Project no. TIP5-CT-2006-031415

INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

D1.3.3 – Final report on Root Causes of Problem Conditions and Priorities for Innovation

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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1. Executive Summary

The stated objective of the INNOTRACK project is to reduce the whole life cost of track maintenance and renewal while increasing annual tonnage and speed by the introduction of innovative products and processes. The process for defining the requirements for innovation was;

1. Determine the European track problems responsible for the problem conditions from national workshops
2. Confirm that these problems result in the highest costs
3. Explain the root causes of these problem conditions
4. Suggest how innovation may be able reduce or eliminate these problems

The national workshops produced results that, once differences due to climate extremes were eliminated, were broadly similar. The cost data provided by the participating IMs confirmed that generally the high cost issues were the same across Europe with only differences in ranking.

The root causes of these problems are generally well known at a high level although for specific instances detailed investigation would be necessary to confirm that the cause was the same as the general case. A number of track experts have added their opinions to the root causes and contributed to the bibliography.

Having defined the root causes of the problems, innovation should be focused on:

- Removing the cause

This may be outside the scope of this project. E.g. high vehicle track interaction forces may be the root cause of certain track degradation conditions. This may be reduced by improved track quality but the great benefits of different vehicle characteristics is not within the scope of INNOTRACK

- Reducing the whole life cost implications by
    - Reducing the damage
    - Reducing the time and cost to repair or replace
    - Reducing the cost of components and processes
    - Avoiding the cost of train delays by predicting incipient failure
    - Improving availability through designs that operate in degraded mode until a suitable opportunity to repair or replace

Two causes of high degradation and failure predominate. These are the energy at the wheel rail interface and secondly the inability of track support to sustain the applied loading.

Priorities for innovation should be based on the root causes of the problems. The suggestions for innovation offered in this report are not exhaustive and will be overtaken in time by new technology. The range of possible innovative solutions is great, and as technology advances ideas that have previously failed may become realistic. An open mind is therefore essential to the process for evaluating innovation.

2. Introduction

Although in many parts of Europe rail travel has increased to the level where capacity is now a serious problem, increasing the capacity by investment in new infrastructure is seriously inhibited not only by the cost of construction, but also by the cost of ownership. A significant reduction in the cost of maintaining and renewing track is essential if funding is to be made available for new infrastructure. The core objective of INNOTRACK is to reduce the whole life cost of track by the introduction of innovation. The process of developing new technology to the point where it can be confidently introduced to the railway network is in itself a major cost and risk issue, and therefore the innovation activities must be well targeted to address the most urgent needs. If this process addresses the broader European needs, it will ensure the largest possible market uptake.

In order to determine the European priorities for innovation, the opinions of the participating infrastructure managers (IMs) was elicited concerning the major problems associated with infrastructure maintenance and repair, through a series of workshops. The ranking of these problems was achieved by cost data provided by these IMs. This process is described in D1.4.6*: A Report Providing Detailed Analysis of the Key Railway Infrastructure Problems and Recommendations for Cost Categories to be Used for Future Data Collection.*

Initially it was planned that the problem conditions would require modelling to understand the root causes, but the results revealed that all the most significant reported problems were generally well known in terms of the causes, although no fully developed cost efficient long term remedies are available. For specific isolated instances of high cost track degradation that does not conform to a pattern for the route concerned, detailed investigation may be necessary to confirm that the cause is the same as the general case.

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This report prioritises the needs to mitigate the causes of the high cost of ownership of tack infrastructure.

3. Root Causes of Problem Conditions and Priorities for Innovation

3.1 Methodology

In this section the root causes of the problem conditions reported are examined and areas for innovation, that could reduce the LCC of the problem, proposed. The problems are addressed in order of magnitude of importance as indicated in D1.4.6

3.1.1 Rail: Cracks and Fatigue

Causes

RCF, rail defect crack initiation, corrosion, welded joints and cracks from machined holes and other notches and misaligned rail joints.

Rolling Contact Fatigue

Rolling contact fatigue cracks on the rail can be classified into those that are subsurface-initiated and surface-initiated. Subsurface-initiated cracks are normally a consequence of high vertical loading in combination with material imperfections. On the other hand most surface initiated cracks are the result of wheel–rail interaction. A more specific division can be made into shelling, head checks, taches ovale, and squats (see UIC 712). Shelling (see Grassie and Kalousec[2]) is a subsurface defect that occurs at the gauge corner of the high rail in curves of railways with high axle loads. An elliptical shell-like crack propagates predominantly parallel to the surface. In many cases the shell causes metal to spall from the gauge corner. However, when the crack length reaches a critical value the crack may turn down into the rail, giving rise to fracture of the rail.

Initiation is dependent on slip processes, governed by cyclic shear stress. Propagation is generally governed by cyclic tensile stresses, and caused by repeated plastic stretching and blunting at the crack tip. The classic evaluation is that when a flat crack is opened by tensile stress, stretching occurs normal to the existing crack tip, thus creating a new surface at the now blunted crack tip. When the stress is reduced back to zero, this new surface folds back on itself, ahead of the crack tip, thereby advancing its position. It is generally difficult to produce sustained crack growth by shear; the cracks usually change direction in response to the tensile stresses and to develop normal to the local maximum principal stress. However in a generally compressive field, such as that under contact, early growth by shear is the only possible mechanism available to advance the crack. Only later, under the influence of bulk bending stresses in the body of the rail, does the crack grow by tensile opening and closing.

Figure 1 below illustrates the inter-relationship of rolling contact fatigue for both wheel and rail. The upper part of the figure illustrates the large shear plastic deformation developed at, and close to, the surface of the material in the contact patch. Cracks will initiate due exhaustion of the ductile of the material in this region under the repeated combined application of surface shear forces and high compressive loads. This process is known as ratchetting. The orientation of the cracks on the surface will be at right angles to the direction of the resultant (of longitudinal and lateral) creep force. This is illustrated in the lower photograph which shows the typical appearance of RCF cracks on the rail surface. Cracks therefore initiate as a result of the accumulation of strain energy in the material from the forces generated at the wheel rail interface. These forces are generated in both the vertical and shear (longitudinal and lateral) directions and arise due to the steering behaviour of the vehicle’s wheelsets.

The mechanism of wear is very similar to that leading to crack initiation, and there is a continuous interaction between the two mechanisms which may lead to wear or RCF formation on wheels and rails. If a small amount of energy is exchanged only RCF will form as the wear rate is very small under such conditions. As the wheel/rail forces, and hence the strain energy absorbed by the material, increases the wear rate also increases and can remove some of the material in which RCF has initiated, reducing the rate of RCF initiation. At higher energy levels wear will become the dominant mechanism, with no observable RCF initiation. This is why RCF tends to form on the gauge shoulder of rails in curves: contact on the crown of the rail does not generate sufficient shear forces to initiate RCF; contact on the gauge face of the rail, usually under flange contact, generates much higher forces which increase the wear rate significantly above the crack growth rate. At intermediate locations on the gauge shoulder the forces are sufficient to initiate RCF cracks without significant amounts of wear.

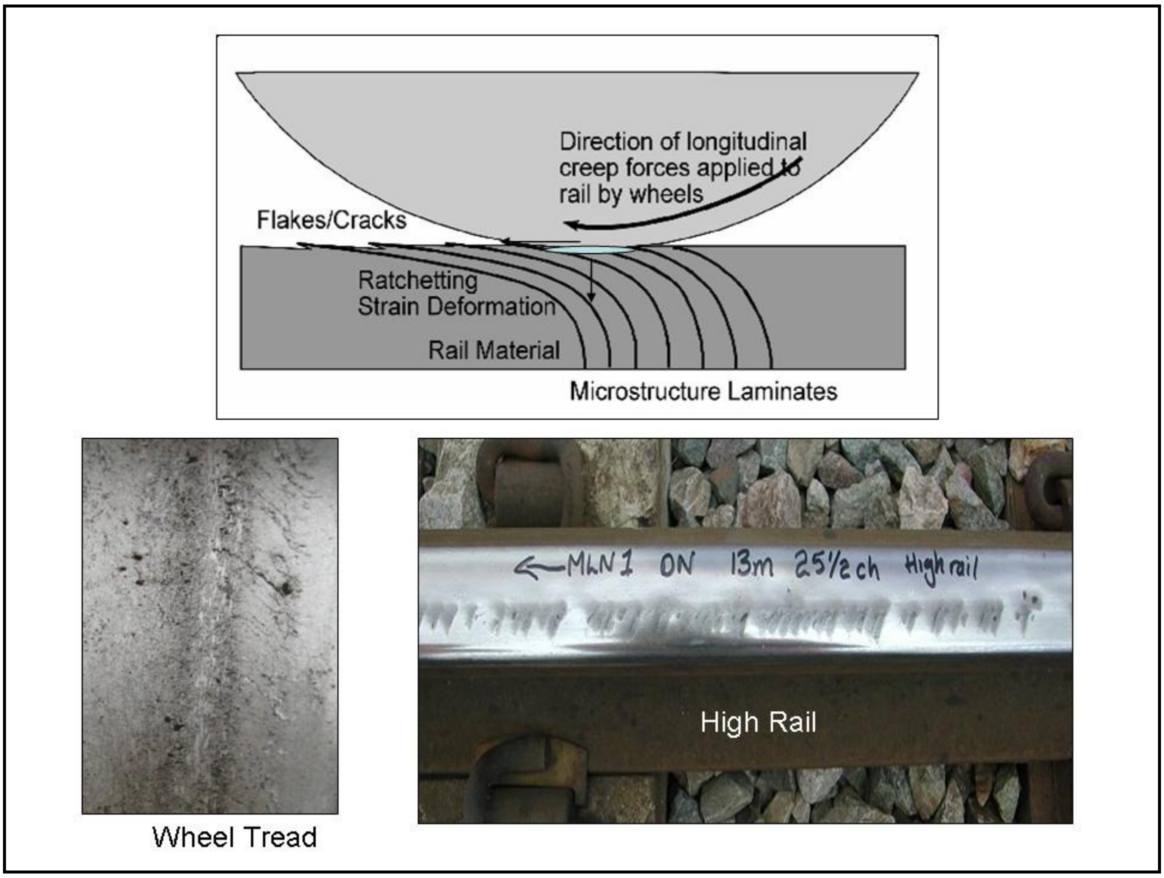

Figure 1 - Rolling Contact Fatigue

The various studies initiated by WRISA (now V/T SIC), such as the “Great Western RCF Pilot Study” and the “C2C RCF Study” were instrumental in formulating a preliminary list of key RCF initiation factors. In both cases, field observations of the actual RCF conditions (crack surface length, position and orientation) were matched to theoretical predictions of wheel/rail forces produced from established vehicle dynamics simulators, such as Vampire™.

The results from the vehicle simulator were used as input to Shakedown Diagrams, a method of predicting surface cracks that uses contact pressure and the shear force coefficient (contact plane forces normalized by normal load) to predict when conditions were prone to allow crack initiation. This method was successful in predicting the existence of RCF and served as the first technique to isolate key factors and to quantify their interaction.

Detailed analysis of cracked rail profiles did show that significant wear and RCF cracks were often both present. This observation led to the conclusion that a wear function, estimated to increase with the level of force, competed with crack formation. Since the Shakedown diagram did not directly predict wear, a function was assumed as depicted in Figure 2.

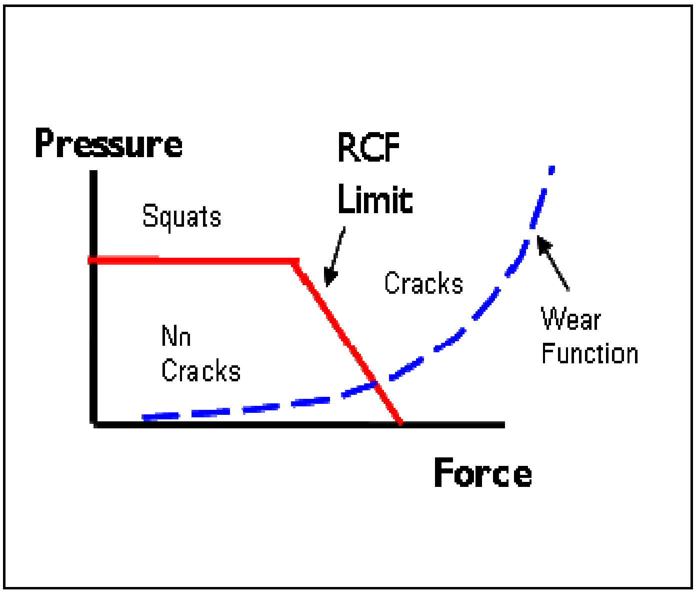

Figure 2 - Shakedown Diagram with imposed hypothetical wear function

Simultaneously, the RSSB funded Whole Life Rail Model (WLRM) was pursuing a methodology that could account for the various stages of crack growth from the early surface initiation, the intermediate “shallow growth” phase and the final vertical growth that is exhibited in broken rails. An important early outcome of this method was the evolution of a crack initiation algorithm that was based upon the concept of Contact Patch Energy (usually denoted by (T-Gamma or Tγ) being responsible for both wear and RCF initiation. This can be conceptualised in the diagram in Figure 3 which shows the competition between the two mechanisms occurring at different rates, illustrating that in some situations RCF will dominate and in others wear will dominate.

Although both the Shakedown and WLRM approaches are capable of predicting the existence of rail RCF, the latter has proven to be the most accurate and useful method, since it directly accounts for both RCF and wear, has an unambiguous numeric output and its Damage Index is relatable to fatigue life. Therefore current research is focused on using the WLRM analysis approach. Figure 4 shows a typical output from the model, comparing the predicted locations of RCF on the two rails through a site with the observed locations of RCF cracks on the site.

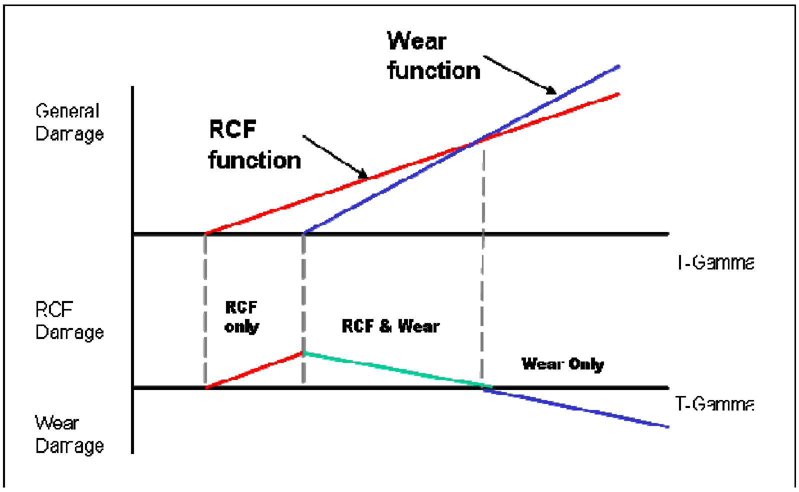

Figure 3 - WLRM Damage Index algorithm, showing separate RCF and Wear functions as well as the composite form

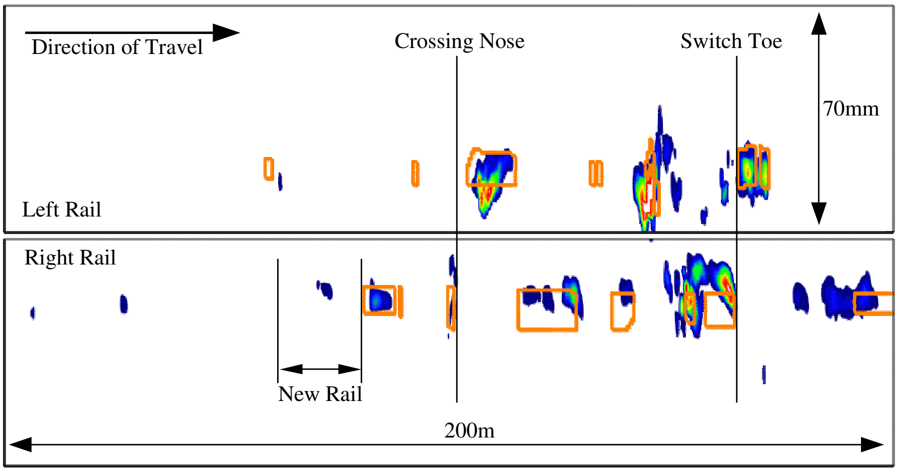

Figure 4 - Example RCF prediction output comparing observed RCF crack locations with predicted positions of RCF on the rail head

Recently many studies have been performed using computer models investigating mitigation techniques of RCF.

Early RCF research efforts conducted in the UK were successful in identifying methods of predicting RCF as well as isolating most of the key factors that contribute to crack initiation. Recently, the parametric studies have created greater insight into the interaction of the factors and have pointed out that the wheel/rail system must be "tuned" in order to reduce maintenance and prolong asset life. It has become clear than a number of mitigation techniques can be employed to address RCF formation such as:

1. Of primary concern is the reduction of primary yaw stiffness in bogie suspensions.
2. Increasing cant deficiency
3. Reducing vehicle weight
4. Wheel and rail profile and condition
5. Wheel rail friction management
6. Vehicle weight and gauge all interact to create circumstances prone to initiate RCF. To achieve a sustainable and cost/effective reduction in RCF, they must be adjusted in concert, not in isolation.
7. The impact of gauge widening in curves is also appearing as a possible factor

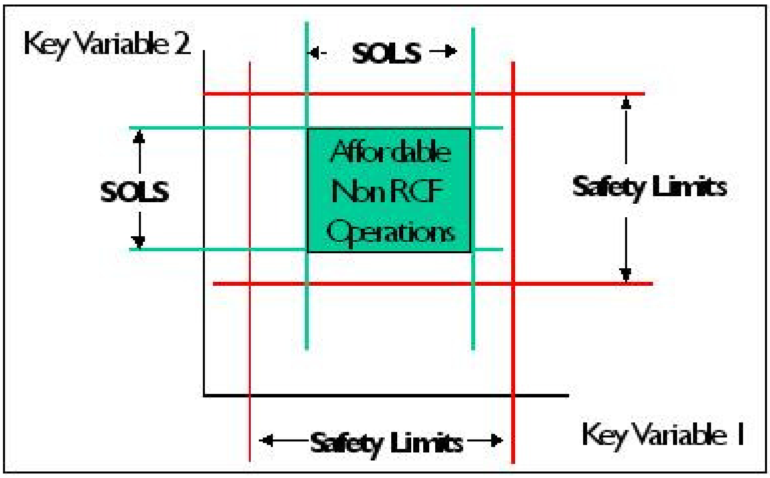

Figure 5 - Sustainable Operational Limits

As the technical issues become clear, the need for cost/benefit analysis increases. At present, RCF trials have already identified how expenditures by one stakeholder can create significant benefit for others. The need, therefore, for universal understanding of the technical and financial issues is becoming increasingly clear as is the need for a straightforward means to balance cost and benefit amongst the different stakeholders.

WRISA (now V/T SIC) had proposed that the industry adopt the concept of Sustainable Operational Limits (SOLs) that would constrain system key variables to a domain within safety limits and would allow for increased system performance in a financially viable manner. Figure 5 depicts the concept for 2 key factors that could represent bogie PYS and track quality that could only be “tuned” with the cooperation of different stakeholders

The concept of SOLs remains valid and can be used to assess the costs and benefits to move the system from its present RCF state to an optimal system configuration: the Ideal Reduced RCF State.

However, these techniques address simple operating or design parameters and do not address track related issues that may initiate RCF damage such as track quality. Further investigations that made it quite clear that improving track quality is essential to reduce RCF damage. Damage seen on the track is strongly influenced by Klingel cyclic wavelengths from the wheel rail interactions. The implications of the influence of Klingel wavelengths are far reaching:

- Firstly, most track maintenance standards are wavelength independent and tend to regulate “big” events which may well have implications for safety and ride quality. But it is now evident that small features of critical wavelength are most important to preserve asset life. This effectively reverses common wisdom.
- Secondly, the findings imply that asset life can not be preserved without some estimation of the axle behaviour so that realistic load spectra can be generated. This implies that track standards must become wavelength sensitive or at least discriminate between straight and curved track.
- The current findings demonstrate that the contact patch energy $T\gamma$ (T-Gamma) is not just responsible for RCF and wear but is the prime energy source for track geometry distortion.

these findings suggest that future track standards must embrace a new intellectual framework:

Future track standards that include infrastructure asset preservation cannot be based upon track geometric quality alone and must include consideration of vehicle behaviour since $T\gamma$ is the primary source of the energy that causes track degradation (external events excluded). Table driven track standards are inadequate.

Therefore, to aide local track engineers in the field to manage RCF damage in the UK, Network Rail has developed simulation and management tools, such as Track-Ex. A combination of localised measured track geometry combined with Vehicle Damage Matrix (VDM) tables from simulations of various wheel and rail combinations, friction levels and vehicles representing the various primary yaw stiffness present on the system are incorporated into a Track-Ex analysis. Track-Ex reads in the latest track geometry in the area of interest and then uses VDM tables for the appropriate vehicles to estimate the vehicle’s response to the track geometry and the resulting RCF and wear damage is assessed. Changes in speed, wheel and rail combinations, primary yaw stiffness, cant deficiency and other parameters, may be studied to determine the best or most desirable solution(s) for the area.

From the studies performed to date (mostly in the UK, but also elsewhere in Europe and the US) it has been found that, although generalized relationships may be obtained, local or route analysis is necessary to find the best or most cost effective solution(s). This is because of the impact of vehicle design, wheel and rail profiles, and track geometry conditions on subsequent crack initiation and growth. The studies performed to date have shown single and in some case multiple solutions, so future analysis and solutions may require the application of techniques such as those used in neural networks to assess the interaction of multiple effects.

Priorities for Innovation

1. Of primary concern is the reduction of primary yaw stiffness and dynamic response of bogie suspensions.
2. Reducing vehicle weight
3. Wheel and rail profiles to minimise energy generated in the contact patch
4. Friction management
5. Rail steels with increased resistance to RCF and wear
6. Methods for absorbing or damping energy away from the wheel rail interface
7. High speed rail re-profiling systems
8. Monitoring systems to better understand wheel/rail interaction so that shear forces and wheel/rail contact behaviour can be optimised

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3.1.2 Track: Bad Track Geometry – Poor track support and sub-optimal maintenance

Causes:

Bad track geometry can represent any of the following conditions:

- Poor vertical profile and cross-level that is often related to poor ballast and/or formation.
- Poor gauge and alignment that often occurs in curves or transitions when track does not possess adequate gauge strength or panel shift strength.

Excessive vertical and lateral wheel/rail forces or poor installation and maintenance including inadequate drainage are other possible causes of track geometry degradation. There is strong evidence that where the installed track quality is good, it will take longer to degrade due to reduced energy input into the track system by rail traffic.

For many IMs, rectification of poor track geometry is one of the highest track maintenance costs, including acquisition and analysis of track recording car data, tamping, ballast cleaning and replacing ballast. However, these activities are designed to reinstate the track quality to the original condition. If there are no other changes to the system, the track quality will degrade as before. Increasing traffic, higher axle loads or speed will result in an increased rate of degradation. There are a number of methods currently used to reduce track degradation rates; specifically under sleeper pads designed to reduce the sleeper/ballast contact stresses and the energy transmitted into the ballast and subgrade. Where poor subgrade is known to contribute to high track degradation rates there are a number of subgrade reinforcement techniques available. WP2.2 has reported 25 sub grade enhancement methods and there is clearly a need to develop a toolset that will assist the maintenance teams to select the improvement technique offering the lowest LCC solution for a specific site. In the absence of such a toolset, one preferred method may be chosen for all sites irrespective of suitability.

Priorities for Innovation:

Reduction in the cost of track maintenance must begin with addressing the high cost of periodically reinstating the track quality. Other measures such as the introduction of high strength steel rails or advanced grinding strategies will be largely negated if the track quality is not maintained at a high level.

Suggested methods to eliminate or reduce the cost of bad track geometry are:

1. A ballastless track design with low LCC
2. Novel sleeper or ladder track designs to reduce the stress on track support
3. Improved designs for energy absorbing devices that are tuned for the traffic and track characteristics, or may be used in combination with novel sleeper designs
4. Self adjusting rail support that maintains track quality to a limited degree
5. Improved design and installation to minimize the influence of track transitions

6. Elastic fastening systems to maintain adequate gauge strength
7. Methods and designs to improve panel shift strength
8. See also 2.1.6 Sub-structure – unstable ground

3.1.3 S&C: Switch Wear

Causes:

A switch forms a discontinuity in any track where one is installed. It is a discontinuity with regards to track support due to the altered sleeper arrangement and during tamping operations it may require a separate operation or manual correction. A switch also forms a discontinuity for the wheel rail contact patch that may give rise to high transient vertical and creep forces. The high lateral accelerations to any vehicle not travelling in the straight ahead position will also cause high forces. The installation and maintenance of a switch is critical to its performance and any error may not be immediately apparent. For all these reasons a switch will experience higher forces than plain line and the life of the switch will generally be reduced by plastic deformations, wear and/or fatigue cracks.

Priorities for Innovation:

The present design of rail vehicles where stability at higher speeds is considered more important than a design for minimum track damage and low angles of attack makes the design of a highly reliable long life switch increasingly difficult. Areas for innovation that should reduce the LCC and improve RAMS for switches include:

1. Novel designs of switch reducing wheel rail forces to the minimum possible and using advanced materials to reduce wear and crack initiation.
2. When properly used, established vehicle dynamics models have proven to be extremely useful for evaluating proposed turnout geometries. However, the model output accuracy is dependant on the inputs data, including wheel and rail profiles, vehicle suspension characteristics and track and rail stiffness parameters. Develop modelling guidelines to be applied specifically for analysis of S&C designs.
3. Revised switch point and closure curve geometry that encourage axle and bogie steering to reduce wheel/rail forces
4. Flange bearing frogs and moveable point frogs to reduce Wheel/Rail impact forces
5. Easily replaceable components where wear and cracking occurs
6. Switches designed for automated maintenance methods, specifically but not only the use of hollow steel bearers to house operating and lock rods and over-the-bearer stretcher bar designs.

3.1.4 Rail: Corrugations

Causes

Rail corrugation is a surface defect of the rail, which is manifested as periodic wear. If the defect is not removed the corrugation may lead to high levels of wheel rail noise and crack initiation. There are many different types of corrugation, some of which are well understood [1]; but the causes and consequent solutions are poorly understood for corrugations in sharp curves, where corrugation is exhibited on the low rail [2].

Potential mechanisms

The mechanism of corrugation can always be defined as the result of both dynamic and structural factors, so for corrugation to occur a wavelength fixing mechanism and damage mechanism is required [2]. The cause of the periodicity will be a function of track geometry and mechanical characteristics, axle mode, curving behaviour of bogie and vehicle speed. It is also expected that tangential forces and creep will contribute to the damage, whilst stick-slip phenomena could play a part in both wear and periodicity [2,4]. It therefore follows that if similar vehicles run over the same track at similar speeds the development of corrugation will be exacerbated [1].

Studies by J.I. Egana et al [2] and Kalousek and Grassie [1] have looked at rail pad softness and found that softer rail pads remove at least one of the corrugation formation wavelengths. It is concluded by Kalousek and Grassie that soft pads decouple the rail from the dynamic behaviours below the rail pad, e.g. the transmission of sleeper resonances back to the rail head. Jin et al [3] conclude from their corrugation calculation model that corrugation will be initiated on smooth curved track even without any initial defects and that “discrete rail support by sleepers is the congenital defect leading to rail corrugation”.

Current Solutions

Current practice consists predominantly of using grinding regimes as corrective action by removing existing corrugations, and preventive action by removing other defects that may trigger dynamic loads and restoring optimum wheel rail contact condition. Harder steel rails may be used on curves to also reduce wear [1].

Priorities for Innovation:

1. Rail steel grades resistant to corrugation and optimised wheel and rail profile management
2. Rail pads and other rail damping devices designed to minimise formation of corrugation
3. Innovative rail and sleeper support systems designed to decouple natural frequencies of vehicles and track
4. Revised axle and drive train designs to minimize torsional vibrations at corrugation wavelengths
5. Methods to manage rail head friction, through use of engineered friction modifiers.
6. Optimised grinding strategy for corrugation management

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3.1.5 S&C: Cracked manganese crossings

Causes and Priorities for Innovation

The failure of manganese crossings is analogous to wear in switches and therefore these priorities are equally relevant for cracked crossings:

1. Novel designs of crossings reducing wheel rail forces to the minimum possible and using advanced materials to reduce wear and crack initiation.
2. The use of circular check rail designs.
3. Flange bearing frogs and moveable point frogs to reduce Wheel/Rail impact forces
4. Easily replaceable components where wear and cracking occurs

3.1.6 Substructure: Unstable ground

Causes

This may be the geotechnical nature of the location, or the method of construction used at the site.

When track substructure is defined as ballast, sub-ballast and formation, causes of unstable ground can be from any of these layers. Very often, unstable ground is also associated with poor drainage.

In the ballast layer, fouled ballast is often the culprit. Fouled ballast has very high stiffness and little damping, and therefore is not capable of accommodating high wheel/rail forces associated with poor track geometry. Due to poor drainage the ballast layer can become weak, deforming excessively. This leads to poor track geometry, which in turn causes higher wheel/rail forces.

A saturated sub-ballast layer (a layer between ballast and formation) due to fouling materials and poor drainage can lose its strength under repeated dynamic wheel loads, thus becoming an unstable layer.

If formation is built with soft or marginal soils, it can become unstable either in a progressive manner or suddenly. Sudden formation failure rarely occurs, unless there is a dramatic change of environment (such as high rainfall and flooding) or load conditions (such as a large increase of wheel loads). Progressive deformation (shear), however, often occurs for the formation built with soft or marginal soil types. This progressive deformation can become rapid, leading to rapid track geometry degradation when speed or axle load increase, because the bearing capacity of formation soil may not be sufficient to withstand the stresses caused by traffic loads. In addition, poor drainage or ingress of water to the formation may reduce soil strength, leading to excessive deformation or unstable ground.

Established techniques for correcting unstable ground include:

Geogrids that can improve bearing capacity of formation

1. Short piling, geo(stone) piers or lime-cement pillars installed under the ballast layer to improve bearing capacity of formation
2. Ballast undercutting and shoulder cleaning to improve ballast drainage
3. Stone blowing or design lift tamping to improve ballast deformation characteristics
4. Sufficient ballast layer thickness with good quality ballast materials to reduce stresses transmitted to the formation
5. Adequate sub-ballast layer (formation protection layer)
6. Removal and replacement of poor formation soil
7. Hot mix asphalt underlay(between ballast and formation) to reduce stresses transmitted to the formation and to prevent surface water penetration into the formation

Priorities for Innovation:

This is a specific case of a problem that causes bad track geometry (see 2.1.2 for innovative solutions) and also:

1. Novel substructure improvement techniques with low LCC
2. Geotechnical practices that can improve track drainage
3. Production use of latest track substructure inspection technologies such as track modulus testing and GPR (ground penetrating radar) testing as an aid to identifying the nature of problem sites

References

1. Li, D. and Selig, E. T. "Evaluation of Railway Subgrade Problems," Transportation Research Record, Journal of The Transportation Research Board, US National Academies, 1995, pp.17-25.
2. Li, D. and Selig, E. T. "Evaluation and Remediation of Potential Railway Subgrade Problems under Repeated Heavy Axle Loads," R-884, Association of American Railroads, June 1995.
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3.1.7 Track: Bad Track Geometry – Wrong or unknown stress free temperature (SFT)

Causes

High rail temperatures result in the necessity to impose speed restrictions, and hence train delays, due to the increased risk of track buckling. This may be a risk due to the rail temperature exceeding the safe limit established from the rail stressing procedure, or a risk due to lack of confidence in the stress free temperature (SFT) in a track section. The problem for the track maintainer is that the SFT is almost always unknown and non-destructive or non invasive measurement technology capable of continuously characterising the SFT of CWR does not exist. Climate change may result in more delays due to speed restrictions imposed as a result of hot rails, raising the priority for solutions to this problem condition.

Priorities for Innovation:

The need for a continuous and non-destructive technique to measure the SFT is generally recognised as the primary innovation for SFT maintenance as shown below. Other areas for possible improvement include:

1. Non invasive methods for determining rail SFT
2. Guidelines for SFT maintenance related to the repair of broken rails during cold weather
3. Evaluation of current SFT and rail stressing requirements in and around S&C.
4. On board train sensors for monitoring rail stress
5. Improved or novel rail support to increase the rail buckling temperature
6. Rail section designed for increased buckling resistance

3.1.8 Rail welds

Causes

Rail welds are track discontinuities in regard to their metallurgical and mechanical properties. Rail welds tend to have lower hardness in the adjacent heat affected zones in comparison to the parent rail. Weld microstructures may also vary significantly from the parent rail. Two weld types comprise the majority of welds used in rail service, Aluminothermic (thermite) welds and electric flash-butt (EFB) welds.

Thermite welds are by nature susceptible to porosity and cleanliness problems, such as inclusions, typical of cast structures. Thermite weld production is highly operator dependant and as a result may experience significant variation in weld quality. EFB welds are much less operator dependant and produce the highest quality welds but are correspondingly more expensive and are less portable. Table 2.1.8.1 summarizes the types of failures associated with each weld process.

Typical Weld Degradation and Failure Modes	Aluminothermic Weld	Electric Flash-butt Welds
Railhead Batter / Dipping	Rail end misalignment. Mechanical Properties: • Hardness • Strength Distribution	Rail end misalignment Mechanical Properties: • Hardness • Strength Distribution
Railhead Shelling / Chipping (Surface and Subsurface RCF)	Mechanical Properties. Cleanliness.	Mechanical Properties. Electrode burns
Horizontal Web Fractures	Fatigue initiation sites • Inclusions • Porosity • Mechanical damage • Weld geometry	Fatigue Initiation Sites • Inclusions • Mechanical Damage • Weld geometry (shear ridges) Wheel loading conditions

Typical Weld Degradation and Failure Modes	Aluminothermic Weld	Electric Flash-butt Welds
	Wheel loading conditions • Vertical loading location • Lateral loading Residual stress distribution	• Vertical loading location • Lateral loading Residual stress distribution
Vertical Base Fractures	Fatigue initiation sites • Inclusions • Porosity • Mechanical damage • Weld geometry Wheel loading conditions Track support conditions Residual stress distribution Rail end misalignment Thermal stress	Fatigue initiation sites • Inclusions • Mechanical damage • Weld geometry (shear ridges) Vertical wheel loading Track support conditions Residual stress distribution Rail end misalignment Thermal stress

Table 1 - Summary of weld degradation and failure modes and the common related causes.

Priorities for Innovation:

1. Develop rail welding methods that incorporate the portability and cost benefits of thermite welding and the weld quality of EFB welds.
2. Weld treatment methods that improve the metallurgical and mechanical properties of adjacent heat affected zones.

4. Conclusion

This report explains some of the principal causes of high track maintenance and repair costs identified by the infrastructure managers of the participating countries in a series of national workshops.

Two causes of track degradation and failure predominate. These are the energy at the wheel rail interface and secondly the inability of track support to sustain the applied loading.

Priorities for innovation should always consider the root causes of the problem, but removing the root cause may have a higher LCC than other solutions. The suggestions for innovation offered in this report are not exhaustive and will be overtaken in time by new technology. The range of possible innovative solutions is great, and as technology advances ideas that have been discounted may become realistic. An open mind is therefore essential to the process for evaluating innovation.