilitator and employing the tools and techniques of Value Management. The aims of the workshop were:

- To raise the awareness of the current situation
- To clarify the overall objectives of Remote Asset Condition Monitoring (RACM)

- To identify the most appropriate organisation to deliver the RACM objectives
- To develop and agree a prioritised and attainable short term action plan

To maximise the benefit of this 1-day session, delegates were given a briefing pack beforehand and asked to bring to the meeting:

- A list of any RACM Systems that had in their opinion been successful
- A list of any RACM Systems that had in their opinion yet to realise their potential

The workshop was attended by 19 delegates from Network Rail HQ, Network Rail regions/zones, train operators, maintainers and RACM equipment suppliers. Some thirty existing Remote Asset Condition Monitoring systems were considered, from a variety of manufacturers and locations.

The attendees perceived eight systems as successful and five that had yet to realise their potential. There were two cases of systems using the same equipment but being used in different regions which appeared on both lists.

Points Condition monitoring systems supplied by cdsrail and installed in Great Western Zone were perceived as successful whereas similar equipment installed at Euston were not.

The prime 'routes to failure' were identified as:

- Lack of planning at the design stage: too much data too little information
- General lack of organised stakeholder support

We will use Condition Monitoring of an electric point machine, the HW, as a vehicle to explore this.

#### THE BUSINESS CASE FOR POINTS CONDITION MONITORING

The Statistics – poor generic business case

A number of different types of points are currently in use within Network Rail and statistical evidence with regard to failures has been collected over a number of years. One report logged faults on around 550 point ends over a five year period and calculated failure rates for three very commonly used types:

HW	0.52 per year
M63	0.70 per year
Clamp Lock	0.91 per year

This evidence alone does not provide a very strong business case for Points Condition Monitoring: an HW point fails on average only once every two years. These figures, however, make no allowance for the train delays that may be caused by points on key junctions. Also points that fail frequently will be averaged out by points that are seldom used and rarely fail.

#### The facts - strong specific business case

The cdsrail Point Condition Monitoring Systems installed in Great Western Zone are located in the area from Paddington out to Reading, which includes very busy commuter routes and where point failures can lead to widespread disruption. Figures compiled by the maintainer over a three month period and covering just 25 point ends within this area show a total of 95 alarms allowing maintenance to be carried out <u>before</u> failure.

By applying typical delay minutes that would have been caused by <u>actual</u> failures on these point ends, the maintainer was able to calculate the total time saved as 7871 minutes.

The best measure of the value of this time saving is to look at the cost to Network Rail. In the track access arrangements with the TOCs and FOCs there is a 'Schedule 8 payment', which is broken down per operator per route. As the routes west of Paddington are operated by a number of different operators each having a different rate then we have taken the UK average figure of £53 per minute delay.

7871 minutes equates to  $\pounds$ 417k – demonstrating that Point Condition Monitoring can pay for itself very quickly.



#### REMOTE CONDITION MONITORING FOR POINTS

Figure 1: HW Point Condition Monitoring Overview

In the UK most Point Condition Monitoring systems employ two types of sensor to obtain 'profiles' from each point end – see Figure 1.

A load pin is a hollow steel pin containing a strain gauge. This replaces the pin normally used in the pivot joint between the point machine and the point mechanism. Electronics within the load pin head convert the force exerted by the point machine to an analogue signal for external monitoring. Because the load pin casing is electrically common to the rails, which in many instances will be carrying track circuit currents, additional galvanic isolation must be provided within the Point Condition Monitoring System to prevent any possibility of power reaching the rails and interfering with the track circuits.

The other sensor is a Current transducer which monitors the current drawn by the point motor.

The time of swing is also an important parameter. This may be measured as the time difference between two events provided by the point position detection relays or alternatively may be derived from the motor current profile.

It is a fact that more than 50% of failures on HW machines occur outside the point machine. New sensors to reveal the root causes of failure are currently being trialled to investigate voiding, proximity, switch creep and the effects of temperature.

Under normal conditions the load and current profiles will vary very little between successive point operations. Incipient failures will, however, manifest themselves as variations in the profiles. Many of these can be detected via simple alarm thresholds, but digital signal processing is able to reveal more subtle problems.



Typical faults on HW point machines:

- 1. Point locking out of adjustment
- 2. Detection out of adjustment
- 3. Throwbar nuts running back
- 4. Worn or high resistance brushes
- 5. Burnt out or high resistance operating contacts
- 6. Obstruction between swing nose and fixed rail
- 7. Loose or broken stretcher bar bracket
- 8. Loose drive lug
- 9. Back drive holding off tips of points
- 10. Dirty commutator

Fault No 3, throwbar nuts running back, is illustrated by Figures 2 & 3. The movement available from the point machine is around double that required to drive the point. The difference is taken up by a boss through which the throwbar slides, adjustment being provided by pairs of locknuts on either side of the boss as shown in Figure 2. One of the stretcher bars is shown at the very end of the switch blades.

The profiles in Figure 3 show profiles from the load pin output for point movements from Reverse to Normal and back again. If the thowbar nuts are backed off less than one full turn the effect on the load profile is noticeable. The motor current profile for the same tests shows no change.

The Potters Bar accident was caused by a similar point end with three adjustable stretcher bars: Point 2182A had missing nuts on two of the bars. The stretcher bar at the very end of the switch blades fractured allowing the curved switch rail to shift against the stock rail and derailing the last carriage on the 12:45 King's Cross to Kings Lynn train with tragic results.

No-one can tell for certain whether point condition monitoring would have picked up this problem but it is quite possible.



Figure 3: Point Condition Monitoring Load Profile with throwbar nuts out of adjustment

Figure 3 also graphically illustrates one of the outputs from the Value Management workshop: a common thread between asset monitoring systems perceived to be unsuccessful was 'too much data – too little information'.

Point condition monitoring systems sample both load and current data at rates of up to 100Hz. Every point swing takes a few seconds and generates a few kilobytes of data. This soon mounts up and results in huge amounts of <u>mostly identical</u> sets of stored data. These need to be captured, stored and reformatted so that unnecessary detail is eliminated by clever digital signal processing.

Operators can only cope with summarised information, NOT lots of data.

Figure 4 shows one of the summary screens developed by collaboration between the supplier, cdsrail and the maintainer, Amey, for four point ends at Southcote Junction. This screen combines data from Point Condition Monitoring and Event monitoring, the latter providing indications of track circuit occupancy, signal aspects etc. Graded alarm thresholds are used to provide prioritised alarms.

This display is typical of those used in Great Western Zone to cover the area between Paddington and Reading. These screens use the data to provide management information that assists the maintainer to move from reactive faulting to proactive maintenance.



Figure 4: Maintainers Fault Screen developed jointly by Amey and cdsrail





Figure 5: An information hierarchy for the railway

We have seen that Points Condition Monitoring yields vast amounts of data. There are many other existing systems monitoring everything from level crossings to track circuits and from points heating to power supplies.

Figure 5 illustrates an information hierarchy for the railway. So far we have considered only the first two layers; we have lots of data and some of it may have been processed within the Data Acquisition System. Now it needs further processing to maximise the information yield and it needs to be made accessible to the right people at the right time. Increasing the amount of processing that is carried out lower down relieves pressure on the top end but data acquisition systems with on board pattern recognition must combine performance with robustness. This means suitability of the design for the harsh rail environment.

A client/server architecture is the minimum requirement to support the diverse needs of multiple users at different locations, all needing concurrent access to multiple sites. Such an architecture is provided by the cdsrail Master Supervisory System shown in Figure 6.

Distributed sites can be routed through one or more Trackwatch controllers which act as gateways to the Master Supervisory System Server, a high specification machine incorporating an SQL database which provides standard connectivity. Such a system can provide multiple alarm options, such as SMS, pager and e-mail. Client machines provide live information on mimics from multiple sites.



Figure 6: Master Supervisory System Architecture



Figure 7: Systems Engineering Approach

To gain maximum benefit from any asset monitoring scheme it is essential that the right people are involved both at the outset of a project and throughout its life. Figure 7 shows a Systems Engineering Approach to the management of such a scheme.

<u>Workshop with Stakeholders</u>: The prime function of this is to establish what data to collect, how often and, importantly, why. The key output is to identify the point at which system *data* is to be converted to *information*.

<u>Functional Design Specification</u>: To define the monitoring regime and system architecture to support the outcomes from the workshop

Implement system: Build, test and implement the system with stakeholder support

<u>Data to information</u>: This stage combines the expertise and experience of railway staff with the systems expertise of the supplier. The output of this stage is first stage pattern recognition leading to data reduction and a clear path to extracting useful information from the data

<u>Information to Decision Support</u>: The outcomes can now be built into the system architecture to simplify, and wherever possible automate, decision support

<u>Review Performance</u>: Reviews should involve all those who attended the stakeholder workshop and will compare the actual performance of the system with the initial expectations. Output from reviews may necessitate revisiting earlier stages and leads to **Continuous Improvement**.

Many projects do not include the time or the funding for the Stakeholder Workshop and Functional Design Specification stages and Network Rail is littered with examples of systems that were not properly thought through. At best the result is an unwieldy system that requires too many people to obtain the intended benefit. At worst the system falls into disrepute and many such systems have never worked.

However we are where we are. Many disparate systems exist and will remain in service for the foreseeable future. Many manufacturers use their own protocols and while it may be possible to bring some third party systems into an MSS style architecture such as that shown in Figure 6 it is certainly not a universal panacea.

#### ENGINEERS WORKBENCH

A new initiative to try to overcome these problems is Engineers Workbench (EWB – see ewb.com), an information management tool which is the first of its kind to give Network Rail a unified view of asset performance. The aims of the system are:

<u>To gather</u>: EWB receives a summary of the information collected by all remote asset condition monitoring systems. The keywords here are 'summary' - not 'detail' and 'information' - not 'data'

<u>To harmonise</u>: EWB overcomes the 'language problem' by defining an XML schema. This leads to an 'asset standard' for each type of asset and requires information as an XML message with a fixed content and format.

<u>To enable</u>: The messages received by EWB for a given asset type are therefore system independent and will allow for analysis of data and benchmarking of systems, suppliers and maintainers.

<u>To distribute</u>: EWB has a central server which can be accessed by Network Rail staff over their corporate network. This allows relevant information to be made available to other corporate systems and to stakeholders in a timely way.

CDSRail has supported Engineers Workbench from the outset, assisting co-ordinators W.S.Atkins in defining the asset standards. A pilot scheme is currently operational at York and is being trialled with a number of remote asset condition monitoring systems from different manufacturers. CDSRail MSS systems are EWB ready and are playing a major role in helping EWB to realise its potential.

Engineers Workbench is paving the way by laying down standards for the upper levels of the information hierarchy but industry needs to harmonise its approach to the lower levels. The may well come about through increasing use of Internet tools to allow equipment to be interrogated directly by using standard Internet browsers.

CDSRail has expertise from concept to product, combining safe measurement techniques, system and domain knowledge with professional project management – see cdsrail.com.

#### **MODERN METHODS OF TRACK INSPECTION**

A.J. Savage Engineering and Safety Director Carillion Rail 1<sup>st</sup> floor Gloucester House 65 Smallbrook Queensway Birmingham B5 4HP andysavage@gtrm.co.uk

KEYWORDS: Track Safety, Track Inspection, Inspection Trains

#### ABSTRACT

In the 20<sup>th</sup> Century the number of staff killed at the railway trackside fell from 200 to 4 per annum. This is still 4 too many and current systems for ensuring trackside safety are probably as good as they can be due to human factors. Railtrack is introducing new procedures to minimise risk of track safety and these are likely to make patrolling of the line more difficult to carry out whilst trains are running. In order to reconcile the need to improve staff safety and to improve the quality of track patrolling a new approach is necessary, and this paper looks at the work being done by Railtrack, and in more detail by Carillion through its Eurailscout GB Joint Venture, to mechanise the inspection of the track with benefits to staff safety, train performance and quality of track inspection and maintenance.

#### **INTRODUCTION - TRACKSIDE SAFETY**

The safety of staff working on and about the track of Britain's Railways has increased drastically over the last 100 years. In 1900 some 200 staff were killed each year at the trackside. This improved to 150 by the time of nationalisation. During British Rail's lifetime a major improvement reduced the figures to about 10 per annum by 1990. In the early 1990's the introduction of Controllers of Site Safety and proper site briefings brought the figures down still further so the average figure is now just over 2 per annum, although 4 staff were killed in 2001. Clearly the figure in 2001, although far lower than the decades that preceded it, cannot be considered a success and the only acceptable figure is zero fatalities.

A review of the accidents that have led to staff losing their lives since privatisation shows that each death usually involved an error by an individual, often as the last link in the chain of errors or omissions, but in each case usually of less than 10 seconds. Without this final very short error the person involved would not have lost their lives. When we look at the number of people working on the infrastructure on Britain's railways, taking a figure of 35,000 people working 48 weeks a year, for 42 hours a week, we end with some 270 billion seconds of work being carried out each year. Whilst these figures can be subject to some debate the fact remains that, if we take a human factors approach, 40 seconds of error in 270 billion seconds of work is an extremely low level of error, and the present average of some 2 fatalities per annum is probably as good as it is going to get. I would suggest that the only way to improve and drive out fatalities from the trackside is a new approach, involving the almost total separation of people and trains rather than trying to carry out work whilst trains are running.

#### TRACKSIDE SAFETY - THE WAY AHEAD

Railtrack have agreed with the approach of separating people and trains and have recently published a new company standard aimed at risk minimisation, commonly referred to as Rimini. In order to drive the separation of people from trains this makes working on live lines more difficult, and also is tied in with simplifying means of taking possession of the track in order to make green zone working, where no trains are running, more effective.

Unfortunately the work involved in the Rimini approach has to deal with what has become known as "the Green Zone Conundrum". This is that it is relatively easy to obtain access to the line without trains

running when there is a low level of service, but not surprisingly when there is a high level of service it is impossible to get useful possessions between trains. Yet at the same time the risks to staff of being struck by trains are far higher when there is a high level of service than when there is a very low one.

If we look at Railtrack's Rule Book, and in particular Rule T2 we see that it takes a fairly large amount of time to take a T2 possession after a train has passed, and similarly to hand it back before the next train arrives. I would suggest that if more than 2 trains an hour are running on a route it is impossible to do any sensible work within a green zone - and the number of routes where train services are one or two per hour is very few.

When we look at carrying out physical work on the infrastructure at a static location the solution is fairly easy to define albeit a lot more complex to introduce. It is clear that the best approach to carrying out static work is to book T3 Possessions on a regular basis, preferably timetabled for all routes, so that work can be done when trains are totally stopped, normally at night. Clearly this approach will have a major effect on timetabling and a stream of work is in hand, led through Railway Safety's Safety Advisory Board and involving Railway Safety, Railtrack, TOC's, Contractors and Unions in trying to take a long term approach to separating people and trains when work is being carried out. For the purposes of this paper I do not propose to follow the issue of work any further, but to remain focused on patrolling.

#### PATROLLING REQUIREMENTS

Railtrack specifies its requirements for patrolling in its Company Standard RT/CE/S/103 currently at Issue 5. Apart from laying down the frequencies and what has to be done there are three key requirements:

- the patrols must be carried out in daylight
- the patroller must walk in the four foot of the track or on the sleeper ends
- the patroller must walk in alternate directions for alternate patrols.

Requirements of Rimini also specify that Red Zone working, when trains are running, is prohibited if

- it takes more than one advance and one intermediate lookout in any direction
- it is necessary to cross more than 2 tracks to a place of safety
- there are more than 4 lookouts other than any site or touch lookouts involved.

Rimini also requires that you have to be in a place of safety 10 seconds before any trains arrive.

A combination of these 2 requirements gives particular problems on 4 track lines where the 4 tracks are in the order Down / Up / Down / Up since it becomes necessary to give warning from both directions when the patroller is on the centre line. This arrangement of fast and slow line is very common, particularly on the busiest lines and it applies between Euston and Roade, Stafford and Crewe, St Pancras to Bedford, Paddington to Didcot, Severn Tunnel to Cardiff and Liverpool Street to Shenfield to name but a few.

The effects of standards 103 and Rimini on patrolling are quite considerable. Clearly if there are 7 or more lines then any line that is 3 tracks or more to a place of safety can only be patrolled under possession.

In view of the mobile nature of the patrolling there has to be a continuous place of safety available throughout the length of the patrol available for the patrolman to use at any time.

If we then look at the patrol itself, and the patroller is working on his own with only a site lookout then at 110mph, assuming 25 seconds to reach a place of safety, he needs 1360 yards visibility in each direction, whilst if the speed increases to 125mph that distance goes up to 1540 yards. How often can one man see <sup>3</sup>/<sub>4</sub> to 7/8 of a mile?

If the Patroller has an advanced lookout in each direction, then that lookout must walk in the cess to be personally safe, and the lookout walking behind the patroller must be able to look both forward to the patroller and back for oncoming trains on a very regular basis. The warning time for an oncoming train increases by 10 seconds because of this, and the distances go out to 1 mile 140 yards at 110mph and 1 mile 380 yards each way at 125mph – less per person, but a greater overall distance.

Whilst Rimini will allow an advance and an intermediate lookout the need to continually look backwards and forwards for each person adds up so that the warning time now becomes 45 seconds for the patroller, and this is at the very edge of legality of Rimini. In order to work this way properly it would also be necessary for the 5 groups, 2 advance lookouts, 2 intermediate lookouts and the actual patrol group to remain at a fixed distance from each other as they walked along the track. I consider that this would be impossible and I will not accept a patrolling system within Carillion Rail that involves more than one advance lookout in each direction on 4 track railways.

If we now look at the level of service against the time available to patrol, again working on the assumption of 4 tracks in the Down / Up / Down / Up configuration, and consider two cases of six trains an hour in each direction and of twelve trains an hour in each direction – and any similarity to the levels of service on the West Coast Route Modernisation is purely deliberate – we find that if the patroller is working with a site lookout only he spends 3 minutes 55 seconds on average in each 5 minutes patrolling, which I would say is quite acceptable. However if the number of trains goes up to 12 trains an hour then the amount of time available in any 5 minute period for patrolling is reduced to 1 minute 25 seconds. I would suggest this is on the very limit of acceptability. If the lookout has an advance lookout in each direction times go up for standing clear and the result is that the patroller only gets the 3 minutes 35 seconds if there are 6 trains an hour whilst 12 trains an hour he is only able to patrol for 1 minute 5 seconds each 5 minutes. This is clearly not acceptable. (I would be very happy to share my calculations with anyone who wishes to look at them in detail but I do not think this conference wants to be tied down with this level of detail!)

Finally Her Majesty's Railway Inspectorate has stated that nobody will be allowed to work Red Zone on any line where trains are operating at speeds over 125 mph – which is the stated long term objective for West Coast Route Modernisation. To conclude my review of patrolling on a 4 line railway I would suggest that we are now at the very limits of what we can do safely with a man walking along a track looking at the state of the track. I would also query whether, in 2002, even if we can ensure the safety of the patrolman himself we should actually rely on manual observation and notes being written down as the patroller goes along as our prime safety defence for the state of the track.

#### A NEW APPROACH TO PATROLLING

Given that the constraints are as I have described on Red Zone patrolling on 4 track railways the only way that I can see of delivering inspection in the future is to move the men off the track so far as is possible. Clearly we cannot do away with the need at some point to walk along the track to physically look at drains, and to inspect and tighten the various fastenings, but this does not need to be done on the same frequency as present patrols. Thus if we take away the need to look at geometry, missing fastenings, broken rails and to look at the line side from the patroller, we can start to consider doing the patrols in the dark as part of cyclic possessions on perhaps a 13 weeks cycle as I described above when I was talking about static work. The patroller then would only concentrate on things like loose fastenings, pads and insulators and litter on the track. To achieve this all the other issues of track recording have to be put somewhere else, and I would suggest that the right place to do this is recording on the train.

Whilst inspection by video and photographic records would be a major step forward with modern information technology systems it is possible to make use of intelligent software and minimise the amount of time where an individual looks at the recordings to decide what is wrong and where actions are needed. Thus we should look at automatic recording of the maximum number of parameters with recognition of exceedances by the computer system rather than the operator. The operator can then focus on the rectification of known defects rather than trying to identify them in the first place.

Railtrack have been doing a considerable amount of work themselves in this area, and have focused on on-train recording using a service train and technology available from Reeves in the USA. This technology is easily fitted to a train, and can be downloaded at the end of each run. It is designed to replace and supplement track recording cars and is an excellent product for what it was designed for. However, I would suggest that it does not carry sufficient capability to replace the patroller and also that whilst it is sensible to fit out trains where there is a captive fleet on a large dedicated route such as the West Coast Mainline or Chiltern routes it becomes much less viable when trains run over a wider range of branches of short distances such as much of the Southern Region, the remote rural lines and perhaps some of the cross country routes. In these cases it might be that the right answer is to have self propelled track recording cars.

#### EURAILSCOUT GB PROJECT

Eurailscout GB is a Joint Venture that has been formed by Carillion Rail and Eurailscout bv, itself a Joint Venture between Strukton, Knape in Europe. Eurailscout bv delivers track recording in Europe from its Dutch base and Eurailscout GB is designed to build on the recording skills of Eurailscout bv and Carillion Rail's knowledge of the UK industry.

Eurailscout GB has ordered two trains for track inspection. The first train, a Class 121 first generation dmu "bubble car" has been converted and in is service. It is designed to carry out what we call a virtual inspection, where the patroller carries out his work at a computer screen instead of on the line.

The second train, a Plasser UFM 160 two car train, is based on state of the art technology, and is currently under trials in Austria to be delivered in the UK later this year.

When we look at the Class 121 we see it has 5 cameras, a lighting system for the rails and a Trackmon geometry system. It can operate at a maximum speed of up to 70mph and, by using Omnicom's OmniInspector system and GPS can locate defects to an accuracy of +/-1 metre.





We see here an example of the different pictures that can be brought up with the OmniInspector software. You will note the extremely close detail of the fastening and how easy it is to see a missing clip from this.



The train is also fitted with Trackmon by AEA, using sensors as we see here.



This is a typical Trackmon output, in this case a Manhattan Skyline showing the improvement and deterioration of track by 1/8 of a mile.

Omnicom Inspector and Trackmon have been interlinked on the Class 121 Train so that it is now possible to pick up geometric exceedances and go straight to them on the video to discover what the track fault is. The chart below explains how the data is created on the train, shipped back to AEA and Omnicom for transferring into a format that can be used by the local staff and then shipped on to the P-Way Supervisors for them to be able to carry out virtual patrols.



Carillion Rail has now developed a procedure that would enable these trains to carry out virtual inspections and reduce by 75% the amount of patrolling carried out on the West Coast Mainline, and we are in debate with Railtrack as to how to take best advantage of this technology.



 Rail Track Geometry
 Automatic Fault Recog

 Phase II - UFM 160 - two car vehicle 100mph running

 Same systems as UFM 120. All measure at 100MPH

Phase 2 of the Eurailscout Project is the UFM160 and we see here a picture of the earlier UFM120 in use on Dutch Railways. You note that the train is fitted with

- GPS
- video for both track and the overhead
- a pantograph to measure overhead behaviour with laser scanning
- geometric recording of track and rails
- a photographic system to look at rail head defects.

The first output screen below shows how the rail profile is measured relative to a new section

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This picture shows how the train can identify missing fastenings.



The system also shows defects in the rail head, which can include rail breaks.



As I said earlier it is important this information is presented in a very accessible way and we see here the screen from the associated Geoview software with all the defects highlighted on one screen. When you click on a particular defect then either a text inscription or a picture is highlighted as we see here for a missing fastening,



Similarly we see here a fish plate shown – the joint is identified by the rail defect software. Thus not only is it possible to look at pictures of each defect or technical information, but Geoview can also summarise the output, bringing parameters together in a similar way to a track recording run.

Finally Geoview sends out similar recording and analysis and puts it forward before the Overhead Line and you can see here how it shows staggers and various other overhead line parameters in the screen.



#### ADVANTAGES OF TRAIN BORNE INSPECTION

I have already explained why our present methods of patrolling are reaching the limits that are acceptable for staff safety and train borne inspection greatly reduces the exposure of staff to trains. At present the only way we can deliver compliant patrolling on foot is by taking a considerable number of possessions and Rimini means that the number of those possessions can only increase. On the other hand the inspection trains can run to a timetable and thus not interfere with trains. Inspection trains are not reliant on human beings to find defects, but deliver objective measures of track quality.

Carillion's analysis shows that the extra cost of the trains is offset by the savings in lookouts, van drivers, in avoiding weather problems, and in speeding up the patrol, both by use of the train and by only reviewing exceedances. Most of these benefits, whilst valid for multi track lines, also show on other routes, and the business case gets better the more a train is used. If the output of the train can also be used to avoid track recording runs the case becomes overwhelming.

#### CONCLUSION

I hope that I have shown that the train borne inspection is the way for the future. Existing means of patrolling are at their limit, being slow, unsafe for the staff who carry them out, and do not produce objective information on the state of the track. They are also on the edge of Rule Book acceptability, and increasing speed and traffic will make them impossible in Red Zones, whilst the effect of Tii Green Zones on the operation of traffic cannot be tolerated.

Train borne inspection offers a solution to all these problems, and the combination of geometric recording with scanned pictures and video, all linked by advanced software, offers a new means of analysis that should enable far better asset maintenance. It can be carried out be special or by service trains, as seems most appropriate for the local geography and service levels.
# **REMOTE STRESS MONITORING FOR RAIL MAINTENANCE APPLICATIONS**

FP Brennan & B de Leeuw University College London NDE Centre, Dept of Mechanical Engineering, Torrington Place London WC1E 7JE, UK b deleeuw@meng.ucl.ac.uk T Roffey AMEC Rail Stephenson House 2 Cherry Orchard Road Croydon CR9 6JA UK

## KEYWORDS: Structural Integrity Monitoring, Continuous Welded Rail, Stress Free Temperature, Stress Monitoring, Rail Integrity, Points Connections

#### ABSTRACT

The continuous collection and storage of data describing the state of a structure provides a wide range of advantages over conventional structural maintenance systems. The most significant of these include the overall increase in the safety of the monitored application as well as a potential long term reduction in maintenance costs as the need for intrusive and costly inspection routines is reduced. This is true for many industries including Rail where track inspections often require closure of the line and a significant manual intervention. Recent developments in electronic sensors and data acquisition and transmission systems have led to an increase in momentum in the development of state-of-the-art technology in the field of Structural Integrity Monitoring. One such system is the new Stress Memory Technology (SMT), developed by FIOSTEC Ltd. and University College London. This consists of a self-contained hand-sized monitoring unit which, when attached to the surface of the structure, passively senses and records the occurrence of pre-defined structurally significant events.

This paper presents the application and results of preliminary field and laboratory trials carried out in conjunction with AMEC Rail to investigate the feasibility of SMT for use in Rail maintenance applications. The two selected applications were the monitoring of the Stress Free Temperatures (SFT) in Continuously Welded Rail (CWR) and monitoring of stresses in Points connections. Initial results indicate a high level of accuracy, repeatability and sensitivity of the SMT technology and demonstrate that the systems are sufficiently accurate to monitor stresses in both applications.

#### INTRODUCTION

The Rail Industry is responsible for a significant portion of the infrastructure of most modern economies and directly effects the everyday life of the community. Its high profile together with a number of fatal rail accidents over the past few years has raised concerns on the general safety of ageing railway networks. This highlights an even greater need to be able to accurately assess a structure's health over its working life in order to avoid catastrophic failures that could lead to loss of lives and significant costs to both the operator and the surrounding economy. Generally the current procedure for ensuring the integrity of engineering structures involves applying a number of established Non-Destructive Testing techniques. These include applications such as visual inspections, acoustic or ultrasonic methods, magnetic field methods or radiography on selected critical members. These inspections usually follow a planned inspection schedule that could span over a period of months and tend to be very costly operations that may require the closure of a particular service for that period.

Although the NDT Inspection methods mentioned above have proved useful in reducing the number of undetected flaws and catastrophic failures in engineering structures in the past they still poses a number of significant shortcomings. Apart from the high costs and potential danger to the operators, one of the main drawbacks is the fact that damage detection is not carried out on a continuous basis. Consequentially, this could lead to the development of undetected flaws between the scheduled inspection periods increasing the risk of structural failure. This could be especially significant during rare or

unexpected events such as earthquakes or tampering with the lines, which could affect the condition of the railways but remain undetected. Such situations highlight the need for continuous 'intelligent' monitoring techniques that have the capability of detecting and assessing damage and subsequently alerting users of danger as soon as a structure is weakened. In the rail industry there are numerous applications to which such a system would be beneficial, ranging from railway axles to track monitoring and railway bridges. An example where such a system could potentially have avoided disaster was in the Alabama (1993), when part of a barge collided with a railway bridge in deep fog. The captain of the barge did not note this hence there was not knowledge that the bridge was weakened. Soon after an AMTRAK passenger train crossing the bridge plunged into the swamp below as the bridge collapsed [1]. This accident claimed over 40 lives and may have been averted had the driver been alerted in some way regarding the weakened bridge.

Another issue that must be considered is the accuracy or effectiveness of current NDT inspections and or the results information in terms of predicting the health of the structure. At best these can indicate the existence, type, location and size of a flaw at a point in time. However they cannot give any indication of whether of not a flaw is likely to develop or when it does monitor its progress, allowing for action to be taken before they become critical. Another problem is the variability that is encountered with some inspection techniques. Visual inspections remain on of the most widely used NDT methods for engineering structures, however a study performed by the US Federal Highway Administration highlights significant concerns regarding this method [2,3]. They found that on average four or five different condition ratings were allocated to a particular inspected area [3]. Reasons for large discrepancies in results included inspector boredom, bad eyesight, inspector expectation, inconsistent reporting and the absence of professional engineers overseeing the work. Such results emphasise the need for more robust, accurate and consistent approaches to structural safety assessment.

### STRUCTURAL INTEGRITY MONITORING

Recent developments in electronic sensors, data acquisition and transmission systems and their reducing costs have led to an increase in momentum in the research and development in the area of Structural Integrity Monitoring (SIM). SIM can be defined as the continuous monitoring of engineering structures using state of the art sensing and data processing techniques with the aim of detecting any weaknesses before they become critical. The continuous assessment and use of modern communication system should ensure that timely action be taken to solve the problem and ensure the safety of people using the service. Although this is obviously one of the main attractions to implementing such a systems there area number of other less obvious but equally important advantages of Structural Integrity Monitoring Applications.

SIM has the potential to provide valuable information with regard to a structure's actual behaviour over time. Analysed data can be stored for future reference, providing an invaluable historical data archive of the structure's behaviour, including performance information during extreme and unexpected events. Not only would this provide a reference point from which to compare similar occurrences in future but this increased level of information would also have very positive implications in the design of similar structures in future. It could eliminate some of the uncertainties in design and reduce the need for over-conservative safety factors. This could in turn lead to reductions in construction costs as the material types and quantities used can be based more on the actual needs of the structure.

In a similar way to which SIM can close the design loop it can play an important role in engineering modelling and simulation. These tools are usually used to provide indications of the dynamic behaviour of an engineering structure under conditions that cannot easily be simulated in the laboratory, such as seismic effects or the loss of part of a structure.

#### REMOTE STRESS MONITORING FOR RAIL MAINTENANCE APPLICATIONS

Stress Memory Technology [4] is a new Structural Monitoring technique developed by FIOSTEC Ltd, a University College London (UCL) spinout company. The attraction of the system is its simplicity in terms of technology and application. The idea behind Stress Memory Technology is simple. Each sensing device is self-contained and passively senses and records the occurrence of pre-defined structurally significant events. It is permanently attached to the surface of engineering structures and acts as a local "Memory". It does this by sensing micro-strain on the surface of the host structure, analysing the monitored strain for structurally significant events and records the occurrence of pre-programmed events. It only communicates its information when required. A Stress Memory System consists of one or more Stress Memory Units and a data reader/computer.

Stress Memory can be used to monitor the integrity of repairs and temporary structures as well as permanently deployed platforms and equipment. The Devices themselves do not require servicing and in the event of failure they are simply replaced. The data can be utilised in asset management calculations and in planning maintenance support to maximise availability. The formulation of the technology has advantages for the rail industry due to its inherent robustness, its passive nature and self-contained characteristics and its inherent low cost of ownership.

By definition Stress Memory Units are based on monitoring the primary cause and effects of progressive flaw development rather than to directly monitor the development of flaws themselves. A crack/flaw inspection/monitoring system having high POD (Probability of Detection) and POS (Probability of Sizing) attributes can at best tell the existence, type, location and size of the flaw at any point in time. It cannot however, give any indication of whether or not a flaw is likely to develop. On the other hand, stress-monitoring systems can identify components, which by the nature of their stress history are more likely to contain stress-related flaws.

Long wires used with analogue electrical and fibre optic strain measurement systems are the cause of signal deterioration and require signal boosters and/or conversion to digital form. The Stress Memory Unit is completely wireless, thus eliminating sources of error associated with wired systems. A major advantage is that the unit itself carries out signal conditioning and analysis meaning that its output can be read and easily understood by non-specialists.

### FEASIBILITY TRIALS FOR STRESS MEMORY UNIT

Two Rail maintenance applications were selected for the trails of the Stress Memory Unit, these were the Monitoring of Stress Free Temperature (SFT) [5] and the Monitoring of Points. The SFT is the rail temperature at which the rail is the same length as it would be in an unrestrained state and at which, therefore there is no thermal force present [5]. Continuous Welded Rail (CWR) is pulled by hydraulic rail tensors to achieve a SFT of 27°C when the temperature is outside the range 21-27°C. A recent publication [6] reports that measurements taken using the VERSE [7] system revealed that the SFT can vary significantly even within a relatively short distance, possibly with severe consequences. The VERSE system can only be used when the line is closed and each measurement requires significant manual intervention. Stress Memory may on the other hand be used as a cheap, fast and unintrusive alternative to monitoring of SFT in CWR.

Signals and Points are an essential part of the Railway network. Mechanical reliability of points is essential to avoid delay and of course maintain safety. Laboratory measurements, field trials using commercially available laboratory strain measurement equipment and field trials using SMT were conducted in order to gain a better understanding of the technical feasibility of applying SMT to both rail SFT monitoring and points monitoring. The following sections report the details of these tests and finally the conclusions that can be drawn.

#### PRELIMINARY FIELD TESTS Purley Preliminary Rail Trial

The first stage of the work was to understand the magnitude and nature of the applied stresses in both a rail under tension and points under normal operation and then under distress. The AMEC Rail training Centre at Purley was visited to take measurements on a rail under load from a hydraulic tensioner of the type used in reality. Measurements were made using a commercially available laboratory strain bridge. One three element rosette electrical resistance strain gauge was fixed to the upper surface of the bottom flange of the rail with element 1 parallel to the longitudinal axis of the rail, element 3 parallel to the transverse axis and element 2 at an angle of 45° to the longitudinal axis. This alignment arrangement of the individual strain gauge elements means that elements 1, 2 and 3 correspond to the longitudinal, shear and transverse directions respectively. Experimental stress analysis was conducted by resolving the three strain gauge element results of the rosette into principal strains, hence principal stresses using a Mohr's stress circle approach and assuming that, nowhere, the yield stress is exceeded. Care was taken to ensure that the shear angle was very small (a large shear angle would indicate that a gauge might not be applied perfectly aligned to the longitudinal or transverse axis). Temperature compensation was achieved through a dummy gauge connected to the half bridge circuit of each element. All strain measurements were made using a Vishay Measurements Group P-3500 Strain Indicator and SB-10 Switch and Balance Unit [8].

Strain measurements were taken by stepping the tensioner pressure incrementally to a maximum of 7,500 psi and back down to zero. *Figure 1* below shows the results obtained where Channel 8 is the transverse rail flange strain, Channel 9 the longitudinal rail flange strain and Channel 10 the shear rail flange strain.



Figure 1: Purley Preliminary Rail Trial Strain Results

*Figure 2* below shows the results of the longitudinal strain in terms of longitudinal stress. The range shown is approximately 60MPa, which is well within the capability of SMT.



Figure 2: Purley Preliminary Rail Trial Longitudinal Rail Stress

Very little scatter is seen giving confidence to the overall set-up and measurement system.

### Clapham Junction Preliminary Points Trial

Preliminary points trials were carried out at a training centre near Clapham Junction where a set of hydraulically operated points was made available for strain measurements. This time it was decided to measure strain on three separate components of the points switching mechanism. There were the  $1\frac{1}{4}$ " connection rod at the drive end (Channel 8), the channel section connecting the drive and back end (Channel 9) and the  $1\frac{1}{4}$ " connection rod at the back end (Channel 10). These locations are shown in *Figure 3* below:



Figure 3: Clapham Jct. Points Preliminary Trial Set-up

The three gauges were again connected to the Vishay Measurements Group P-3500 Strain Indicator and SB-10 Switch and Balance Unit [8]. The points were switched twice normally and then were switched with obstructions placed at back end on track T1, the back end on Track T2, power end track T1 and power end track T2. *Figure 4* shows the stress results from the three locations.



Figure 4: Clapham Jct. Points Preliminary Trial Stress Results

Firstly it is clear that Channel 9 is relatively insensitive to the changes in stress, likely to be due to the large cross-sectional area of the connecting channel section. The other two locations (the 1<sup>1</sup>/<sub>4</sub>" connection rods at the drive and back ends) by contrast show good response to the switching operations. Normal switching of the points shows approximately a 10 MPa range. Obstructions placed at the back end (10 T1 and 10 T2) showed between a two and four fold increase in stress with the back end rod being most responsive giving in excess of 40 MPa in both cases. The obstructions placed at the drive end (8 T1 and 8 T2) did not show any related change in stress at any location.

### LABORATORY TESTS

Having understood the type of stresses to expect in both applications laboratory tests were carried out in order to test the SMT before deployment in the field. Two types of test were conducted (i) 1<sup>1</sup>/<sub>4</sub>" steel rod loaded under uniaxial tension, and (ii) a rail section loaded under four-point bending.

### 1<sup>1</sup>/<sub>4</sub>" Rod Tension Tests

A 400mm length of 1<sup>1</sup>/4" steel rod was machined at the ends to allow it to be gripped into a 100kN (10 Tonne) materials test machine. Various tests were carried out but the most important was one to calibrate the SM reading into a stress value. The SM unit automatically runs through an initialisation routine, which finds the mid-point of its operating range. This means that different units connected to different strain gauges are likely to have unique starting points, however, the relative difference between readings should be the same for the same amount of strain.

*Figure 5* below shows the results from two different units on the same bar in the laboratory normalised to their first reading at zero stress.



Figure 5: Normalised SM Readings plotted against Load

Straight-line fits to each set of data show very similar behaviour and very low level of scatter. Relating both of these to the Stress in each bar by simply dividing the load by the cross-sectional area allows the data to be presented in terms of stress as shown and compared with Strain Bridge measurements in *Figure* 6 below. The SM readings can be seen to be sensitive in the 0 - 40 MPa range as measured during the Clapham preliminary points trial.



Figure 6: Normalised SM (Stress) Readings plotted against Strain Bridge Measurements

#### Four Point Bending Rail Tests

Again in preparation for the field trials of the SM equipment, a length of rail was set-up under four-point bending in a 1000kN (100 Tonne) servo hydraulic testing machine (*Figure 7*). The specimen was oriented upside down in the set-up shown so to give tension in the lower flange as would occur under rolling stock loading.



Figure 7: Rail Section in 1000kN Test Machine under Four Point Bending

As with the rod, the rail was strain gauged and connected to the Vishay Measurements Group P-3500 Strain Indicator and SB-10 Switch and Balance Unit [8] and loaded incrementally up and down. The results of this "calibration" are shown in *Figure 8* below.



Figure 8: Strain Bridge Stress Measurements plotted against Load

Finally, to compare stress measurements from both SM units and the strain bridge data, all data was plotted together and is shown in *Figure 9*. Good correlation of the quality expected from laboratory equipment is again apparent.



Figure 9: SM and Strain Bridge Stress Measurements plotted against Load

### FIELD TRIALS

Two different field trials were conducted using SMT following the laboratory tests. These are detailed in the following subsections.

#### Trials on Points at Clapham 16 December 2002

Two SM units were fixed to the power and end  $1\frac{1}{4}$ " connector rods of the points described previously. The following sequence was followed showing the main observations:

7	Switched to T2	14	Switched to T1, Obstruction at D	23	Switched to T2
8	Switched to T1	15	Switched to T2	24	Switched to T1
9	Switched to T2, Obstruction at B	16	Switched to T1	27	Switched to T2 – adjusted back
10	Switched to T1	17	Switched to T2, Obstruction at C	30	Switched to T1 – adjusted other way
11	Switched to T2	18	Switched to T1	31	Switched to T2
12	Switched to T1, Obstruction at A	21	Switched to T2 – points adjusted		
13	Switched to T2	22	Switched to T1		



Figure 10: Clapham Trial Results – 16 December 2002

Figure 10 above shows the SM results over the period of the trial. It is important to note that the points had clearly been maintained since the first visit, fresh grease was apparent at all joints. SM1 data is the record taken from the unit at the power end, SM2 was located at the end connector rod. SM1 shows clearly every switching giving a range of approximately 10 MPa as seen before. SM2 at the back end shows a very much smaller response to normal switching. But SM2 does show very clearly all back end obstructions and readjustments.

Step 9 is the first switching with an obstruction at B. Both units register a stress of approximately 40 MPa as seen before with the commercial laboratory equipment. A similar response is seen at Step 12 where an obstruction is placed at A. As before obstructions at the power end are not registered by either unit. SM2 picks up the manual readjustment of the points, and both units register clearly the large change in signal switching stress due to the maladjustment. Finally locks were placed to prevent drive end motion, neither SM unit registered any change in stress.

The trial results demonstrate that SMT is capable of reliably measuring obstructions in the back end of the points and maladjusted points. The signal was not as clean as it could be due to the poor quality of the soldered connections. Installation was difficult. These latter two issues of reliable, quick and easy deployment of SMT in the field will be dealt with in the final section.

# Trials on Rail at Purley 17 December 2002

SM Units were fixed at two points along the test rail at Purley as shown in *Figure 11* below.



Figure 11: SM set-up on Rail at Purley

*Figure 12* below shows a close up view of the SM unit with a sub unit clamped to the upper surface of the bottom flange and connected to the main SM unit.



Figure 12 Stress Memory Unit connected to rail base

This time there was no need to incrementally step the load as the SM units recorded continuously. Results from both units are shown in Figure 13 below.



Figure 13: Sample SM results from the Rail Trial at Purley – 17 December 2002

The results show very consistently the loading up and down of the rail and an unplanned overload of 8000psi can be clearly seen. The accuracy of the system is well within 10MPa and this attribute alone is likely to rival any other system.

The stresses measured were approximately twice those measured with the strain bridge. The reason for this is likely to be due to the fact that the tensioner position was different in both cases. This equipment was designed for and is used in reality to pull the rail. In this case for convenience the set-up was used in compression. In compression, the stress is likely to vary with position due to the influence of a buckling mechanism, which is not present if the rail is split (actual tension case). Confidence can be gained in both trial results due to the repeatability between successive loadings and with respect to the SM trial the close correlation between both SM devices.

## SUMMARY AND CONCLUSIONS

Laboratory and Field trials were conducted on rail SFT monitoring and points stress monitoring using a commercially available laboratory strain bridge equipment and the new wireless SMT. These trials demonstrated that SMT is sufficiently accurate to monitor stresses in both applications and could be packaged as a commercial rail maintenance system. The following observations and conclusions are made:

- SM tests on points show that a stress monitoring system will only register stresses due to back end obstructions and maladjusted points. Drive end obstructions that do not transmit load into the points mechanism will not induce stresses.
- SM tests on rail show that this technology could be very useful in monitoring SFT and possibly wheel induced transient bending stresses.

AMEC Spie and FIOSTEC are working towards field trials on live rail in May 2003. If successful a new SIM system will be available for the continuous monitoring of SFT in rails.

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# TRACK-SUBSTRUCTURE INVESTIGATIONS USING GROUND PENETRATING RADAR AND TRACK LOADING VEHICLE

A Smekal & E Berggren Swedish National Rail Administration Technical Department SE-781 85 Borlänge Sweden <u>alexander.smekal@banverket.se</u> <u>eric.berggren@banverket.se</u> K Hrubec GImpuls Přístavní 24 170 00 Prague 7 The Czech Republic <u>hrubec@gimpuls.cz</u>

KEYWORDS: Track-Substructure Investigation, Ground Penetrating Radar, Track Loading Vehicle, Track Stiffness

#### ABSTRACT

Upgrading of existing railway lines for higher axle loads and speeds requires new modern methods for in situ investigation. Combination of measurements of track irregularities, continuous track stiffness and non-destructive geophysical methods like Ground Penetrating Radar (GPR) can be a good example of how important information about the status of existing railways can be obtained. GPR and Track Loading Vehicle (TLV) have been tested on the Swedish Western Main Line where subsoil of very soft clays under the track has caused a lot of problems. Results from investigations are going to be used for mitigation of excessive settlements, slides and especially environmental vibrations. Track stiffness was measured several times along the track with different excitation frequencies and travelling speed with Banverket's Track Loading Vehicle. Track irregularities have been measured twice a year for several years. The GPR measurement was based on verified measurements that have been done for the Czech Railways. The GPR records were processed into the form of longitudinal sections to the depth of 3 m. Statistic methods have been applied for studies of relations between the parameters measured by the GPR and Track Loading Vehicle.

#### **INTRODUCTION**

It is obvious that the quality of railway track depends on general condition of all layers situated under the sleepers, including subsoil. The ballast thickness, resistance to vertical and lateral forces, ballast fouling, track geometry and properties of sub-ballast and subsoil are the main characteristics that can have a great impact on the track performance. Construction of railways started 150 years ago under different traffic conditions as regards axle loads, speeds and requirements on substructure and subsoil conditions under the track. Those existing railways will be used even in the future for new traffic conditions. In many cases there is a need for upgrading of the subsurface of the railway track to improve the quality of existing track and decrease expensive maintenance. Conditions of railway track and subsurface can also have a great impact on vibrations caused by railway traffic. Especially increased axle loads and speeds can cause annovance to people and structures in the vicinity of railway lines. Traditional methods of geotechnical investigation are very slow, expensive and insufficient to provide complete information about subsurface conditions along the railway line. Therefore many railway authorities have started usage of nondestructive continuous methods for investigation of existing lines. With non-destructive methods problem spots can be detected and additional geotechnical investigation can in a better way concentrate its efforts on explanation of causes and help to design mitigation of problem for particular places. Track loading vehicle (TLV) has been developed in connection with Banverket's participation in the European Union research project Eurobalt II with the aim to measure continuously track stiffness. Ground penetrating radar (GPR) technology has been used in various applications for a couple of years. There are many examples showing that GPR has been successfully used for monitoring of subsurface conditions for railway purposes. Swedish National Rail Administration (Banverket) has carried out a project in which measurements using both methods, on a railway line close to Gothenburg have been performed. The aim has been to investigate a combination of both the above mentioned non-destructive methods for track geotechnical monitoring.

## CHARACTERISTICS OF THE MEASURED RAILWAY LINE

Changing of the track stiffness caused by special geotechnical conditions and by a number of man made structures is typical for the measured railway line. Banverket and GImpuls have carried out measurements on approximately 7 km of the Swedish Western Main Line situated close to Gothenburg. This line is well known for very high traffic since it connects Stockholm and Gothenburg. From the very beginning this particular section of the track has had a lot of problems including landslide and extensive vibrations, and soil improvements had to be carried out to assure safe availability of the line. The double track structure consists of UIC 60 rail placed on Pandrol rubber pads (10 mm) and concrete sleepers with spacing 0.65 m. The total height of the structure should be, according to the records, about 0.8 m, consisting of ballast (0.5 m) and sub-ballast (0.3 m). The track was built about 100 years ago. The subsoil consists of very soft marine clays with undrained shear strength about 10 kPa. Only 100 m of the tested line has a moraine as the subsoil under the track. Wooden piles and concrete slab on concrete piles have been used for soil improvement (250 m) after a landslide that occurred a couple of years ago. There are two bridges on the measured line both founded on piles. Approaching embankments close to the bridge have been founded first on concrete slab on piles followed by lime cement columns and concrete piles to eliminate problems of changing stiffness in transition areas close to the bridges. Due to very soft soil conditions under the track and heavy loads Banverket has received many complaints about extensive vibrations from inhabitants of houses in the vicinity of the railway line. Measurements of vibration levels have shown that in some houses the particle velocity has been more than 2.5 mm/s. Countermeasures to decrease vibrations are required and mitigation design is under preparation today.

## GROUND PENETRATING RADAR

A four-channel digital apparatus SIR 10 with the 100 and 500 MHz antenna systems was used for the GPR measurements. The essential issues dealt with were as follows:

- to present speed and technical nature of the GPR measurement
- to test a possibility of interconnecting the GPR apparatus with the TLV
- to test optimal operating frequency and configuration of the GPR antennas
- to statistically evaluate the relation between the qualitative parameters scanned by the GPR method and stiffness measured by the TLV
- to process vertical sections along the railway track body and divide the track segment into quasihomogeneous blocks
- to evaluate the railway track body structure and provide data for qualified assessment of defects.

### Field work

The GPR master unit was connected to the Banverket's track loading vehicle. The antenna systems were installed on a subsidiary "CRAB" carriage and pulled by the test train (figure 1). The measurement speed on a railway track line was up to 15 km/h, and up to 5km/h when running through switches. Equidistant scanning frequency was controlled by an IRC sensor (encoder) integrated on a "CRAB" carriage. The spatial scanning frequency was 1,0 m. During the measurement we marked into the records the points of passing the hectometres/milestones, having so connected the measured data with railway track mileage.

Both of the tracks were subjected to the measurement of the following profiles with the use of the following antenna configurations:

- profile 1: axial profile 500 MHz bistatic\* and monostatic\*\* measurement
- profile 2: inside profile 500 MHz bistatic measurement (between the tracks)
- profile 3: outside profile 100 MHz bistatic measurement
- profile 4: 100 MHz monostatic measurement transmitter outside profile x receiver in track axis
- profile 5: 100 MHz monostatic measurement transmitter outside profile x receiver inside profile
- \* bistatic transmitter and receiver in one box = transceiver system
- \*\* monostatic antenna has two single parts transmitter and rerceiver

Technical characteristics of antenna configurations and the measured intervals are presented in table 1. The scheme of placing antennas on the measured profiles is shown in figure 2.

Figure 1: GPR connection scheme



Figure 2: Scheme of placing antennas on the measured profiles



GPR investigation results are presented in two points of view. First comparison of the processed GPR records made by different antenna systems is presented. The relation between the GPR signal amplitude and stiffness is tested then. A standard type of processing of the GPR records from an axial profile was the second type of output. It is a vertical cross section through a railway track body and the dielectric constant of the ballast bed is determined.

#### Automatized outputs of the GPR measurement

In the fieldwork, two different antennas with operating frequencies of 100 MHz and 500 MHz respectively were tested. Both antennas were used in bistatic and monostatic configurations. The GPR records were processed in a standard way by numerical methods. The goal was to compare "readability" of the records for further processing.

Comparison of "readability" of the GPR records definitely confirmed that particularly the records from 500 MHz antenna systems are the best applicable for further processing. The results of measurements performed at 100 MHz were strongly affected by interfering effects in the immediate vicinity of an antenna. The GPR records were strongly deformed and even after the numerical processing a relevant result could not be obtained. With regard to the fact that interference was caused by rails, a track loading vehicle and an antenna carrier, it cannot be expected that in common conditions of railways this system of both bistatic and monostatic measurement would provide results suitable for complex interpretation.

The measurement performed at a frequency of 500 MHz with screened antennas provided much clearer results. The GPR record both in a track axis and behind the sleepers' heads was well differentiated and after a routine numerical filtering is understandable even to a common client. The least deformed result was obtained from the profiles behind the sleepers' heads (3 profiles for each track). The axial profiles where the whole primary records are influenced by sleepers have given comparable results. With regard to the fact that we talk about a visual judgement, a qualitative criterion for "readability" cannot be constituted.

For the processed GPR records, average amplitude of a GPR signal in four different time windows was determined (tab.1). The windows were chosen in order to vertically capture the profile (for a given configuration) from the ballast bed itself through its base as deep as subgrade. Average amplitude  $(\underline{A}_a)$  was calculated according to formula 1 as a sum of absolute values of a signal  $(\underline{A}_i)$  in the window to the window length  $(\underline{i})$ .

$$A_a = \frac{\sum |A_i|}{i} \tag{1}$$

We compared the calculated value with the stiffness values measured immediately before the GPR investigation. We started from a paper dealing with the GPR method published recently, in which the authors focused on the testing of relation between these quantities (Narayanan et al. 2002).

	Window width (ns) /Depth interval* (m)									
Profile / antenna	level 1	level 2	level 3	level 4						
Profile 1/500 bistatic	2-10/0.1-0.6	10-18/0.6-1.1	18-34/1.1-2.0	34-66/2.0-4.0						
Profile1/500 monostatic	2-9/0.1-0.6	9-17/0.6-1.1	16-33/1.1-2.0	32-65/2.0-4.0						
Profile 2/500 bistatic	2-9/0.1-0.6	9-16/0.6-1.1	16-32/1.1-2.0	32-64/2.0-4.0						
Profile 3/100 bistatic	4-12/0.2-0.8	12-19/0.8-1.6	19-43/1.6-2.5	43-67/2.5-4.0						
Profile 4/100 monostatic	4-9/0.3-0.6	9-40/0.6-2.5	40-63/2.5-4.0	63-87/4-5.5						
Profile 5/100 monostatic	4-9/0.3-0.6	9-25/0.6-1.5	25-49/1.5-3.0	49-73/3.0-4.5						

**Table 1**: Average amplitude of a GPR signal – width of summed windows

\* for monostatic systems the relation between depth and window is non-linear

The conditions at the measured railway track segment included both the interstation railway track segment with ballast bed on subgrade and intervals where the measurement was performed in the stations, switches, bridges or high embankments; subgrade was locally stabilized by piles or a concrete slab. Even visual assessment of the graphs gives evidence of the fact that there is no significant relation between stiffness and amplitude of a signal. Amplitudes of a GPR signal are of high variability, and correlation of in this way fluctuating values with stiffness was practically zero. Therefore, values smoothed by the running averages method – smoothing window width of 5 metres – were compared. By statistical comparison of the measured values the coefficients of correlation from 1% to 15% were identified, i.e. it is two independent variables. From the results it can be stated that under common conditions on a railway track there exists no relation between a GPR signal amplitude and stiffness.

#### Standard interpretation of the GPR measurement

The complex interpretation is based on axial profiles of each of the tracks. Joint bistatic and monostatic measurements allow the dielectric constant of the ballast bed to be calculated and its thickness then to be interpreted more accurately. The basis for interpretation is, in addition to the GPR record which may serve for determination of individual boundaries, however, without qualitative specification, also a detailed description of the existing structure (supplied by the customer). The interpreted longitudinal sections then adjoin the quantitative parameters (depth and disturbance) to each of the structure units, i.e. qualitative units. The measured segment is divided into quasihomogeneous blocks. Each block is classified into one of the three following categories:

- (+) block without disturbances each structure layer in the block is well observable, distinct thickness for each structure layer
- (?) block with partial anomalies each structure layer in the block is observable, the reasons for classifying the block in this category may be the following:
  - Distinct changes in thickness of layers,
  - boundary between layers is not strict, this may indicate partial mixing of materials,
  - in the block are detected layers not corresponding to an expected structure,
  - indications of anomalous structures in subgrade,
  - GPR signal was influenced by railway track superstructure for example switches,
  - it is advisable to get more detailed results in the block by the application of additional geotechnical methods, such as a dug test pit
- (!) block with significant disturbances distinct deviations from expected state or obvious disturbances have been detected in the block; the block is classified in this category provided that:
  - identification of the layers is questionable, boundaries between them cannot be observed continuously,

- layer thicknesses are to a great extent variable, by their shape indicating that the structure is pressed down into subgrade,

- there are detected structures that may relate to disturbances in underlying layers in subgrade,

- in order to assess accurate condition of the block and to properly quantitatively evaluate the GPR results it is necessary to test the structure and its physical parameters by a test pit/probe, and/or to perform laboratory tests of samples.

The blocks delimitate a railway track segment where according to the GPR signal identical structure and comparable condition of the railway track body can be found. Classification of blocks into the qualitative classes is subjective, however, supported by the results reached during the preceding investigations when various types of anomalies were particularly confirmed by dug test pits but also by other diagnostic methods (penetration, loading tests, etc.). In the GPR records are also indicated courses of individual detected boundaries. Ballast bed base, course of subbase layer, indication of subgrade level and/or other unspecified boundaries were observed. Attention is also paid to anomalies both in horizontal and vertical directions.

The results are graphically presented in the form of section. Boundaries and categories of the blocks together with brief characteristics of potential anomalies are summarized in tables (Table 2).





Figure 3: processing GPR records of 500MHz antenna & amplitude of GPR signal in different level







**Table 2:** Quasihomogeneous blocks (example from presented part)

Figure 5: Example of the presentation of longitudinal section with corresponding legend and comments



Figure 6: Km 448+200 - 449+200 interpreted longitudinal section from axe profile of the left track / GPR records of 500 MHz antennas after processing / dielectric constant of ballast bed

## TRACK STIFFNESS MEASUREMENTS

Continuous track stiffness measurement is a new tool for condition assessment of railway track. Only a few countries have access to measurement equipment of this kind and research are performed at several places (Berggren et al. 2002), (Wangqing et al. 1997), (Li et al. 2002), (Rasmussen & Man 2000). Evaluation principles and correlation with track maintenance parameters are at present time an objective of comprehensive research. The present measurements constitute one step in this development.

Continuous track stiffness is measured with a trolley beneath the Swedish Track Loading Vehicle as shown in figure 7. The measurement principle is based on a dynamic load excitation through a flange free measurement wheel. The force and the acceleration is measured and processed to obtain the stiffness, see figure 8. The applied load is 30 kN static load and 10 kN dynamic load on each wheel. The applied load is restricted in the present prototype version of TLV. Higher load will be applied in a future version. The measurement principle is described in detail in (Berggren et al 2002).



Figure 7: TVL with trolley

Three different measurement runs were performed with the following frequencies and speeds:

Table 5. Comomation of a	speed and exertation negue	They for summess measurem	
Run	Speed	Excitation frequency	Length of one period
1	20 km/h	5.7 Hz	0.97 m
2	20 km/h	3.42 Hz	1.62 m
3	10 km/h	2.85 Hz	0.97 m

$-\mathbf{r}$
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The speed / frequency combination is chosen so that the sleeper passing frequency, or any of its overtones, will not coincide with the length of one period of excitation. The sleeper spacing is 0.65 m (1.5 \* 0.65 = 0.97 m; 2.5 \* 0.65 = 1.62 m).

The track stiffness presented in this paper is the so called total track stiffness, meaning that an axle load of for example 200 kN that deflect the rail 1 mm will give a track stiffness of 200 kN/mm.





## Combined evaluation

In figure 9, 1 km of track is shown. In the upper part of the figure, the track stiffness (20 km/h, 5.7 Hz) and some track and structure data are shown (embankment height from visual inspection, permanent improvement of subsoil, platforms, bridges and culverts). In the middle part the interpreted GPR-profile is shown with depth of different layers. The reasonable penetrating depth for good interpretation of GPR measurement was for this case approximately 2.5 metres. Therefore the GPR presentation does not show the bottom of the embankment fill around the bridge as indicated in the figure. Finally in the lower part, measurements of track irregularities (from an inertial track recording car) from three consecutive years are shown evaluated as a swept standard deviation over 20 metres (longitudinal level). Between the second and third measurement (red and green line in the figure), maintenance with a tamping machine has been performed.

First of all, the problem areas in this part of the track can be identified with the track irregularity measurements. There are at least five problem points that can be identified (swept std longitudinal level > 2 mm, corresponds approximately to real values of 5 mm). These are marked with the letters A to E in the figure. The interesting question arises: Is it possible to explain the origin of these problems with the help of stiffness and GPR measurements?

A, In km 448+250 - 448+325 the track is reinforced in two different ways. First there is a concrete slab (up to km 448+285) and then there are wooden piles (km 448+285 - 448+325). There is also an embankment height of approximately 3 meters (from visual investigation). If we study the different layers (measured with GPR) we can clearly see variations of all layer depths (ballast, subballast, embankment fill). Around km 448+280, the longitudinal level has a peak. At this area there is a change of several parameters: There is a sudden change of track stiffness, the embankment height (from visual investigation) decrease and the substructure reinforcement changes. The track stiffness change is probably a result of the other changes. Without any further investigation we can not say whether the problems have arisen from variation of layer depths or substructure reinforcement.

**B**, Km 448+550 is in several ways similar to case A. There is a known structure (underpass – walking tunnel), which results in stiffness variations and variation of layer depth.

**C**, The largest longitudinal level problem point has been detected around km 448+630. There is a platform for regional trains next to this problem point. The stiffness variation is very large, almost a factor of three. We can not see any larger abnormalities in the GPR-profile, but the layer of embankment fill is increased and the ballast layer is decreased around this point. (Since this problem point is next to a regional train platform, possible consequences of braking of train should also be mentioned.) Noteworthy is also the even larger stiffness variation at the end of the platform (km 448+680). This gives no problems in longitudinal level.

**D**, Around km 448+800 there is also a problem as seen in the longitudinal level. At this place we can see a little change in stiffness and no major changes in GPR-profile.

**E**, Finally close to km 449+000, at the end of a 30 metres long bridge, we can see a typical bridge end problem. On both sides of the bridge there is approximately 10 metres of concrete slab on piles underlying the embankment. Directly after the bridge, we can also see a sudden decrease of track stiffness. From the right bridge support (km 448+991) up till the end of the concrete slab on piles (km 449+000) the stiffness decreases from 180 to 120 kN/mm.

Other notes that can be made is for instance the relation between embankment height increase and corresponding increase in stiffness from km 448+810 up to the bridge (km 448+960).



**Figure 9:** Longitudinal section km 448+200 – 449+200 Western Main Line in Sweden, Track stiffness and track structures, Interpreted GPR-measurements, Track irregularities (Longitudinal level)

## Environmental vibrations

Environmental vibrations that have caused annoyance to people living close to this track are well known. Measurements have been done in several houses, and the worst case is situated close to the track at km 449+050. If the figure 9 once again is studied, we expect to find low values of stiffness as indication of vibration problems. At this position the stiffness is relatively high. GPR-measurements have detected that the subballast layer disappears / is disturbed at this position. This might contribute to the vibration problem.

Why is the stiffness relatively high when we have a severe vibration problem? The embankment height (from visual investigation) is about 3 metres at this place, which means that the stiffer embankment will suppress the effect of soft subsoil (clay) on the track stiffness. The vibration problems though, are highly dependent on the underlying soft clay, which often has a resonance between approximately 3 - 5 Hz. Since the other layers behave quite similar at low frequencies it is possible to compare stiffness measurements at different frequencies to detect vibration problem areas that origin from soft subsoil. With this method we will filter the layers that behave similarly at the different frequencies. In figure 10 this comparison is done. Differences between measurements at 5.7 Hz and 2.85 Hz are shown. From this evaluation, the vibration problem point at km 449+050 can be detected.

This type of evaluation was not planned when the measurements were performed, therefore optimal frequencies were not chosen. Nevertheless, this evaluation method seems to be useful for detection of possible vibration problem areas. The other peaks in the figure are not close to any buildings, therefore we don't know about any vibration problems at those places.



Figure 10: Difference in stiffness between 5.7 Hz - 20 km/h and 2.85 Hz - 10 km/h

### CONCLUSIONS

The present paper describes measurements for condition assessment of the track substructure. We have investigated the simultaneous application of two different measurement methods: Continuous vertical track stiffness and Ground penetrating radar. We have examined the measurement methods both locally, by comparison with known problem points and on a network level with statistical methods.

Comparison with known problem points:

It has been shown that several problem points partly can be explained with the help of combined evaluation of stiffness and GPR measurements. In some cases there are large stiffness variations at problem points without any variations in the GPR-data. Also, in some cases there are large stiffness

variations at places without any detected problems in longitudinal level. Possible vibration problem areas could be detected with comparison between stiffness measurements with different excitation frequency.

Comparison on a network level:

The correlation between measured vertical track stiffness and average amplitude from GPR is low. Correlation between 1 and 15 % was obtained, which practically means that the variables are independent. This does not need to be negative, because if the two variables are independent they can give us different information about the track.

The interaction between different layers in the substructure, together with ballast tamping conditions and superstructure is a very complicated task – especially on a network level. There are many parameters that can vary with distance and / or time, for example different degrees of water content, particle size and layer depths. The track stiffness gives us in some sense the combination of all this, as seen from the view of the train. The GPR-profile gives some of the interaction parameters, but not all. The results from this project have shown that it is possible, with continuous measurements, to detect and partly explain some of the problem points along the track. Though, lots of more measurements and experience are needed before guidelines can be given for interpretation and last but certainly not least, countermeasures. Since countermeasures of substructure problems can be quite large operations, more thorough investigation of the problem points detected with continuous measurements might need to be done before starting the design of countermeasures.

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# THE CONTRIBUTION OF RAIL METALLURGY TO TRACK INTEGRITY

Dr. S Jaiwsal Corus Rail Technologies Swinden Technology Centre Moorgate Rotherham S60 3AR, UK jay.jaiswal@corusgroup.com

KEYWORDS: Rail, metallurgy, track, integrity

### ABSTRACT

The complexity of the track system is widely recognised but more importantly, despite considerable research, the rail-wheel interface and its implications for track and vehicle degradation and maintenance continue to challenge the industry. Reference is often made to "the System's Solution Approach" for engineering a 'through-cost' solution to meet the requirements of the track engineer. However, evaluating proposed solutions in a system's context is often overlooked in favour of the isolated assessment of an individual parameter affecting system performance. Hence, it is necessary to establish the definition of the track system and the disciplines required to achieve and maintain the desired level of track integrity.

A key statement describing the role played by metallurgy in other fields is that over 70% of the steels in use today were invented in the last ten years and yet the vast majority of the track in any country utilises steels that were invented quite some time ago. The metallurgical developments of rail steels have largely been left with the manufacturers in contrast to the earlier practice in the industry of active participation of bodies such as the "Improved Rail Steel Liaison Group" that brought together the permanent way expertise of the industry with the metallurgical knowledge of the rail manufacturers. However, the effective use of any newly developed steel is dependent on the knowledge of what is required – "you can only provide an answer if you know the question". This paper addresses many of these issues.

### 1. INTRODUCTION

The complexity of the track system is widely recognised but more importantly, despite considerable research, the rail-wheel interface and its implications for track and vehicle degradation and maintenance continue to challenge the industry. Reference is often made to "the System's Solution Approach" for engineering a 'through-cost' solution to meet the requirements of the track engineer. However, evaluating proposed solutions in a system's context is often overlooked in favour of the isolated assessment of an individual parameter affecting system performance. Hence, it is necessary to establish the definition of the track system and the disciplines required to achieve and maintain the desired level of track integrity.

In general, a system is a complete product incorporating several components or smaller product systems that together deliver the defined functionality. This functionality encompasses all aspects important to the user including the technical, economic and environmental specifications. In the context of the track, the system boundaries extend from the wheel-rail interface downward into the rail, pad, fastening, sleeper and finally into the substructure and formation. Clearly the optimisation of this complex system requires the bringing together of a range of disciplines including:

- ( Vehicle dynamics and contact mechanics
- ( Permanent way and civil engineering
- ( Metallurgy and materials technology

The order of the above disciplines is intentional as it reflects the focus of recent research. In particular, metallurgical developments of rail steels have largely been left with the manufacturers in contrast to the earlier practice in the industry of active participation of bodies such as the "Improved Rail Steel Liaison Group" that brought together the permanent way expertise of the industry with the metallurgical

knowledge of the rail manufacturers. Nevertheless, a number of rail steels are available today and the contribution of rail metallurgy to track integrity needs to be assessed with reference to the requirements of the system.

The functionality required of the rail is highly dependent on the track and traffic characteristics and hence even within a single network the demands made of rail steel can vary widely, from those for high-speed plain line to tight curves on mixed passenger and freight lines. It is, therefore, essential that the choice of rail steel be based on its ability to address the issues that affect the life cycle costs identified by the track engineer. This paper presents a brief evaluation of the wide range of rail steels available to the track engineer with reference to these in-service performance issues.

# 2. MATERIALS DESIGN TO ADDRESS DUTY REQUIREMENTS

It is appropriate to briefly consider the selection of materials within another sector of the transport industry. Figure 1 below demonstrates the multitude of parts within a car and a wide range of steel qualities and other materials that go towards satisfying the total system functionality.





As apparent from Figure 2, Railways are invariably not a single stretch of track in which the rail is subjected to the same duty all along its length. Instead, Railways are joined up segments each having its own duty conditions depending on factors such as track curvature and vehicle type. Hence, the functionality required of the rail is highly dependent on the track and traffic characteristics and even within a single network the demands made of a rail steel can vary widely, from those for high-speed plain line to tight curves on mixed passenger and freight lines. Furthermore, the duties imposed on the high rail

of curves are significantly different from those for the low rail. It is, therefore, essential that the choice of rail steel be based on its ability to address the issues that affect the life cycle costs identified by the track engineer.

# 3. THE KEY RAIL DEGRADATION MECHANISMS

The three key causes of a rail requiring rectification or being cascaded down or removed from service are:

- ( Loss of transverse section and/or longitudinal profile
- ( Loss of rail integrity through fatigue Rolling Contact and bending fatigue.
- ( Increased Risk of Rail breakage from internal quality, residual stresses, surface quality, welding.

Although the rate of rail degradation is a function of many system variables, rail metallurgy provides the baseline for optimisation of life. As shown in Figure 3, a number of rail steels have been developed through systematic and dedicated metallurgical research over the decades and demonstrate increasingly attractive properties as assessed in the laboratories. Currently, the family of rail steels available to the railways extends to hardness levels well beyond 400HB and beyond pearlitic microstructures into a variety of bainitic steels on trial from different manufacturers.



Figure 3 Range of Pearlitic Steel Rail Grades

Network Rail (NR) have always favoured the use of Grade 220 which is the most widely used grade in both tangential and curved track and until recently is believed to have provided relatively long rail life. The current usage of this grade is likely to account for more than 90% of the total.

Although Grade 260 is the most widely used grade throughout Europe and elsewhere in the world, its use within the NR network has been restricted with limited installations in S&C and curved track.

The adoption of the heat-treated grade 350 HT was slow in the late eighties but increased steadily to  $\sim$ 6,500 tonnes in 1999 reaching a cumulative supplied tonnage of  $\sim$ 40,000 tonnes.

Clearly the choice of rail steels to the railways is vast and it goes without saying that all these steels will have been evaluated in the laboratories against one of the recognised rail steel specifications. Hence the key question that must to be answered is:

"How do laboratory determined properties influence the in-service performance issues that are responsible for the curtailment of rail life or increased cost of track maintenance."

Although the above question does not mention the wheel side of the interface, it cannot be overemphasized that any benefits to track accrued from optimising rail metallurgy is also beneficial to the wheel and the vehicle system. Equally, optimising wheel metallurgy is beneficial to the track and is a subject in its own right.

However a parallel controlled assessment of the true in-service performance of the family of rail steels available remains to be undertaken by even the most modern railways, the closest comparisons being those undertaken at test tracks such as the one the at FAST. Clearly, assessments at such test tracks are a significant step forward from laboratory hardness, tensile, or twin disk tests but still cannot take account of all the track system and vehicle variables that exist in the all the real railways. Hence the assessment presented in this paper is based on the examination of the aspects of rail steel specifications that influence the causes of rail life curtailment. The way forward to bring the diverse skill sets of vehicle dynamics, contact mechanics and track engineering to enable the definition of a matrix of rail steels to satisfy the requirements of different track and traffic conditions.

The key aspects of metallurgical attributes that are included in recognised rail specifications are:

- ( Chemical Composition
- ( Steel Cleanness
- ( Microstructure
- ( Hardness and Wear Resistance
- ( Tensile Properties
- ( Fatigue and Fracture Properties
- ( Residual Stress

The key causes of rail life curtailment listed earlier are discussed in the following sections with reference to the above metallurgical attributes. Since the composition provides the foundation for the properties realised in all rail steels, it is appropriate to first discuss the composition and microstructure of rail steels.

# 3.1 Composition and Microstructure of Rail Steels

The steels in regular use within all major railways have a pearlitic microstructure of the type shown in Figure 4. The key microstructural change between the various grades is the refinement of the microstructure with finer interlamellar spacing, which provides the higher hardness and tensile properties. The strengthening mechanisms employed to enhance the properties are:

- ( Chemistry enrichment through both higher carbon contents and addition of alloying elements to increase hardenability and thereby refine the pearlitic microstructure.
- ( Accelerated cooling to refine the pearlitic microstructure.



Table 1 below lists the Network Rail specifications for three key rail grades. The control of composition is very similar from all modern rail manufacturers as is apparent from the composition of 220 grade rails supplied by the five suppliers to the network and listed in Table 2. The specifications for the residual elements for the three steels are given in Table 3.

#### Table 1 Chemical Composition of Rail Grades in use within NR Network

Grade	Composition, wt. %									
	С	Si	Mn	Р	S					
220	0.50-0.60	0.20-0.60	1.00-1.25	0.030 max	0.008-0.030					
260	0.70-0.80	0.20-0.60	0.95-1.25	0.030 max	0.008-0.030					
350HT	0.70-0.82	0.13-0.60	0.65-1.25	0.025 max	0.008-0.030					

#### Table 2 Comparison of Composition of Grade 220 Rail Steels from 5 Suppliers

Supplier	С	Si	Mn	Р	S	Cr	Mo	Ni	Al	Cu	Sn	Ti	V
1	0.54	0.32	1.11	0.016	0.016	0.030	0.004	0.026	0.002	0.017	0.006	0.006	0.007
2	0.55	0.30	1.13	0.013	0.013	0.026	0.001	0.039	0.003	0.001	-	0.006	0.015
3	0.54	0.30	1.12	0.010	0.016	0.048	0.006	0.025	0.003	0.023	0.001	0.006	0.007
4	0.55	0.30	1.13	0.016	0.018	0.020	0.005	0.029	0.002	0.066	0.002	0.005	0.007
5	0.54	0.27	1.10	0.016	0.017	0.024	0.003	0.017	0.003	0.010	-	0.005	0.006
NR spec Min	0.50	0.200	1.00		0.008								
NR spec Max	0.60	0.600	1.25	0.030	0.030	0.150	0.020	0.100	0.004	0.150	0.040	0.025	0.030

Table 3NR Specifications for Residual Elements

	Cr	Al	N	Мо	Ni	Cu	Sn	Sb	Ti	Nb	V	Cu+10Sn	Cr+Mo+Ni +Cu+V
220	0.15	0.004	0.008	0.02	0.1	0.15	0.04	0.02	0.025	0.01	0.03	0.35	0.35
260	0.15	0.004	0.010	0.02	0.1	0.15	0.04	0.02	0.025	0.01	0.03	0.35	0.35
350HT	0.10	0.004	0.010	0.02	0.1	0.15	0.04	0.02	0.025	0.03	0.03	0.35	0.25

The other rail steels with hardness values in between that of Grade 260 and the heat-treated Grade 350HT employ additional alloying elements such as chromium and vanadium to achieve the desired level of hardness.

It is apparent from the above Tables that there is little difference between the compositions of Grade 260 and Grade 350HT and yet, as shown in Figure 3, the latter has significantly greater hardness and tensile strength. These enhanced properties are achieved through controlled accelerated cooling either directly from rolling heat or after subsequent reheating.

Demands for further increase in hardness and strength from some railways has led to two significant areas of rail steel development:

- Ultra high carbon (UHC) or hypereutectoid rail steels
- Low carbon carbide free bainitic steels

The ultra high carbon steels, as the name suggests, rely on the high strengthening coefficient of carbon and therefore employ carbon contents of around 0.95% compared to the ~0.75% for Grade 260 or 350HT. The high carbon content in such steels makes them susceptible to deleterious cementite networks around the grain boundaries during natural cooling (NC) after rolling. Fortunately, this effect can be prevented through increased levels of silicon in the composition. Alternatively these steels can be accelerated cooled (AC) immediately after rolling. Although accelerated cooled version of such steels are believed to be

have been supplied into the Canadian rail network, they have not been introduced into the main European railways.

Bainitic rail steels have been a research topic for well over a decade and although a number of trial sites have been established both in Europe and the North American railroads, they are yet to be made available commercially.

The known properties offered by these steels and those by the more conventional pearlitic rail steel grades are evaluated against the key causes of rail life curtailment.

## 3.2 Loss of Rail Profile

The loss of rail profile is a major cause for premature replacement of rail in curved track. In view of the close attention to even minor differences in profile that could affect vehicle dynamics, it is interesting to note that quite significant change to profile can be tolerated over the life of the rail. Clearly, the ability to maintain rail profile optimum for the conditions for as long as possible is highly desirable and hence the use of steels that could minimise loss of transverse profile is a move towards improved track integrity.

The occurrence of corrugations could also be regarded as loss of rail profile in the longitudinal direction particularly since it is not categorically established whether corrugation is a result of differential plastic deformation or differential wear or both.

The material property parameters contributing to the control of both these issues are:

- % Proof strength
- % Hardness and Wear resistance

# 3.2.1 Proof Strength

As is apparent from Figure 5, 0.2% PS values of up to  $\sim 1000 \text{ N/mm}^2$  are available from a number of rail steel compositions currently in the development stage. Nevertheless the current Grade 350HT has a 0.2% PS of  $\sim 900 \text{ N/mm}^2$  which is approximately double that of Grade 220 rail steel. Although the other key property requirement of fatigue needs to be considered in the choice of rail steel for a given location, it is evident that the requirement for deformation resistance and maintaining profile longer can be satisfied.

### 3.2.2 Hardness and Wear Resistance

The study of wear of rail steels has been of considerable interest to the industry over the years as is apparent from the actual site measurements (Park Junction) undertaken over several years in British Rail network and shown in Figure 6. Although the data is well over ten years old, the magnitude of wear at Position B at the gauge corner is evident and was a primary cause of early rail replacement. Hence, the need for more wear resistant rail steels to counter high wear rates in tight curves is evident. This need was satisfied through the use of a harder steel (327 HB - 1% Cr Steel) which resulted in a significant reduction in the wear rate and hence an increase in rail life.





Figure 6 Measured Wear Rates of Grade 220 and 1% Cr Rail Steels

Further reductions in wear rate have been achieved through the use of harder grades such as 350HT. The hardness of a range of rail steels is shown in Figure 7 and the corresponding relationship between hardness and wear resistance is shown in Figure 8.




In summary, the rail steels that could be available to the industry provide a combination of high proof strength, hardness and wear resistance to potentially meet the demands for an effective response to the issues of the control of rail profile and corrugation. However, it must be emphasised that both wear and corrugation are system properties and hence optimisation of other aspects of system design and operation need to taken into consideration in parallel with the choice of the optimum rail steel.

#### 3.3 Loss of Rail Integrity Through Fatigue

Rails are subjected to cyclic loading in service, the stress range and the magnitude of stresses being dependent on a range of variables including the rail and wheel profile, the contact patch position and size, and the dynamic track forces from the vehicle. Consequently, the phenomenon of fatigue becomes of critical importance to longevity of rails. Although fatigue in rails manifests itself in many ways, the two major classifications of rolling contact fatigue (RCF) are "squats" and "head checks" both of which can be associated with early propagation of surface or near surface initiated rolling contact fatigue cracks. The hive of research and development activity in both the UK and other European Railways on RCF since the Hatfield derailment is a clear indication of the importance of this issue for safety and the longevity of rails.

Since fatigue in rails is closely associated with the surface of the rails there is need to assess the fatigue behaviour with reference to the surface material properties such as the magnitude of the decarburised layer and the initiation of RCF cracks is the extremely hard white etching layer. It may also be possible that the interface between the hardened layer and the rail matrix is a weak link in the chain and the loss of ductility at this point contributes to the development of shallow sub-surface cracks. These subjects are live research activities that need to be pursued to gain a better understanding of the metallurgical changes that could have a bearing on the initiation and development of RCF cracks.

There are two crucial factors in the fatigue life component - the initiation of the crack followed by its propagation to cause failure. In the case of rails, the first stage of failure is spalling since it makes the rail inspection using conventional NDT techniques impractical. The stages in the life of RCF cracks are:

- Crack initiation
- Shallow angle crack
- Turn down and growth of turned down cracks

Thus, based on the above criteria, the key material property parameter that a new rail steel must be judged on is a measure of the RCF resistance

- A measure of RCF resistance in terms of
  - Period or cycles to initiation
  - Growth rate of cracks during shallow angle stage
  - Growth rate of cracks following turn down

Clearly, a detailed discussion of the factors contributing to RCF is outside the scope of the current paper and is discussed in a separate paper within this programme. However, it is still important to relate this key factor governing rail life to the properties included in the major rail specifications. The relevant specifications for a range of rail steels are given in Table 4 and their relevance to rail life curtailment by fatigue is discussed briefly below.

Table 4	Fatigue and Fracture Property Specifications

Property	Parameter	Rail Grades		
		220	260	350HT
Fatigue Strength 5x10 <sup>6</sup> Cycles	Initial Stress Range, MN/m <sup>2</sup>	280	320	450
	Minimum Fatigue Strength; MN/m <sup>2</sup>		280	
Fatigue Crack Growth Rate	ΔK = 10 MNm <sup>-1.5</sup> ; m/Gc	17	17	17
	ΔK = 13.5MNm <sup>-1.5</sup> ; m/Gc	55	55	55
Fracture Toughness	Mean value of K <sub>1c</sub> , MNm <sup>-1.5</sup>	35	29	32
	Lowest value of K1c, MNm <sup>-1.5</sup>	30	26	30

# 3.3.1 Fatigue Strength

The determination of fatigue strength employs a simplified push-pull test and hence the simplified stress conditions are clearly not representative of those responsible for the development of RCF. The initial stress range specified for the determination of fatigue strength suggests that a higher value is expected from the harder steel grades, although the minimum fatigue strength requirement of 280 MN/m<sup>2</sup> is the same for all grades. However, there is debate whether this level can be achieved in lower strength grades such as Grade 220. The observed values do reveal an increasing fatigue strength with the hardness of the grade with the value for the 350HT grade being nearly twice that of Grade 220. Although the test provides a relative ranking of the grades in use, it is yet to be demonstrated that this ranking can be translated to the degree of susceptibility to rolling contact fatigue in track.

# 3.3.2 Fatigue Crack Growth Rate

The observed fatigue crack growth rates are broadly similar for the three rail grades and easily satisfy the specified common requirement. Any relevance of so determined fatigue crack growth rate for the early stages of shallow angle crack growth is highly complex because of the different mechanisms involved. However, the data could be applicable for the latter stages of RCF crack growth, particularly after turn down. Hence availability of such data is useful for the selection of rail steels, although it could be argued that prevention of the initiation of defects should be the criteria for material selection and system design.

# **3.3.3 Fracture Toughness**

The fracture toughness values are again broadly similar for all three grades and reflect the relatively low fracture toughness of high carbon pearlitic steels but, in terms of relative ranking, Grade 260 appears to have the lowest fracture toughness value. Clearly, for given loading conditions, fracture toughness is a key parameter in the determination of the critical defect size at various locations in the rail and hence should be a criterion for the selection of rail grades. In view of the poor fracture toughness of high carbon pearlitic steels, a very significant improvement in this parameter would be required to make any appreciable change to track integrity.

# 3.3.4 Rolling Contact Fatigue Resistance

The resistance to RCF of rail steels does not feature in any rail steel specification. It is determined in the laboratory using a twin disc test arrangement in which the rotating discs represent the rail and the wheel and the number of cycles to crack initiation is measured. Although it is acknowledged that this test arrangement does not reflect the real rail-wheel contact conditions, its use has continued for investigating the development of RCF and to provide a comparative ranking of the steel grades available and to understand crack development under simplified but more controlled contact conditions.

Figures 9 and 10 below show the resistance to RCF initiation as a function of hardness and 0.2% PS. It is apparent that a wide range of steels are potentially available whose resistance to RCF initiation is several fold that of Grade 220, Grade 260, and even Grade 350HT.

The laboratory twin-disc tests provide two sets of results; the number of cycles to initiation and the number to spalling. The laboratory tests suggest that the ratio of the number of cycles to spalling to that for initiation is inversely dependent on hardness with the majority of the harder and more RCF resistant steels showing a relatively small gap between crack initiation and spalling. This is not necessarily disadvantageous since the least interventionist maintenance programme would be one that is planned soon after crack initiation to ensure complete removal of cracks with only a relatively light grind.

However, the key question that needs answering is how close is the correlation between the laboratory observed resistance to RCF and that experienced in track. Clearly, establishing this correlation or defining an alternative test that reproduces in-service conditions should be one of the major areas of focus for the industry.





#### Figure 10 RCF Resistance of Rail Steels as a function of 0.2% PS

#### 3.4 Increased Rail Breakage Risk

Fracture mechanics principles clearly demonstrate the importance of key material property parameters to make rail steels more tolerant of in-service conditions. The material properties that are relevant to the assessment of the risk of rail breakages are:

- Fracture toughness and Charpy Impact properties
- Fatigue crack growth rate
- Full rail section bending fatigue strength
- Defect size tolerance
- Level of residual stress in various parts of the rail

A detailed discussion of these properties is outside the scope of the current paper primarily because the risk of rail breakage is influenced by a whole host of system variables and their optimisation provides a more effective means of minimising the risk of rail breakage. The reduction in the number of rail breaks within the NR network from a peak value of over 900 just a few years ago to around 450 for the year ending March 2003 is a clear indication that the risk of rail breaks can be substantially reduced without resort to changes in rail metallurgy. It is therefore appropriate to briefly examine the nature of rail breaks as discussed below. Although the analysis is based on data for the Year 2000/2001, it serves the purpose of demonstrating that rail breakage risk is more appropriately addressed as a system issue. It is, however, acknowledged that improvements in fatigue and fracture properties would be beneficial.

The analysis presented below is based on a total number of breaks of 719 but the removal of duplicate entries reduced the eventual figure to 706. This small change is not considered to materially change the conclusions of this analysis.

A top level breakdown of the breaks provides the following distribution according to the longitudinal location of the break:

- Mid Rail Breaks: ~41%
- Within Weld Limit Breaks: ~25%
- Within Fishplate Limits: ~23%
- Uncategorised ~11%

and the top six category of rail breaks account for over 80% of the total. The league table being:

- Mid-rail V/T failures:
- Thermit welds all types:
- Bolt Hole failures:
- Not categorised:
- H/L, V/L within FPL:
- Corrosion

It is likely that mid-rail V/T category is probably a "catch all" category to encompass a number of vertical/transverse breaks and hence a further breakdown of the V/T breaks into the constituent defect categories of 202,211,221, 231,241 and 251 is necessary.

Such an analysis suggests that the defect categories of 201, 211 and 221 together account for a high proportion (~24%) of rail breaks for the year. Since the rail end breaks from welds or bolthole related failures have been separated out, these categories are likely to comprise failures from the Classic Tache Ovale breaks, RCF failures and weld repair breaks mistaken as Classic Tache Ovales. Assuming that the

Classic Tache Ovale failures are more likely in pre-concast rails, the above analysis was extended to examine the age profile of the rails in the mid-rail V/T break category.

Although this analysis suggested that the majority of the mid-rail V/T breaks were in pre-1976 rails and hence could have been Classic Tache Ovales, this conclusion is considered misleading since some old rails have been observed to have severe category RCF cracks. It is widely recognised that the incidence of rail breaks from classic Tache Ovales associated with inclusions or hydrogen cracks is small and decreasing but the question remains whether such failures should have been detected and removed at the last inspection or is the inspection interval too long based on the expected growth rate.

The second largest contributor to the annual rail breaks total is an alumino-thermic weld. It is generally recognised that alumino-thermic welds produced under well-controlled conditions can give long lives and early failures are usually associated with a failure of some aspect of the process. Clearly, the failure of alumino-thermic welds needs to be addressed separately from rail metallurgy although there is a link in that different weld formulations are required for different steels.

The key failure mechanism within the fish plate limits (FPL) is bolt hole failure and although an improvement in fracture toughness of rail steels would be beneficial, the root cause of such failures is high dynamic forces resulting from poor geometry and maintenance of the joint. Equally, the H/L and V/L breaks within fishplate limits are likely to be related to track geometry around the joints.

The sixth largest category in the league table of rail breaks is corrosion initiated breaks. The direct entry into this category account for  $\sim 4\%$  of the annual total and the foot initiated V/T failures and other unknown category V/T failures could increase this total to a much higher figure. Although a reduction in the residual stresses in the foot (increasing the realisable fatigue strength) or an improvement if fracture toughness of the rail steels could reduce the incidence of corrosion initiated rail breaks from the foot, the difficulty of inspection suggests that a preventative solution of the use of corrosion prevention coatings would offer a better solution in areas of known corrosion risk such as tunnels and crossings.

Finally, although not in the top league of rail break causes, failures from weld repairs are believed to account for a large number of V/T or Tache Ovale type defects. Clearly, the metallurgical challenge here is to develop a more robust procedure for weld repair or develop a more readily weld repairable rail steel. In view of the existing need for weld repair to remove isolated squats or wheel burns, a more robust weld repair methodology would produce early gains.

# 4. Conclusions and the Way Forward

It is recognised that enhancing track integrity requires bringing together of a diverse range of skills encompassing vehicle dynamics, contact mechanics, permanent way engineering and materials technology. A key statement describing the role played by metallurgy in other fields is that over 70% of the steels in use today were invented in the last ten years and yet the vast majority of the track in any country utilises steels that were invented quite some time ago. The metallurgical developments of rail steels have largely been left with the manufacturers in contrast to the earlier practice in the industry of active participation of bodies such as the "Improved Rail Steel Liaison Group" that brought together the permanent way expertise of the industry with the metallurgical knowledge of the rail manufacturers. However, the effective use of any newly developed steel is dependent on the knowledge of what is required – "you can only provide an answer if you know the question".

Although further discussion with the various disciplines is required, the basic framework of a way forward is:

• Network Segments: Railways are not a single stretch of track and hence it is necessary to break the network into segments firstly according to the track characteristics of curvature and cant etc. followed by further classification according to the duty imposed by traffic and vehicle type.

- Duty Imposed: The rail and track are subjected to different levels of duty dependent on the track design and the traffic carried. The duty imposed in terms of the track forces, contact patch size and position would then need to be estimated to facilitate the choice of the rail steel. This approach would also facilitate choice of other track components and design.
- Material Property and In-Service Performance Correlation: Although a number of metallurgical tests are specified in rail steel specifications, their direct relevance to in-service performance is not clearly established. This gap in knowledge needs to be filled in with in-service trials. Initially the trials could be restricted to a narrow selection of track characteristics and traffic conditions but could then be expanded to other combinations of track traffic conditions based on the above categorisation. No worse than before
- Rail Metallurgy Developments: A wealth of work was done on the development of structure property relationships for both low and high carbon steels. Such work laid down the foundation stones for the development of many steels in current use in a wide range of industries. A similar study would be necessary to link measured in-service performance of rail steels with their basic metallurgical properties currently measured or the development of new tests and property parameters to better explain in-service behaviour.

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