Project no. TIP5-CT-2006-031415O

INNOTRACK

Integrated Project (IP)

Thematic Priority 6: Sustainable Development, Global Change and Ecosystems

D4.1.4 Rail Degradation Algorithms

Due date of deliverable: 30/6/09

Actual submission date: 06/11/09

Start date of project: 1 September 2006 Duration: 36 months

Organisation Name of lead contractor for this deliverable: Corus Rail and voestalpine Schienen

Revision [draft]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	Y
PP	Restricted to other programme participants (including the Commission Services)	
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)	

Table of Contents

Glossary

RCF – Rolling contact fatigue (in the UK RCF is both a general term for all forms of rolling contact fatigue but is also used to describe what, in the rest of Europe, are called head checks)

IM's – Infrastructure Managers – i.e. the railway partners involved in the project

MGT – A measure of traffic carried in units of million gross tonnes

EMGTPA - A measure of traffic based on an annual amount – equivalent million gross tonne per annum PTI - period to initiation of cracks

GC - Gauge corner

SCL - Surface crack length

CDGR - Crack depth growth rate

1. Executive Summary

The degradation of rail in track is the major cause of maintenance and renewal for all railways. To enable rail grade selection guidelines to be developed, a detailed understanding of the performance of the available rail steels under different loading conditions is required.

Over the last 30 years track monitoring of small sections of track has been carried out by both Infrastructure Managers (IM's) and rail manufacturers throughout Europe. As part of the Innotrack project this data has been collated, analysed and used to derive rail degradation algorithms for wear and rolling contact fatigue (head checks). This report summarises the analysis of data and reports the developed algorithms as a function of rail grade, traffic and track conditions. In addition the deliverable also contains information on the reasons for the large scatter in the collected results and where future track monitoring can be improved by collection of appropriate data.

The developed algorithms have been used to predict the wear and RCF behaviour on a route of over 100km to allow an understanding of how changing the rail grade selection criteria affected the rail degradation over its length and the impacts on rail life with its implied effects on life cycle costs.

2. Introduction

Over the last 30 years there has been extensive research into understanding all causes of rail degradation by both the railways, supply industry and academia. This research has been carried out through laboratory investigations, mathematical modelling and in track investigations. The research has been extensive resulting in a cornucopia of publications far too numerous to mention, a starting point is here [1, 2].

This deliverable (and the interim deliverables D4.1.1[3] and D4.1.2[4]) re-examines the results of in track studies of rail degradation carried out by both the infrastructure managers and the rail manufacturers. These investigations have been carried out for two main reasons; the first is to understand the performance of innovative rail steels, usually in comparison to current ones, in full scale (real world) conditions. The second reason is to increase the knowledge of the different rail degradation mechanisms prevalent on different networks, one example of this type of investigation is a comprehensive series of site monitoring to understand Rolling Contact Fatigue (RCF) on current rail steels. The results of these investigations are largely data on the wear and rolling contact fatigue performance of different rail steels for a range of sites with different loading conditions and track geometry (radius and super elevation).

Different organisations and people have collected the data over a large number of years. Therefore data processing has been carried out to allow a compilation of results into one database. This database has then been used to allow an understanding of rail degradation in terms of wear and RCF for a number of European railways. A key part of this has been to derive rail degradation algorithms from the data to allow a prediction of degradation as a function of track curvature and traffic. These formulae have then been used to examine how a long section of track would be expected to degrade and the benefits of using premium grade rail steels.

The ultimate aim of this deliverable is to develop an understanding of rail degradation as it actually occurs in track, with the information being used to develop a rail grade selection strategy (D4.1.5[5]) based on reducing the requirement for track maintenance and hence the life cycle costs of the railway.

3. Rail Degradation

The key degradation mechanisms that limit the serviceable life of rail are [6]:

- Loss of rail profile
  - Vertical and Side Wear
  - Corrugation (work on corrugation being carried out in WP4.2, see D4.2.4[7])
  - Plastic Deformation
- Rolling Contact Fatigue (RCF) – head checks and squats
- Rail breaks and defectives from various sources

The different degradation mechanisms can be combated by different material properties, a number of rail steel grades have been developed and are available to the industry with a range of different properties. The main deliverable of WP4.1 is a recommendation of the appropriate rail grade for different sections of track: this will take into account the different degradation mechanisms. However, it must be emphasised that rail degradation is the result of the whole system and hence rail metallurgy cannot be addressed independently. Optimisation of other aspects of the systems design and operation need to be taken into consideration in parallel.

3.1 Loss of Rail Profile

The loss of rail profile is a cause for premature replacement of rail in track. This loss of rail profile can be through wear in both vertical and horizontal directions stemming from the action of wheels on the rail. Plastic deformation of the rail also results in loss of useable rail profile. Some examples of profiles from a range of locations are shown in Figure 1 note that these do not represent the same amount of traffic. In view of how minor differences in profile affect the dynamic behaviour of vehicles, it is interesting to note that quite significant changes to the profile can be tolerated over the life of the rail.

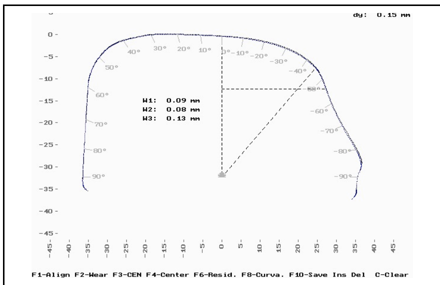
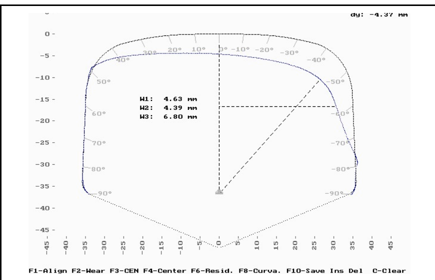
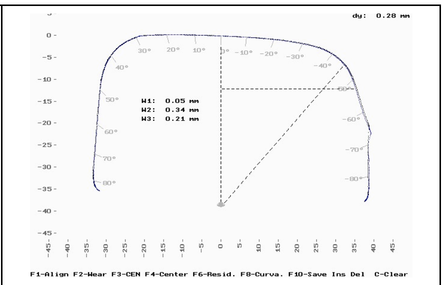
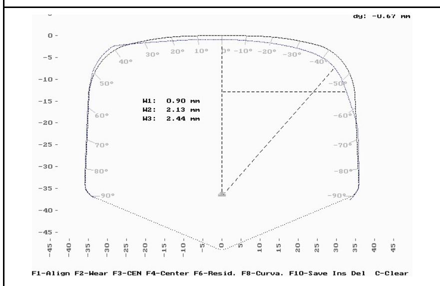
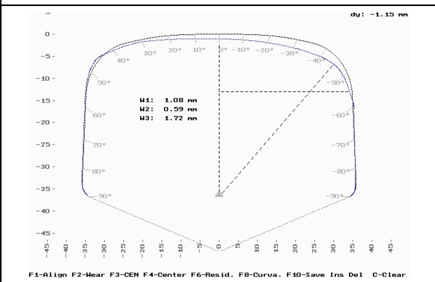
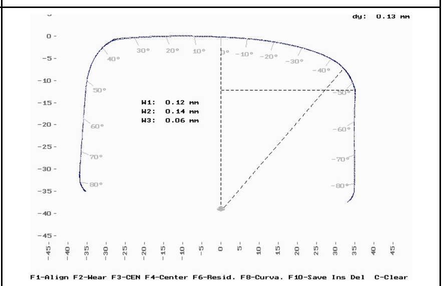
		
450 m Radius	**960m Radius**	**1200m Radius**
		
2000 m Radius	**3000 m Radius**	**Tangent Track**

Figure 1: A Range of Rail Profiles Encountered on Railways

Clearly, the ability to maintain the optimum rail profile for the different contact conditions for as long as possible is highly desirable, hence the development and use of steels that minimise the loss of transverse profile.
The occurrence of corrugation could also be regarded as loss of rail profile in the longitudinal direction particularly as it is not categorically established whether corrugation is a result of differential plastic deformation or differential wear or both[8, 9].

The material property parameters contributing to the control of both wear and plastic deformation are:

- Proof strength
- Hardness and wear resistance

3.2 Rolling Contact Fatigue (RCF)

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. Therefore the phenomenon of fatigue is of critical importance to longevity of rails. Although fatigue in rails manifests itself in many ways (such as shelling and tache ovals[10]), the two major classifications of rolling contact fatigue (RCF) that are primarily of interest to mixed traffic railways are "squats" and "head checks" (Figure 2) 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[11].

Figure 2: RCF Cracks (head checks)

The stages in the life of RCF cracks are:

- Crack initiation
- Shallow angle crack growth
- Transverse branching (turn down of cracks) and growth of transverse cracks

The resistance to RCF of rail steels does not feature in any rail steel specification. However, in view of the growing acknowledgement by most railways that RCF is a key cause for rail life curtailment, it is essential to establish a measure of RCF resistance in terms of:

- Period to initiation (in terms of amount of traffic from installation to first observation of cracks)
- Growth rate of cracks during shallow angle stage
- Growth rate of transverse cracks following turn down

Data that has been collected by site monitoring has been carried out on “head checks” as this occurs in known locations allowing monitoring from installation until and beyond crack initiation. Squats, on the other hand, occur at random locations with no obvious relation to track geometry meaning that they can only be monitored once they have initiated. Therefore data from site monitoring includes little information on squats. Squats are very much an area of current research and have been investigated in Innotrack WP4.2[7].

3.3 Increased Risk of Rail Breakage

Rail breaks and defectives, Figure 3, form the third category of rail degradation and fracture mechanics principles clearly demonstrate the importance of key material properties required to make rail steels more tolerant of in-service conditions. Rails break from a number of causes including:

- Rail foot corrosion
- Failure at rail ends, including from bolt holes
- Failure of welds
- Internal defects
- Transverse RCF cracks

The material properties relevant to the assessment of the risk of rail breakages are:

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

Figure 3: Rail breakage from a fatigue crack initiating at a corrosion pit

Data that has been collected from the various trial sites does not contain information on rail breaks and defectives. Therefore this report does not discuss them further. Work has been carried out in work package WP4.2 into identifying the cause, development and the actions required when broken and defective rails are found. A good overview of the work is given in D4.2.6[12].

4. Rail Degradation Data and Processing

Track data have been collected over a number of years by Corus and voestalpine together with the Infrastructure Managers from various European countries including Network Rail, SNCF, DB, ÖBB, Banverket, SBB and Prorail to monitor the performance of rails in service. The data has been stored in different locations and in different formats and hence the data has been merged together through use of a spreadsheet ensuring that the data is in the same format and with the same units. The two companies have used this spreadsheet in different ways. Therefore before any analysis could be carried out initial treatment of the data was required to make the data compatible. The combined data is stored as a database, presented in D4.1.1, [3] which can be expanded as more track results become available.

4.1 Received Data

4.1.1 Corus

Site monitoring has been carried out at a number of locations around different European networks. Each monitored site has several test locations, often three but sometimes more, with the same track geometry. A number of site visits have been carried out at periodic intervals of 3-6 months. The track sites often have total inspection timescales ranging from 1-2 years to one site that was monitored for over 11 years. Therefore the Corus database contains just under 2000 measurements. The degradation mechanisms monitored were wear for all sites, in the form of profile measurements and RCF surface crack length and crack depths for the majority of sites. The track radius for each site was known and the gauge and cant also monitored.The information on traffic volumes and types was often limited to a measure of traffic in equivalent million gross tonnes per annum (EMGTPA). For all sites there was almost no knowledge of maintenance procedures, such as tamping, although visual inspection revealed if grinding had been carried out, but the exact date, metal removal etc. were unknown. Each individual measurement has an identification number; numbered in the range 1 to 10000 and 20001-30000.

To allow analysis of the data, the measurements for the same site have been aggregated together based on line reference, location, radius, rail grade, traffic direction and project. Further information on this is given in section 4.3. This gives 111 individual sites with the number of measurements ranging from 3 to 105 for each. The sites are numbered in the series 1-100 and 301-399. The aggregation on the sites would be preferable if they included cant but in the majority of cases this has been measured and therefore displays wide variability and therefore have been omitted. To allow the degradation to be analysed in terms of amount of cant, nominal values have been assigned to each site that are close to the mean value of the individual curve..

4.1.2 voestalpine(VAS)

The data received from voestalpine Schienen contained 206 data measurements; a similar aggregation process was carried out using radius, rail grade and daily traffic (traffic wasn't used for the Corus data as it was found to be the same for each site). The results show that for the majority of sites only 1 or 2 measurements have been reported, the data arising from the end or maximum values for each site, therefore there are 110 sites numbered in the range 101 to 300. To ensure traceability of data the record identification number for data from voestalpine lie in the range 10001 to 20000.

4.2 Limitations of Data

To allow a comprehensive analysis of the data, account has to be taken of all possible variables that may affect the performance of rails in service. The data that has been collected has concentrated on the rails themselves with only key track geometry features, such as radius and cant, being recorded. Due to the aims and nature of the projects, from which the data has been taken, there is significant variability in the information that has been recorded, an example is wear and is discussed further in section 4.3.1. The current section contains information that has an effect on the results and therefore would be useful to know when interpreting the data but in the majority of cases is largely unknown. It is recommended that when people are initiating track site monitoring projects in the future, investigation and recording of the following list of parameters is taken into consideration.

The key areas where information is lacking include:

- Track Layout and Geometry – The features recorded are normally limited to curvature and cant. Those often absent include:
    - The location of the site in relation to stations, switches & crossings and signals. This will have an effect on the dynamic behaviour of the trains and consequently the forces that the rail experiences.
    - Longitudinal gradient, which affects the behaviour of the vehicle and the forces on the rail.
    - Sleeper spacing. This is rarely recorded and therefore the standard design parameters used for each railway have been used.
    - Track Quality. All track is maintained to a standard that is acceptable for the operation of trains. Unfortunately the range of acceptable parameters is wide and therefore there is a large variability in track quality on an individual railway and an even greater difference between IM's. The quality of the track has a major impact on the contact stresses that are responsible for rail degradation and hence there is a large spread in degradation results for what is nominally the same type of curve.
    - Support Stiffness. Related to track quality. Although possible to measure it is largely unknown for the monitored sites.
    - Transition curve. The rate of change of cant and curvature in the transition curve can have an effect on the vehicle behaviour in the body of the curve; this fact is rarely recorded or taken into account.
- Traffic – The only data usually provided is an annual traffic figure (eg EMGTPA). The type of traffic running on a test site affects the loading parameters and, therefore, the stresses that the rail is subjected to. Detailed information such as the following is often not available:
    - Accuracy. Often no details are provided on how the traffic figure has been calculated. Some traffic data is calculated from the working timetables which include all trains whether they run or not (freight trains in working timetables often do not run). Others can be calculated from the signalling system.
    - Type of traffic/vehicles, also whether they are loaded or unloaded. An important set of parameters as different vehicle types result in different contact stresses.
    - Wheel Profiles. Wheels often have a design profile but this deteriorates in service. Therefore a rail is subjected to many thousand of wheels with different profiles resulting in the rail experiencing a range of contact stresses.
    - Speed. The only readily available figure is maximum line speed. No breakdown is available of the speed of different vehicles (freight trains travel at much lower speeds than passenger trains on the same line) which will result in different contact stresses.
- Maintenance Activities. The maintenance of track is a key activity that affects the life of the rail.
    - Grinding is carried out to remove RCF cracks as well as to restore the profile of the rail. During site visits, recent grinding is evident by the presence of residual grinding marks. What is often not known is the date of grinding or the magnitude of metal removal. Metal removal by grinding is only a minor problem as it can be taken into account during calculations, see section 4.3.1.
    - Tamping. To attain correct track geometry, tamping is carried out during the period of site monitoring. It can therefore affect the cant and hence the curving properties of the vehicles. Unfortunately it is rare that information on tamping is passed to those carrying out the site monitoring hence its effect on the results is unknown.
    - Lubrication. The effectiveness of lubrication to reduce the side wear of the high rail in tight curves is difficult to monitor over long periods of time. It is possible to judge the performance during site visits by taking measurements of friction coefficient with tribometers but the performance with time under different climatic conditions is hard to know (e.g. in cold weather the viscosity of the lubricant increases and the effectiveness can be severely

reduced). Lubricators also require regular maintenance to ensure that they continue working.

- Meteorological Conditions.
    - The effect of the variability of the weather on the performance of rail in service is an unknown that has to be accepted. The lubricating effect of rain on the wheel/rail contact has a major effect on the friction coefficient and hence on the contact stresses between the rail and wheel. Only the installation of a weather station alongside a test site would give accurate information on the climate conditions that the rails are subjected to.

It can be seen from the list above that all of the variables, which are unknown for some or all test sites, have an effect on the contact stresses between the wheel and rail. This is important because rail degradation is as a result of the stresses arising from the contact between the wheel and rail. All of the above will affect these stresses to a greater or lesser extent. Liaison with the infrastructure managers may allow some of the variables to be filled in although this will be difficult for some of the older tests sites. Even so there are other variables that will remain unknown and are therefore part of the scatter and errors present in the derivation of rail degradation algorithms.

One major limitation of the data is that the vast majority is for curves; there is only limited data available for tangent track or transition curves. This is because the major rail degradation mechanisms are much more prevalent on curves which have therefore been of greatest interest. Transitions have only been monitored as an add-on to the monitoring of the associated curves, transitions contain more variables which make interpretation of results more difficult and therefore are not targeted separately for monitoring.

4.3 Combined Data

The calculations described in this section have been used to normalise the data for the different amounts of traffic that the monitored sites have encountered.

4.3.1 Wear Calculations

Rail profile is measured by a device such as a Greenwood Engineering MiniProf[13] and comparing either with a standard as rolled profile or with a previous measurement. It is characterised by several parameters with the common measures being vertical, 45°,horizontal and the worn area. The first two parameters have been used by Corus for all their measurements with the second two only being reported occasionally. VAS in contrast have used all four parameters but the values reported differ between each site due to the requirements of each project. To give a statistically meaningful analysis the measurements that have been used to study the wear of rail are 45° and vertical wear of the high rail.

One important aspect with the wear data is the effect of grinding, which if not taken into account will result in a much higher wear rate than the true wear. Similarly re-railing also has to be taken into account otherwise the wear would be too low. Therefore where grinding or re-railing has occurred the wear has been reset to zero from the date of the maintenance activity and the wear for subsequent inspections has been reported in terms of traffic from that date. All data has been normalised so the data from post grinding are included in the initial results.

As the Corus data contains many different measurements for each site, a method to calculate the wear rate is required; this has been carried out in two ways. One method is to use a linear regression analysis to calculate a line of best fit. There will be no wear with zero traffic therefore the intercept for the equation is prescribed as zero.

Figure 4 shows the results for Site 41, a curve with a radius of 3000m. The equations from regression analysis and measure of best fit (R^2) for the site are:

$$\text{45° Wear (mm)} = 0.03076 \times \text{Traffic (MGT)} \qquad R^2 = 0.967 \qquad (1)$$
$$\text{Vertical Wear (mm)} = 0.02166 \times \text{Traffic (MGT)} \qquad R^2 = 0.907 \qquad (2)$$

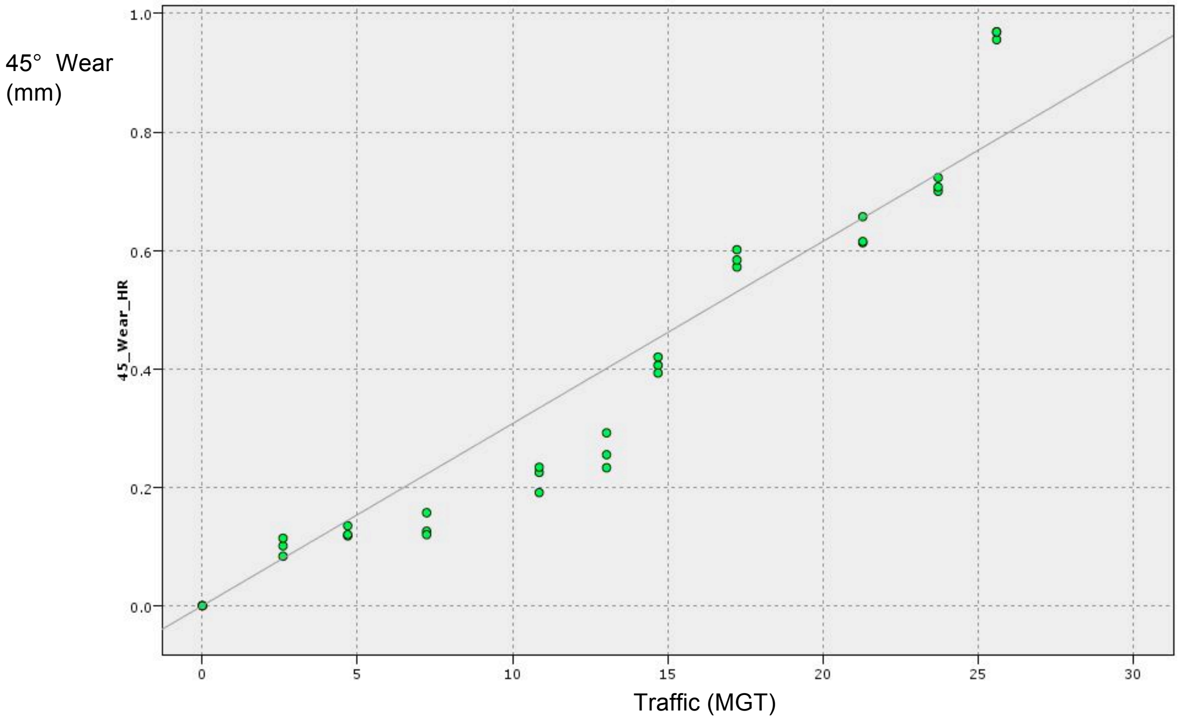


Figure 4: High Rail 45° Wear against traffic – Regression Analysis

Figure 4 demonstrates that wear is often not linear but alters with the evolution of the rail profile and therefore a second method of calculating wear using the largest recorded values has been carried out. All data points with greater than 75% of the maximum traffic for each site have been averaged, see Figure 5. The mean wear is then divided by the mean traffic to give a gradient of a straight line, with a constant of zero; this is equivalent to a wear rate.

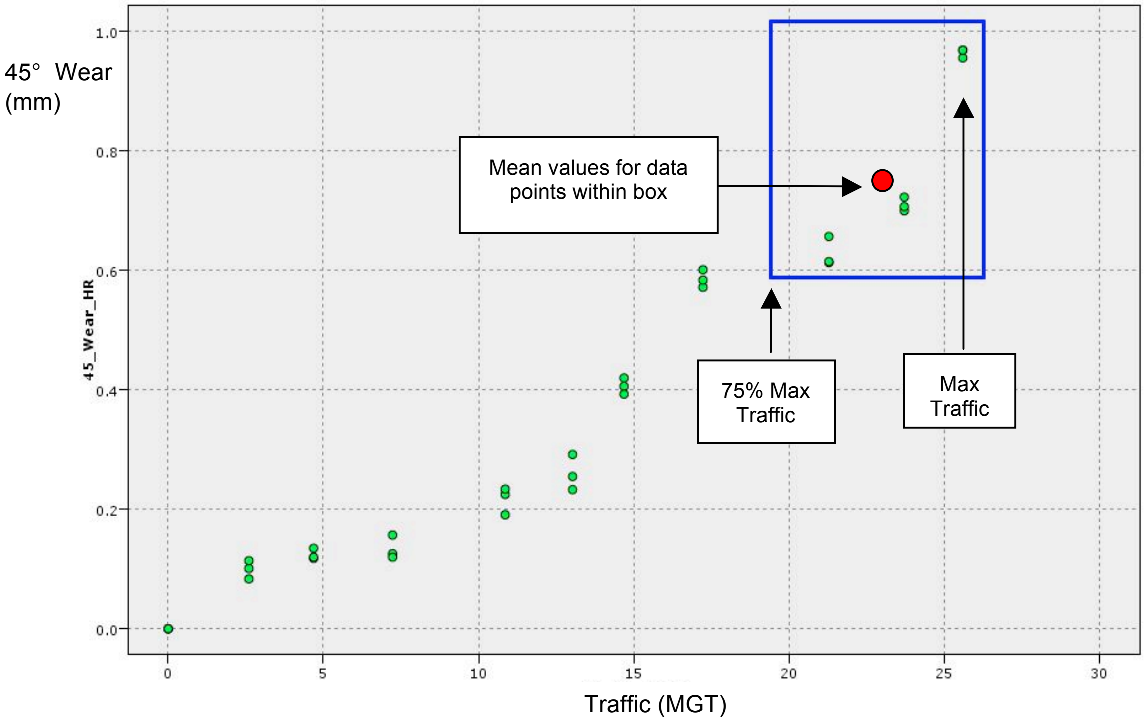


Figure 5: 45° Wear against traffic – Maximum Wear Rate Analysis

For the same site as above:

$$45° \text{ Wear (mm)} = 0.0326 \times \text{Traffic (MGT)} \quad (3)$$

$$\text{Vertical Wear (mm)} = 0.0249 \times \text{Traffic (MGT)} \quad (4)$$

As the wear is often non linear, Figure 4, the maximum rates have been used for analysis as these represent the worst case scenario in terms of effect of wear on rail life.

4.3.2 Rolling Contact Fatigue (RCF) Calculations

The data on rolling contact fatigue from site monitoring is much more sparse than wear data. The two parameters that have been measured are the surface crack length measured using a ruler and the crack depth which has been measured by either eddy current or alternating current potential drop (ACPD) equipment. The data also allows the calculation of the interval from installation of the rail until the cracks become visible(approximately 1-3mm in length), this is known as the period to initiation. To allow some quantification of the tendency for sites to produce rolling contact fatigue, the following calculations on the growth of cracks with traffic have been carried out for both surface crack length and crack depth.

Several different measurements of crack growth are possible depending on the data available; the equations given below are for surface crack length with similar equations used for crack depth. To calculate the growth of cracks during the monitored period equation 5 has been used for all sites.

$$\frac{\text{Maximum Crack Length (or Depth)} - \text{Minimum Crack Length (or Depth)}}{\text{Maximum Traffic}} \quad (5)$$

where maximum traffic is calculated from the number of days from the first site date to the final inspection date multiplied by the daily traffic. This is the parameter that has been used for understanding the crack growth for different rail grades. If grinding has been conducted during the monitoring period then growth rates are calculated before and after with an average of the growth rate reported.

It is also possible to measure the rate of crack growth since the rail was installed using equation 6.

$$\frac{\text{Maximum Crack Length (or Depth)}}{\text{Total Traffic}} \quad (6)$$

where total traffic is the number of days since installation to the date of the maximum crack length multiplied by the daily traffic in tonnes. For the voestalpine data in the vast majority of cases the results are identical to equation 5, the only difference being in cases where the rails have been ground.
The calculated growth rate since installation includes the period required for crack initiation (PTI). It is therefore not a true growth rate but a measure of RCF damage. This parameter gives a rate for the growth of RCF from when the rail installed until the crack has grown to the length observed it could also be used to predict when maintenance intervention becomes necessary. Figure 6 demonstrates how the period to initiation affects the crack growth rates. The period to initiation is also an important parameter in terms of characterising RCF life as it allows an estimation of the vulnerability of rail to initiation of RCF.

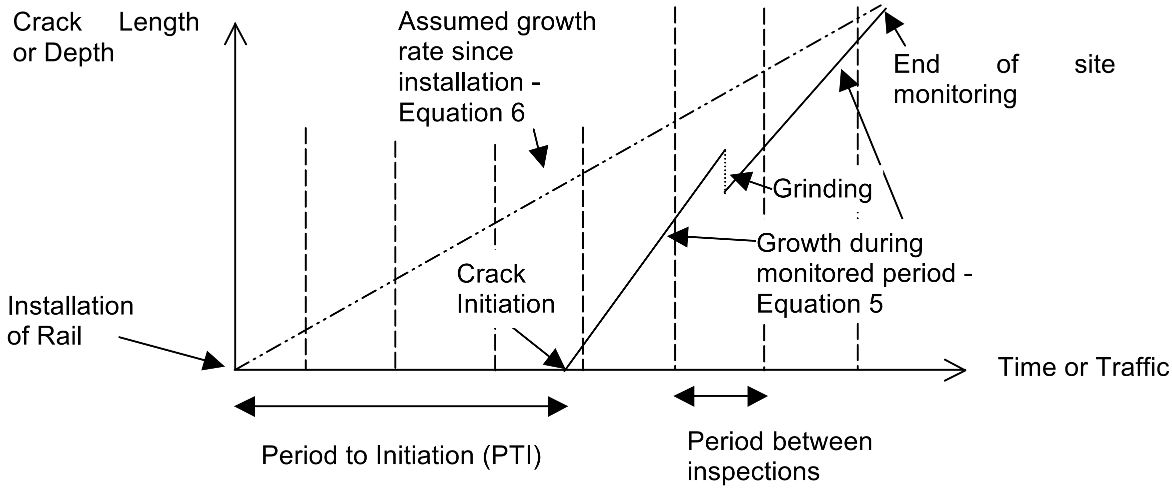


Figure 6: Schematic of inspection cycle superimposed on RCF crack development

5. Available Rail Grades

The rail steels that are widely available and used throughout Europe are specified in the standard EN13674-1: Vignole railway rails 46 kg/m and above. The current version was issued in 2003 with an amendment in 2007 of the 60E2 profile. A new draft version (prEN13674-1:2009) has recently been produced and includes two further rail steels that are currently in commercial use in Europe. All rails within the European specification are conventional pearlitic grades, Table 1.

Bainitic rail steels are also available and have been used in recent years for trials. At present these grades are starting to be introduced to the railways on a commercial basis specifically to combat rolling contact fatigue. Alternative hypereutectoid rail steels, not covered by R400HT are also currently undergoing trials in both the heat treated and as rolled condition. These aim to combat both wear, RCF and plastic deformation.

<table>
<tr><th rowspan="2">Rail Grade</th><th rowspan="2">Running Surface Hardness Range (HB)</th><th rowspan="2">Min. Ultimate Tensile Strength (MPa)</th><th colspan="2">Min. Fracture Toughness K_{IC} (MPa.m$^{1/2}$)</th><th rowspan="2">Description</th><th rowspan="2">Chemistry</th><th rowspan="2">Branding lines</th></tr>
<tr><th>Single</th><th>Mean</th></tr>
<tr><td>R200</td><td>200-240</td><td>680</td><td>30</td><td>35</td><td>C-Mn</td><td></td><td>None</td></tr>
<tr><td>R220</td><td>220-260</td><td>770</td><td>30</td><td>35</td><td>C-Mn</td><td></td><td></td></tr>
<tr><td>R260</td><td>260-300</td><td>880</td><td>26</td><td>29</td><td>C-Mn</td><td></td><td></td></tr>
<tr><td>R260Mn</td><td>260-300</td><td>880</td><td>26</td><td>29</td><td>C-Mn</td><td>R260 + 1.5%Mn</td><td></td></tr>
<tr><td>R320Cr</td><td>320-360</td><td>1080</td><td>24</td><td>26</td><td>Alloy - 1%Cr</td><td></td><td></td></tr>
<tr><td>R350HT</td><td>350-390</td><td>1175</td><td>30</td><td>32</td><td>C-Mn Heat Treated</td><td>R260 + up to 0.15%Cr</td><td></td></tr>
<tr><td>R350LHT</td><td>350-390</td><td>1175</td><td rowspan="3">26</td><td rowspan="3">29</td><td>Low Alloy Heat Treated</td><td>R260 + 0.30%Cr</td><td></td></tr>
<tr><td>R370CrHT*</td><td>370-410</td><td>1280</td><td>Alloy Heat Treated</td><td>R260 + 0.50%Cr</td><td></td></tr>
<tr><td>R400HT*</td><td>400-440</td><td>1280</td><td>Hypereutectoid Heat Treated</td><td>0.95%C +0.30%Cr</td><td></td></tr>
<tr><td colspan="8">Table 1: Pearlitic rail steels available in Europe, from EN13674-1:2003 (*prEN13674-1:2009)</td></tr>
</table>

6. Wear

The calculated wear rates (in mm/100MGT) as described in section 4 have been used to understand the relation between wear of different rail grades and the track geometry.

Vertical wear data for the high rail in curves are plotted against track radius in Figure 7; the shapes indicate different rail grades while the shapes indicate track type. To allow presentation of graphs the results for tangent(straight) tracks are plotted at 6000m. The results indicate that vertical wear is similar for all track geometry with some evidence of greater wear for the tighter radius curves, but there is considerable spread in the results. The spread is a result of the many factors listed in section 4.2 that have not been monitored or were unknown for the different sites.

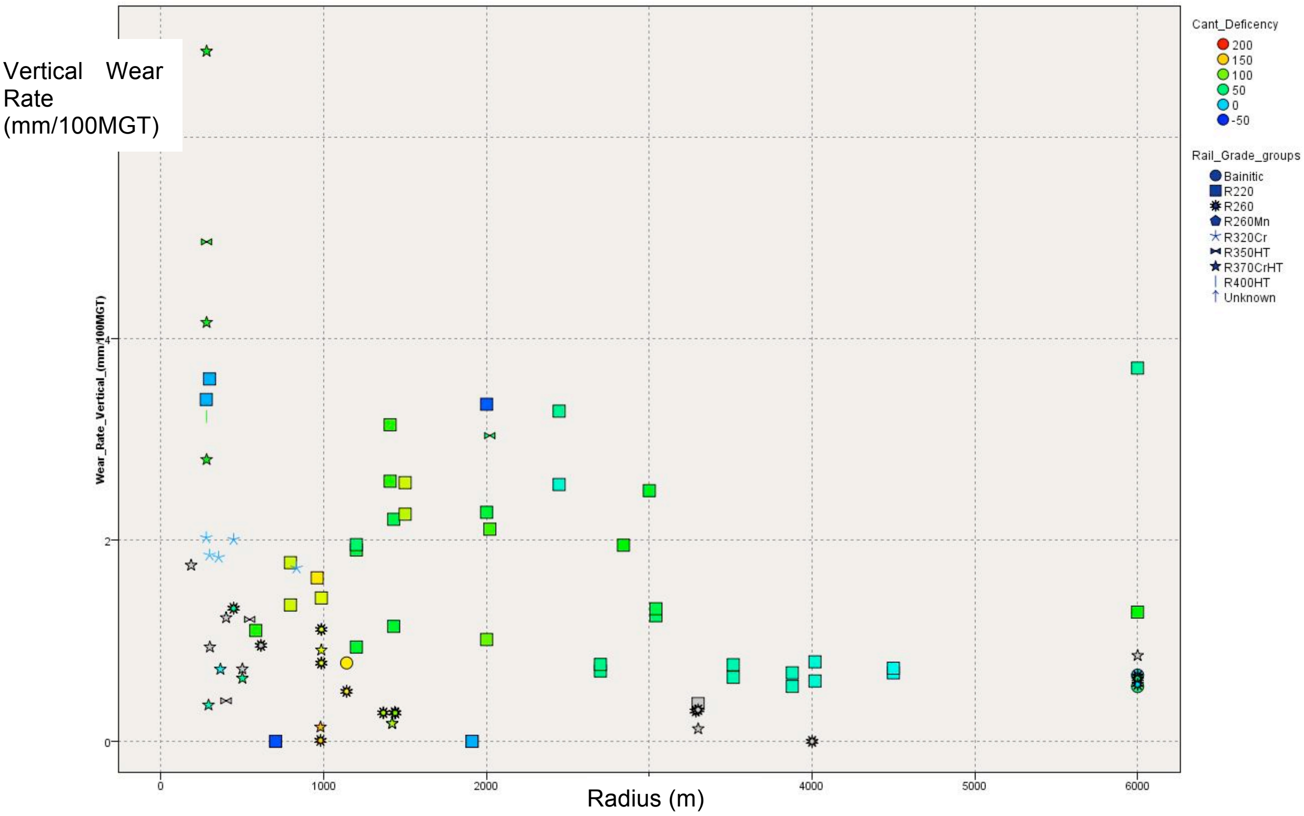


Figure 7: Vertical wear rate against radius for different rail grades

Figure 8 shows a similar plot for the 45° wear of the high rail also demonstrating a similar trend in results as the vertical wear. The colours in this plot indicate the cant deficiency, h_d, calculated using equation 7(after Esveld[14]):

$$h_d = h_{id} - h = \frac{11.8V_{max}^2}{R} - h \qquad (7)$$

where

h_{id}	=	Ideal cant(mm)
V_{max}	=	Line speed (kmh^{-1})
R	=	Radius
h	=	Actual cant

The results show that there is little correlation between wear and cant deficiency for these data. The most probable reason for this is the vehicle speeds used in the calculation. Cant deficiency has been calculated from the maximum permitted speed for each section of track. In many cases the train speed will be lower than this, especially with mixed traffic railways where freight trains are running alongside passenger trains. The actual speed of trains at each test site is largely unknown.

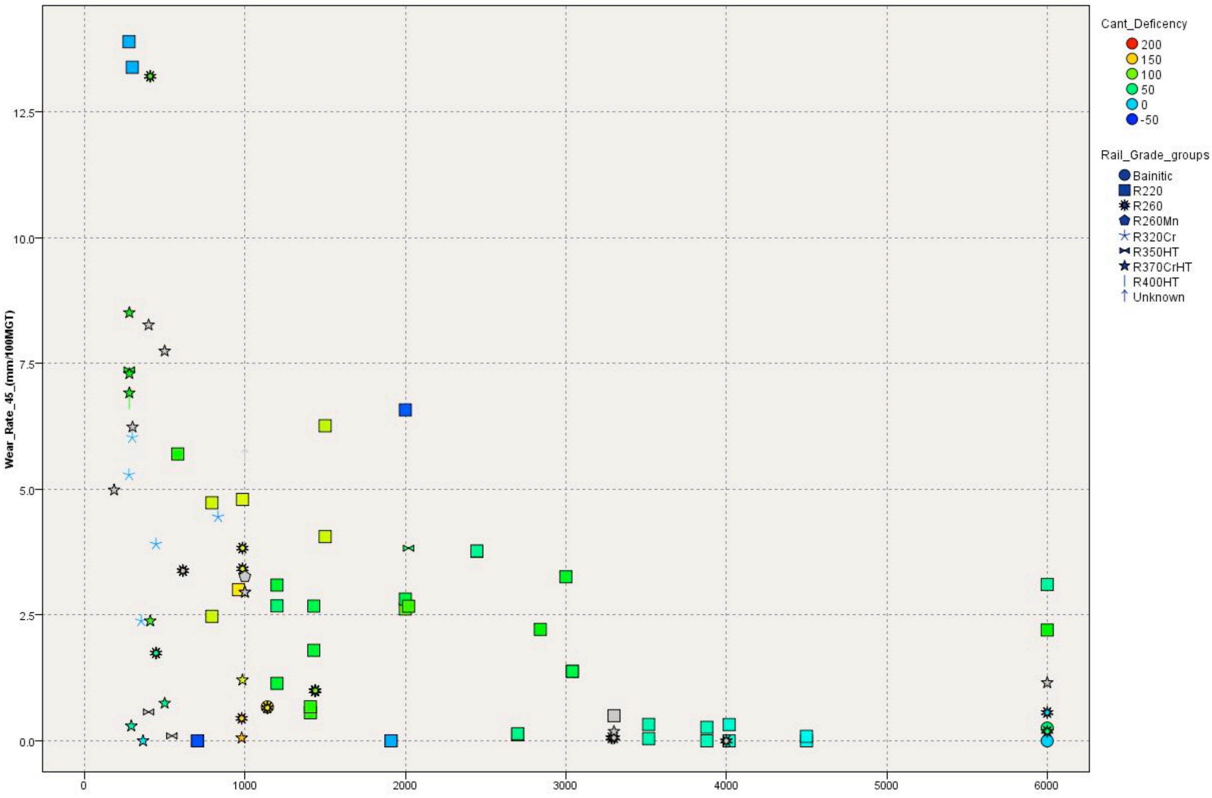


Figure 8: 45° Wear rate for different rail grades

The reason for the spread in results for wear (the same arguments apply for RCF) is the fundamental nature of the railway. Railway tracks are long linear assets that encounter widely different conditions that are difficult, if not impossible, to measure and record for even a small section of track. Previous examples of the observed spread in the performance of rail have shown similar results, after the Hatfield accident in 2000, investigations demonstrated that of the curves deemed most likely to have RCF only 35% actually had[15].

The parameters given in section 4.2 are all responsible for the variability in the monitored degradation. Rail degradation results from the transfer of stresses from the vehicles through the contact patch to the rail. Anything that affects the contact stresses (bending, longitudinal and residual stresses also have an effect on the later stages of RCF development) effects the degradation of the rail[16].

In view of the variability in results, a statistical analysis has been carried out to understand rail degradation. Rail grade R220 has been used for this analysis since this is the grade for which there is the greatest amount of data (all rail grades used are according to the provisional European standard prEN13674-1:2009[17]). The data has been averaged over the following radius ranges:

- Radius < 300m
- 300m ≤ radius < 700m
- 700m ≤ radius < 1000m
- 1000m ≤ radius < 1500m
- 1500m ≤ radius < 3000m
- 3000m ≤ radius < 6000m
- Radius ≥ 6000m ≡ Tangent

The minimum, maximum and mean values for each radius range is plotted in Figures 9 and 10 for vertical and 45° wear for grade R220. Equations have then been fitted to the average values using regression analysis with the relationship with the highest correlation being used; for wear this is a power law relationship. The results for 45° wear have a much higher regression fit (R^2) value than those for vertical wear. These relationships therefore allow the prediction of wear as a function of curve radii. The variability in the results used for deriving the algorithms means that the prediction of wear for any particular curve will only be an indication of the wear expected and will not be an exact prediction.

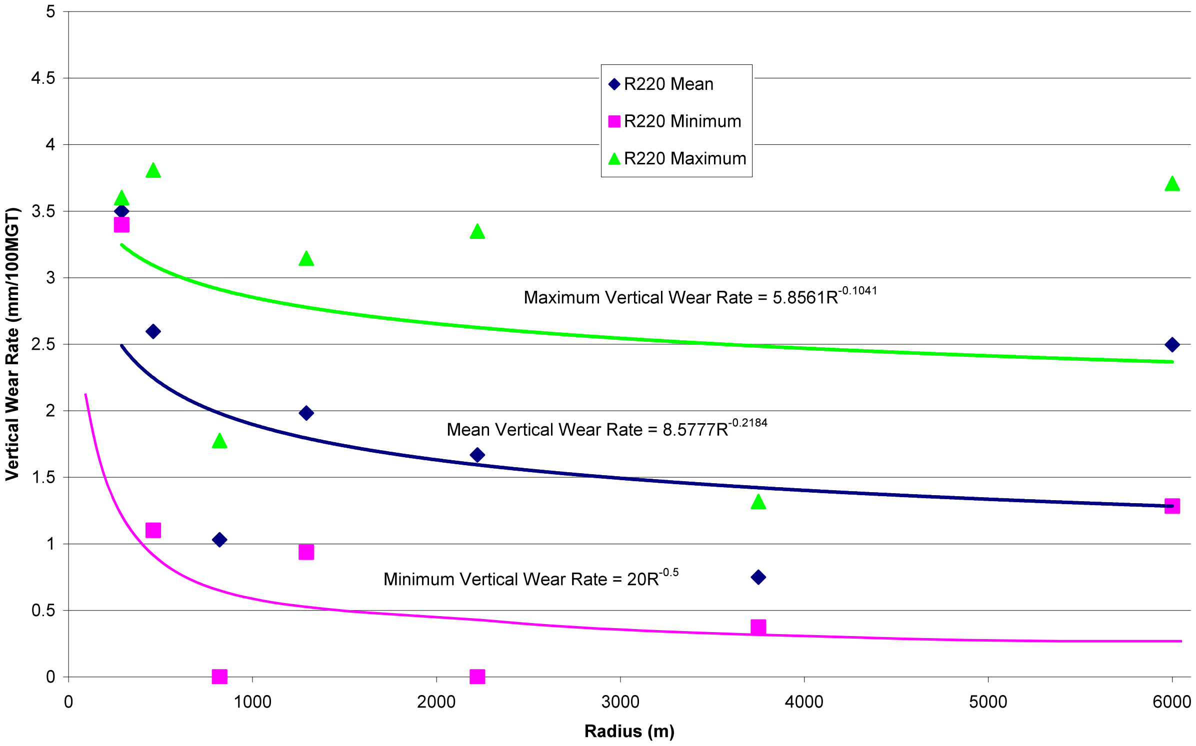


Figure 9: Vertical Wear Rate of Grade R220

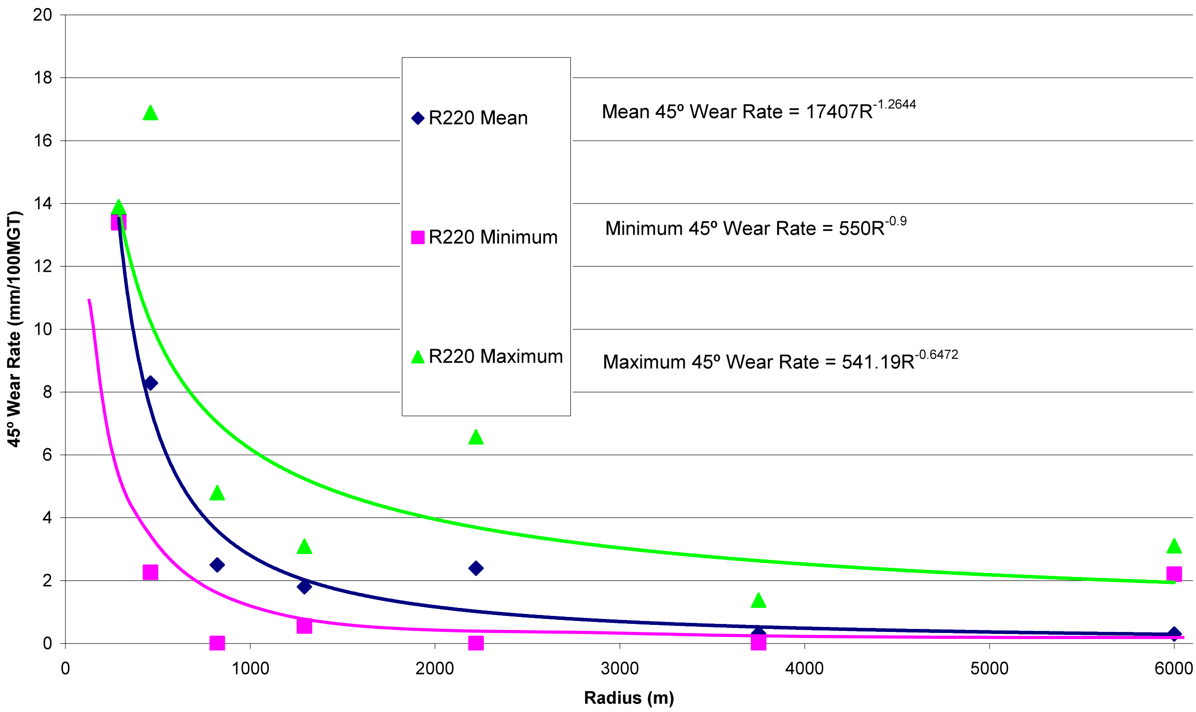


Figure 10: 45° Wear Rate of grade R220

The idea behind the degradation algorithms is to be able to understand the performance of different rail grades in different track locations. To understand how different rail grades perform the mean values of wear rate for the different rail grades have been plotted in Figures 11 and 12. Although the data for all rail grades has been plotted in these graphs, there is insufficient data at larger radius curves to be able to carry out regression analysis for R350HT and R320Cr and therefore the algorithms have been derived only for R220, R260 and R370CrHT. The number of sites with R350HT and R320Cr are limited and therefore the values plotted are averaged over a limited number of sites. The data therefore exhibit greater spread in results as can be seen in the extremes in 45° wear for R350HT.

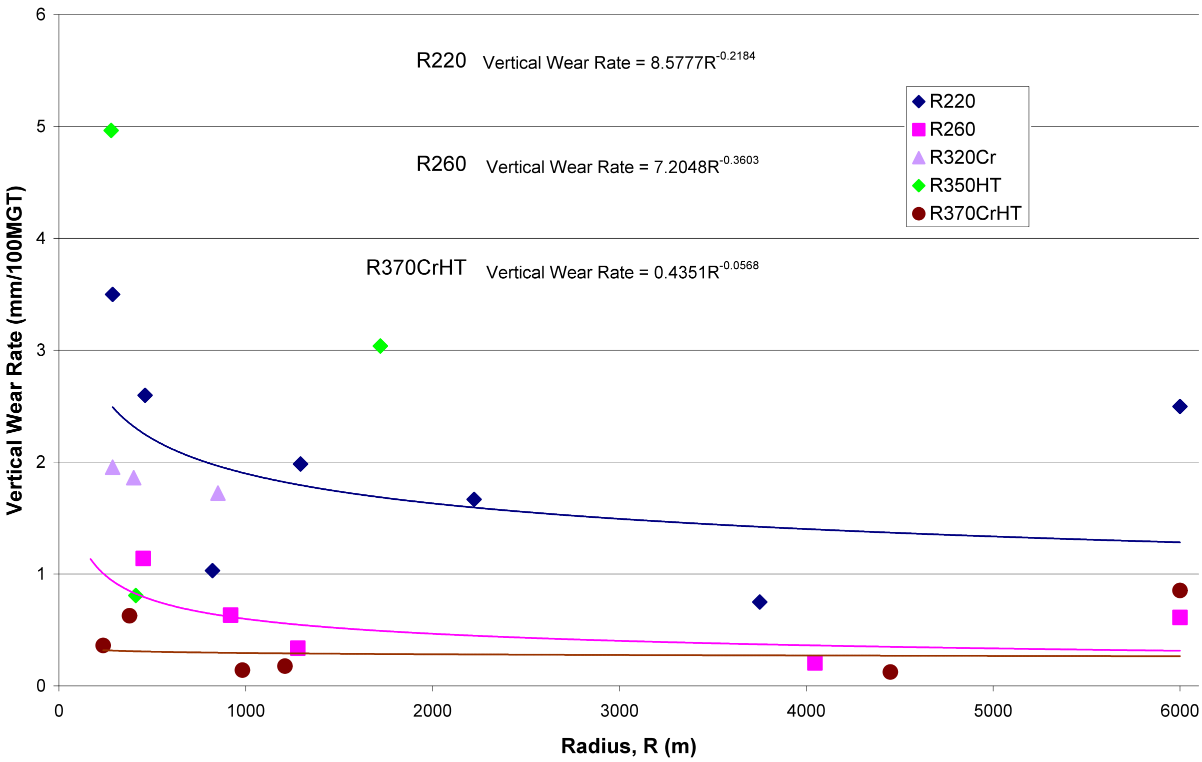


Figure 11: Mean vertical wear rate for all rail grades

Figures 9 and 11 show that there is only a slight trend in the vertical wear with track radius and the spread in results mean that vertical wear is largely independent of track curvature. This is in accordance with what has been reported in the past for both the British[18] and Dutch[14] railway systems. There is a dependence of wear with rail grade, with increasing rail hardness serving to reduce rail wear. The rates for vertical wear in the past were similar to the average values and well within the spread of results reported here. The wear rates have been measured to be about 1mm/100MGT for rail grades similar to R260[14] and 2mm/100MGT for those equivalent to R220[18].

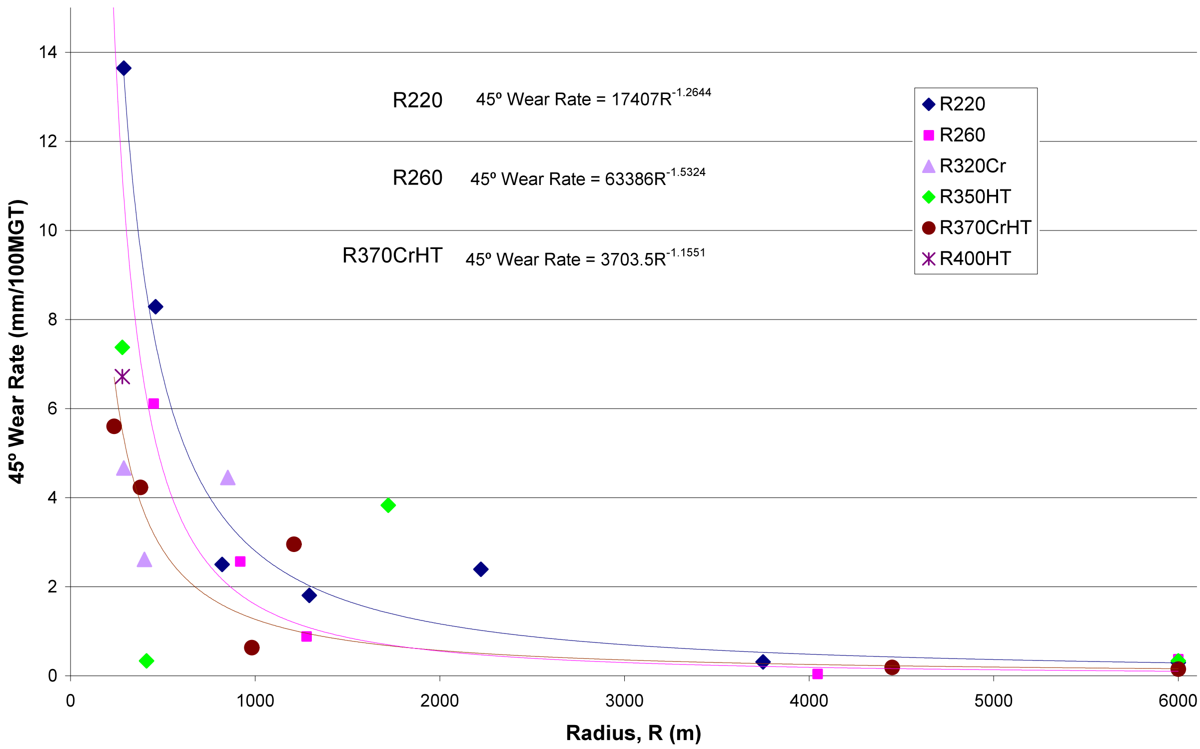


Figure 12: Mean 45° wear rate for all rail grades

In contrast to vertical wear, 45° wear is much more dependent on track radius with higher wear occurring on tighter radius curves, Figures 10 and 12. (The data for horizontal wear is lacking for the majority of sites so the algorithms have only been calculated using the 45° wear data; although this is not side wear it is a function of both vertical and side wear and is much more dependent on the latter). This is a well known fact and is the reason why very tight radius curves are provided with gauge face lubricators. This is also why the UIC publication on rail grade selection targets the use of premium grade rail steels to curves of less than 700m radius[19]. The effect of rail grade is a reduction in wear in inverse proportion to the increasing hardness with the effect being more pronounced for the tighter radius curves. An exception is R320Cr which has similar 45° wear to R370CrHT even though it has a much lower hardness. This corresponds to the experience of some IM's that R320Cr has better wear performance the problems of welding this grade means that it is currently rarely used. One of the problems with the 45° wear data is the effect of gauge face lubricators. These have a major impact on the wear behaviour of rails, and in some cases have been reported to be more effective in reducing wear than by changing to harder rail steels[20].

Comparison with literature results for a Canadian heavy haul line with axle loads of 33tons, the 45° wear for a curve radius of 220m without lubrication was 5.5-6.5mm/100MGT for grades similar to R320Cr and 3-4 mm/100MGT for heat treated grades[21]. In spite of the difference in the conditions between mixed traffic and heavy haul railways the results are similar.

7. Rolling Contact Fatigue - Head Checks

Analysis of rolling contact fatigue (RCF) (head checks) degradation data has been carried out in several ways in terms of the growth of cracks and has been reported in a similar manner to wear. The growth of RCF cracks has been characterised in two ways, crack depth growth rate and surface crack length growth rate as explained in section 4.3.2. Units for both are millimetres of growth per 100 million gross tonnes of traffic. Crack depth and surface crack length growth rates are plotted in Figures 13 and 14 respectively. The crack depth has been measured using either eddy current or alternating current potential drop (ACPD) equipment, both of which report the penetrated length of cracks and not the actual depth of the crack below the surface.

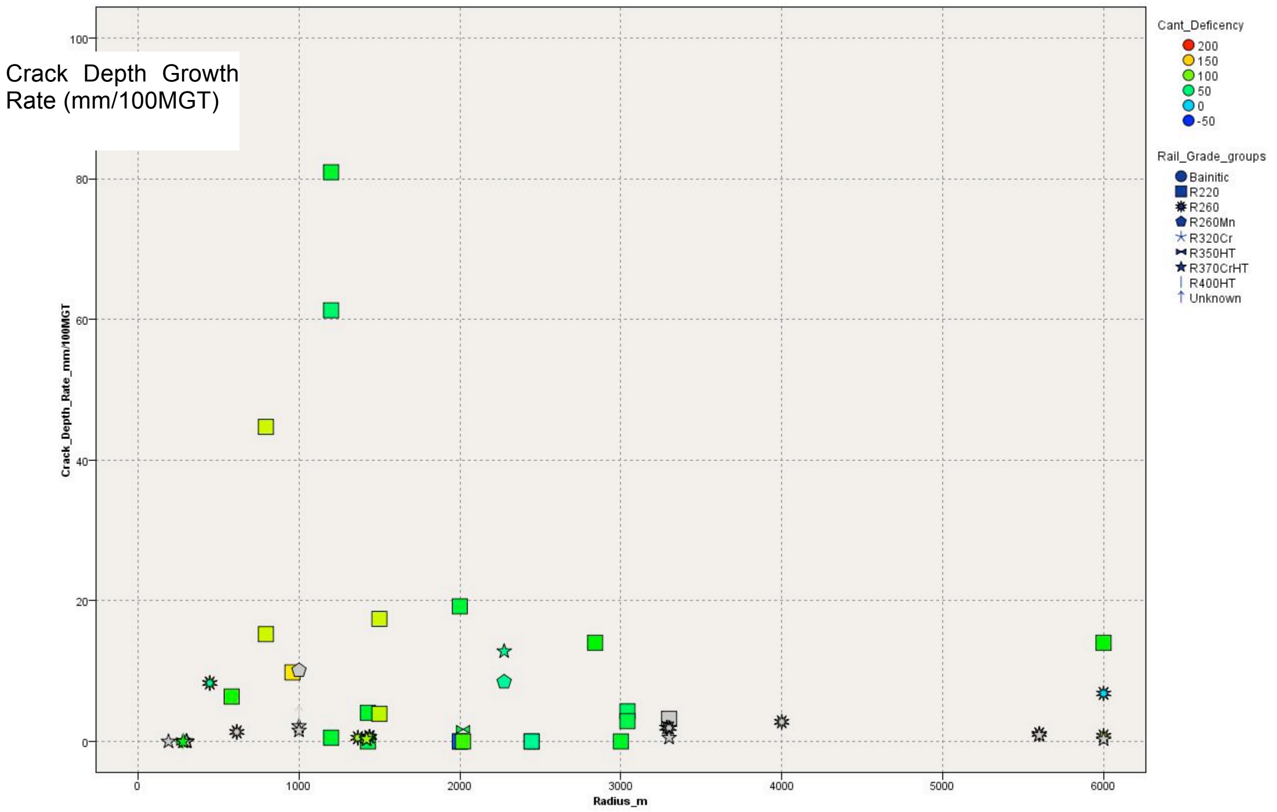


Figure 13: Crack depth growth rate

The results for both crack depth and surface crack length demonstrate similar trends although a difference in magnitude and in the variability of results. Both magnitude and variability are greater for crack length than depth. It can be seen from these graphs that the crack growth rates are greatest for curves between 700 and 3000m radii. There is a lack of data for curves greater than 3500m and the data available for tangent track have often been taken from areas where track features, such as switches and crossings, are present and have caused the RCF problem.

In terms of rail grades, the majority of data available is for grade R220 and equivalent rails with rather limited data for the premium grade rail steels. The most significant area of limited information is for grade R260 rails. The limited data combined with the spread in results make interpretation difficult, but there is sufficient evidence to conclude that where premium grade rail steels have been used in curves susceptible to RCF they demonstrate better resistance to growth than R220 or R260 grades. This becomes clearer when comparing data for the different grades from the same test sites, Figure 15.

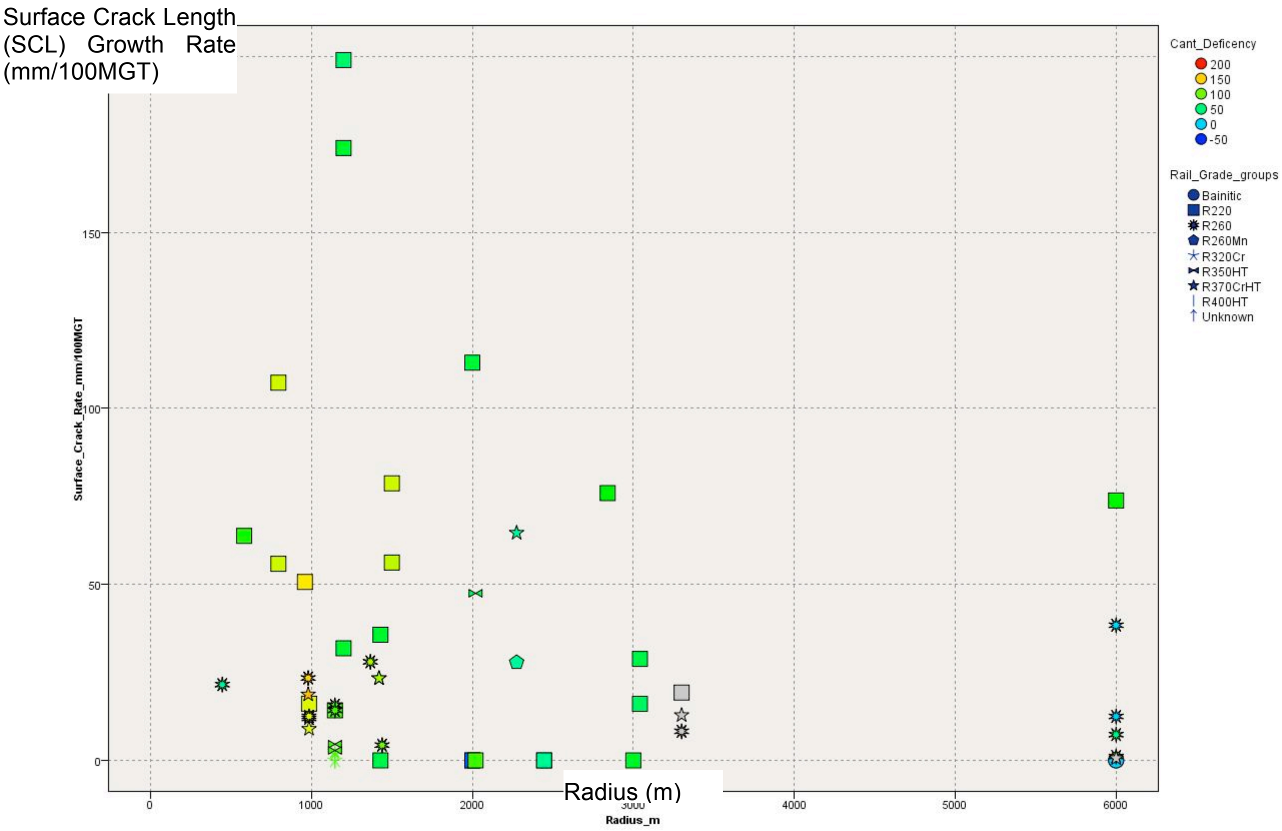


Figure 14: Surface crack length growth rate

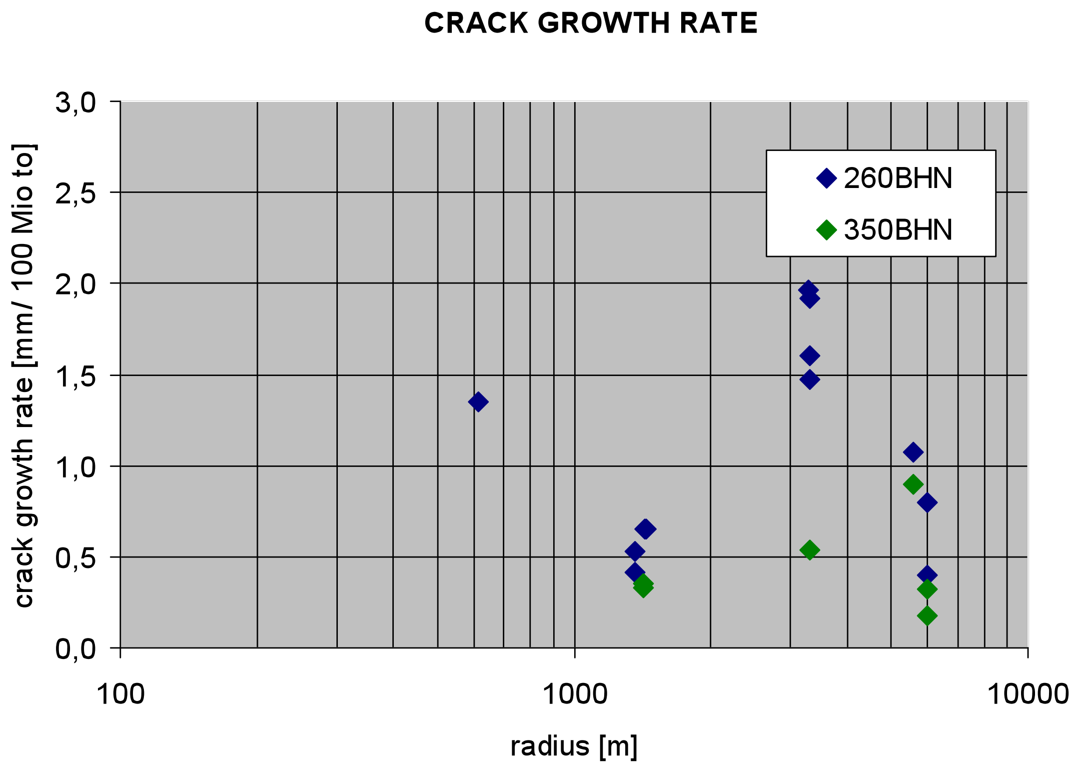


Figure 15: Comparison of RCF crack growth of grade R260 and R350HT

By grouping the results together for curves of similar radius using the same ranges as those for wear, algorithms to describe crack growth have been derived. These are plotted in Figures 16 and 17 for grade R220 to demonstrate the spread in results by plotting maximum, minimum and mean values for both crack depth and surface crack length growth rates. The lines have been fitted to the data with the form of the curve chosen to give the best correlation .

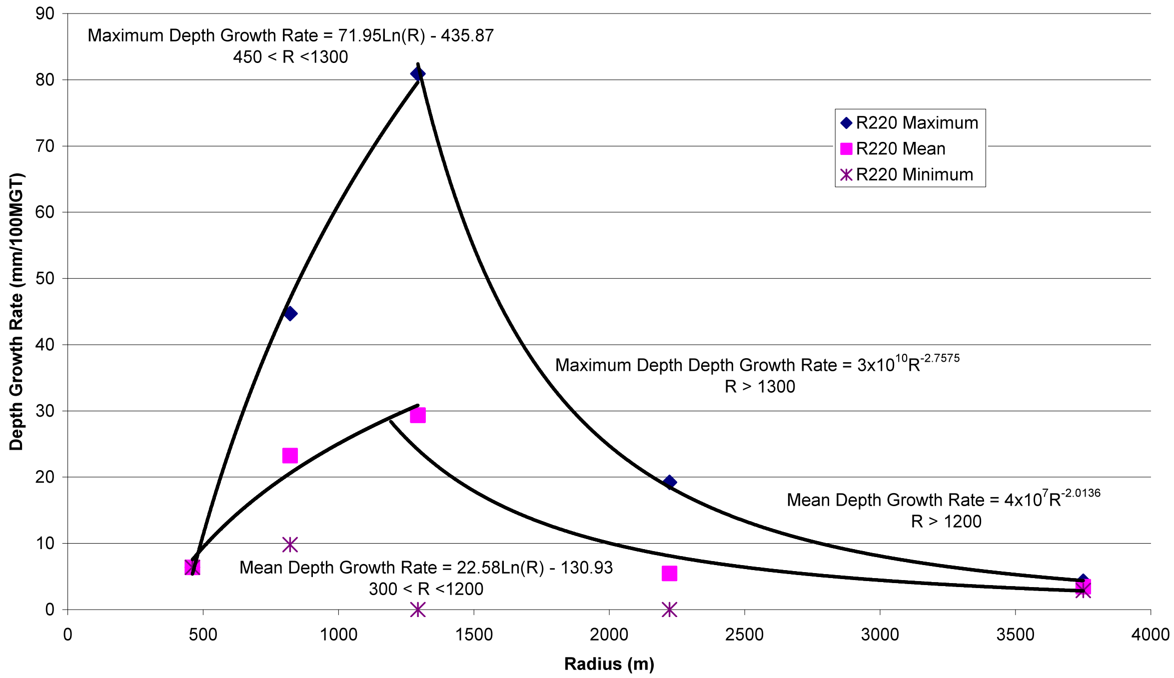


Figure 16: Crack depth growth rate for grade R220

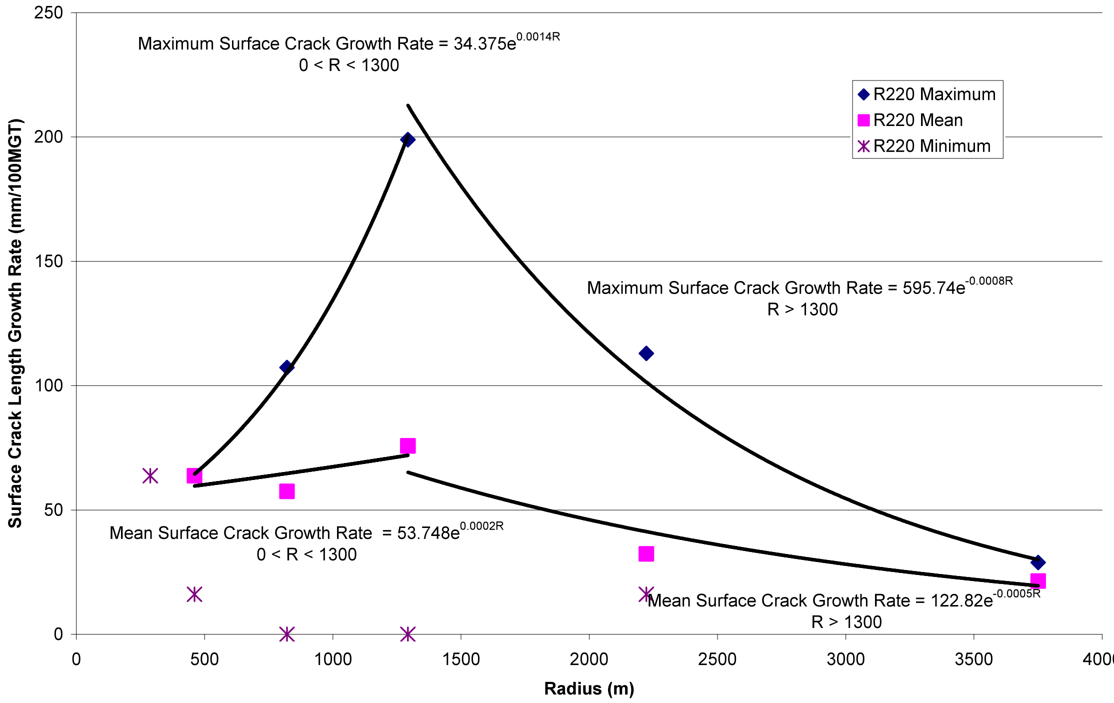


Figure 17: Surface crack growth rates for grade R220

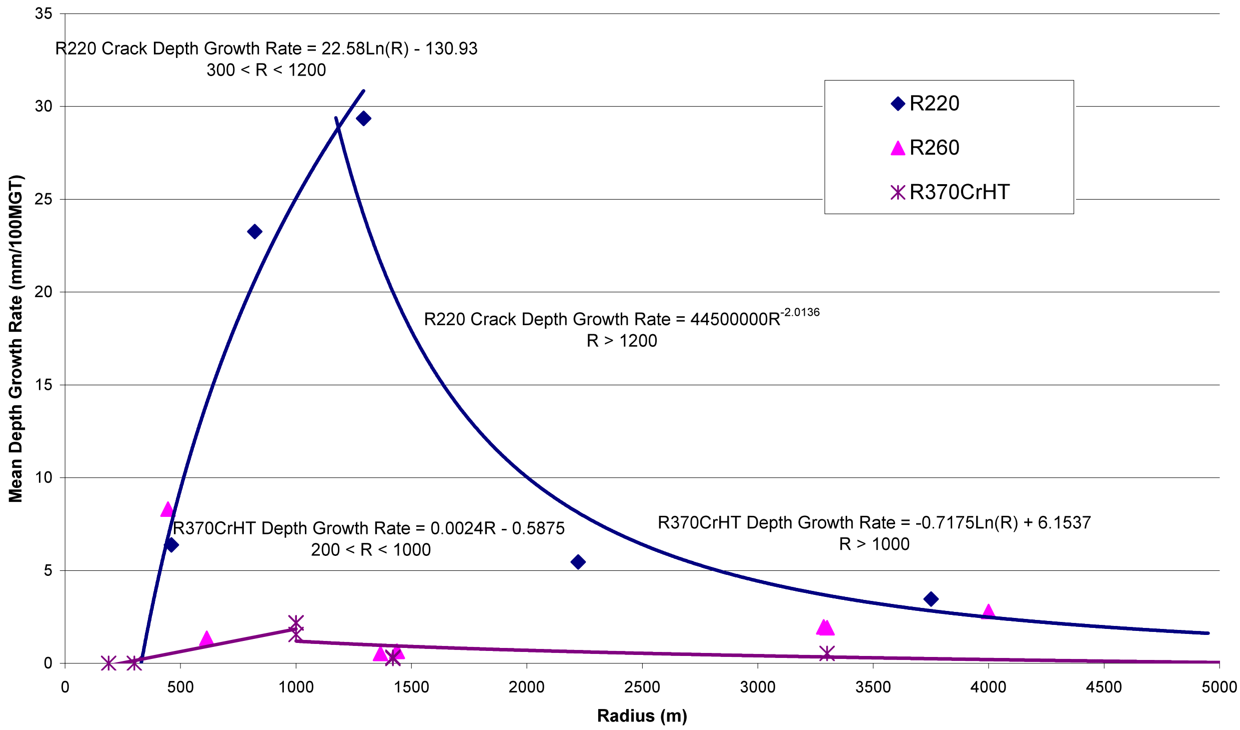


Figure 18: Mean crack depth growth rates for all rail grades

Figure 18 highlights the comparison between rail grades using the mean crack depth growth rates. Only the data for grade R220 has been grouped together, all available data for R260 and R370CrHT are plotted. Equations 8 and 9 give the crack depth growth rates (CDGR) in mm/100MGT for grades R220 and R370CrHT as a function of radius (R) in metres:

R220	CDGR = 0	$0 < R \leq 300$	(8)
	CDGR = 22.58 ln(R) – 130.93	$300 < R \leq 1200$	
	CDGR = 44500000$R^{-2.0136}$	$R > 1200$	
R370CrHT	CDGR = 0.002R – 0.587	$200 < R \leq 1000$	(9)
	CDGR = – 0.72 ln(R) + 6.15	$1000 \leq R < 5000$	
	CDGR = 0 $R > 5000$		

It should be emphasised that crack growth has been measured from the rail surface observed on the day of inspection and is therefore not a true crack growth rate.

As wear and RCF are in competition the observed crack growth rates are actually the true growth rates minus the amount of metal lost by wear. Figure 19 plots both crack growth rates and 45° wear rates for both R220 and R370CrHT rails. The presence of observed RCF cracks means that the natural wear rate is insufficient to remove them and therefore the only option is to control crack propagation by grinding. The results for R220 grade indicate that the difference between the natural wear and the crack growth rates mean that it will be difficult to control RCF cracks with grinding once that have reached their maximum rate of growth. The only way to control the cracks in R220 will be to intervene at an earlier stage, when the crack growth rates are lower[16]. Unfortunately this stage in the case of grade R220 rail will probably be before the cracks become visible. The higher wear for curves of less than 300m results in the cracks being removed without grinding and effectively provides an RCF free rail, in which the life determining factor will be wear. The lower crack growth rates in premium grade rails mean that it is much easier to control by grinding even at the maximum crack growth rates as less material removal is required.

Comparing wear and RCF growth rates from observed cracks demonstrates the similarities with the predictions from the contact patch energy ($T\gamma$) model [23, 24]. The curve radii where RCF dominates between 700 and 2000m are the same as those predicted from the $T\gamma$ model for intercity trains with curves of tighter radius being dominated by wear. One of the key factors found by the $T\gamma$ model to be responsible for RCF occurring on different radius curves is primary yaw stiffness of the vehicles. The different vehicles, with different primary yaw stiffness, running over the test sites mean that the observed results demonstrate a large spread in curve radii where RCF is the dominant degradation mechanism.

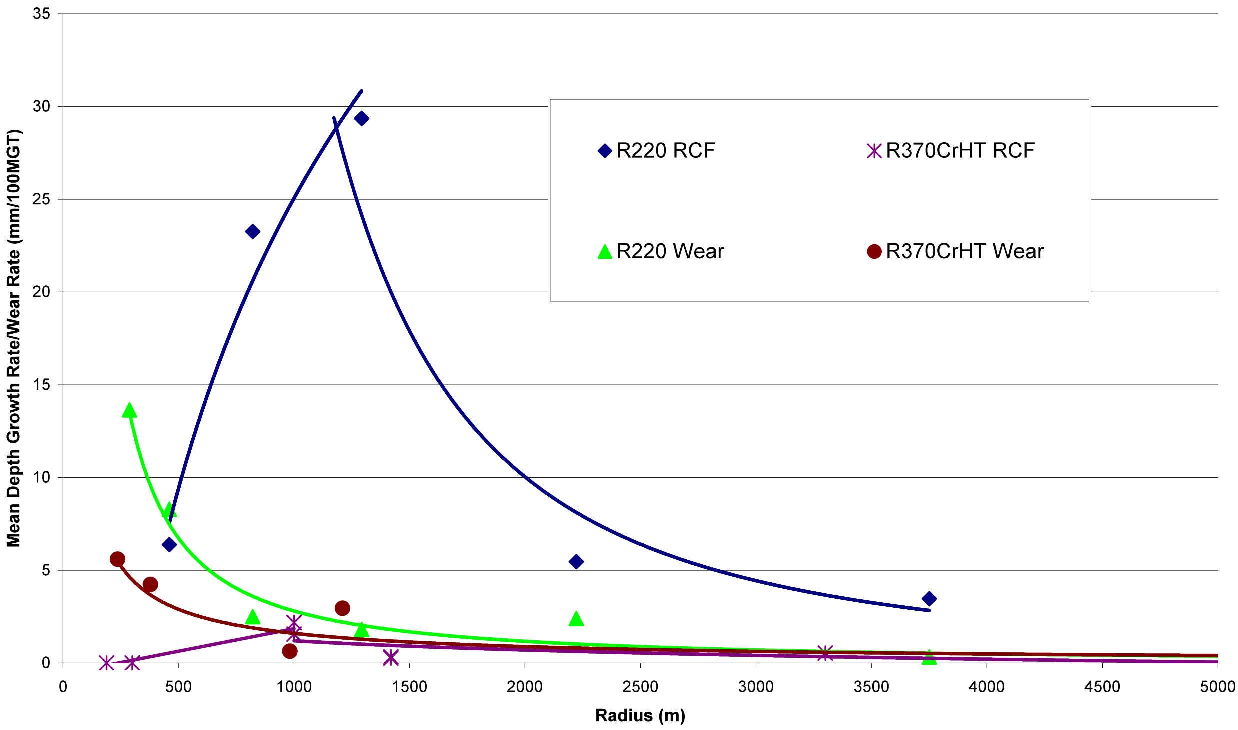


Figure 19: Interaction of RCF and Wear

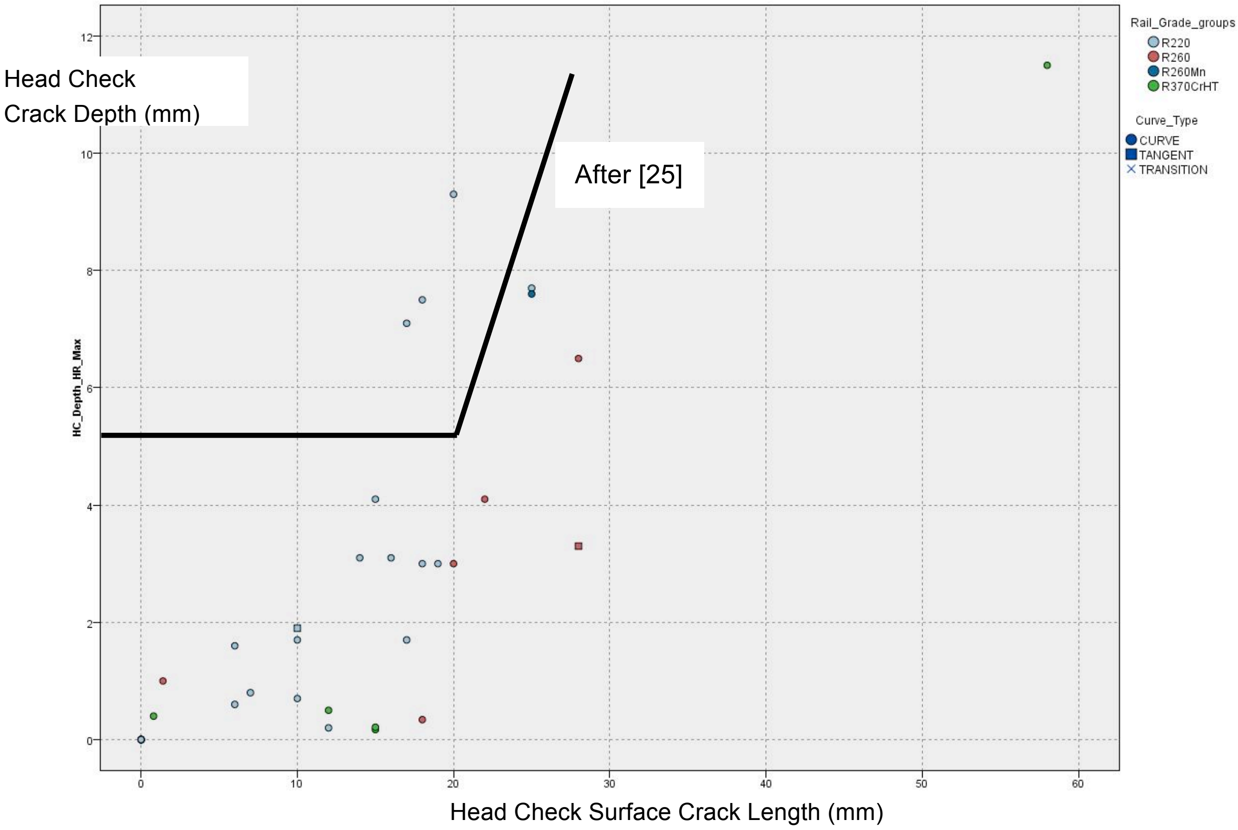


Figure 20: Crack depth against surface crack length

Plotting the observed crack depths against the observed surface crack length, Figure 20 allows an understanding of the behaviour of crack growth for different rail grades. In the case of grade R220 it can be seen that for observed surface crack lengths of less than 17mm the crack depth is less than 5mm, but above 17mm the crack length increase up to a maximum of 10mm. The reason for this is the mechanism by which RCF cracks grow, illustrated in Figure 21, whereby cracks initially grow at a shallow angle to the surface after propagating to a certain length, observed experimentally to be approximately 5mm, after which the cracks branch and turn down into the rail.

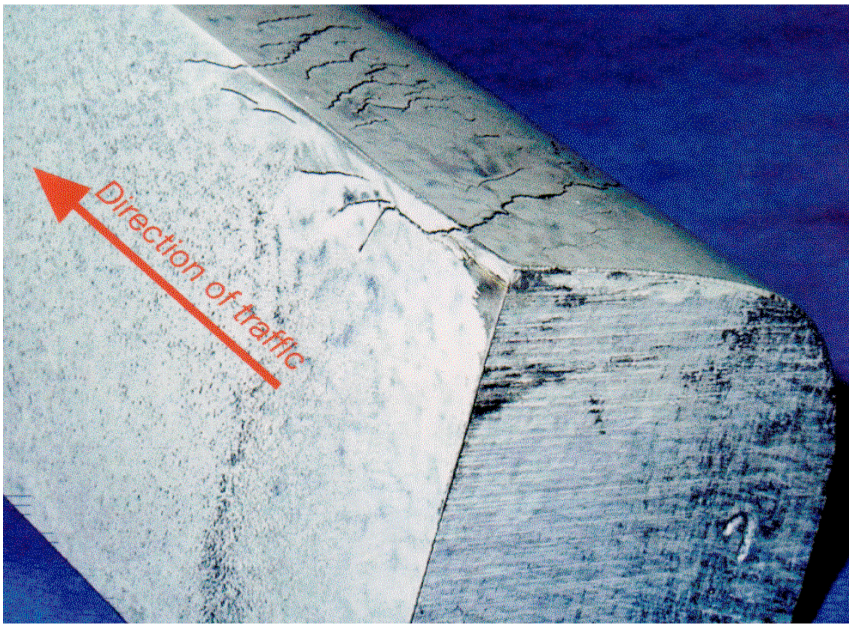


Figure 21: RCF crack growth[25]

The 17mm surface crack length appears to be the point at which cracks turn down into the rail. Previous investigations involving sectioning samples of rails equivalent to R220, removed from service, demonstrated that the turn down point was a surface crack length approximately 20mm [25]. The reasons for the difference are due to the measurement techniques used; the previous work reported maximum depths below the surface measured by sectioning of samples. In contrast the crack depths reported here are measured by ACPD or eddy current techniques, both of which measure the penetrated surface crack lengths, Figure 22. For cracks orientated at 90° to the rail surface both measurements are the same but for cracks at a shallow angle the actual depth will be much shallower than the penetrated length, although the difference would be expected to be greater than that observed. An additional cause of the difference is likely to be from the accuracy of the measuring equipment and the difficulties associated with ensuring that measurements are made at the maximum crack depth

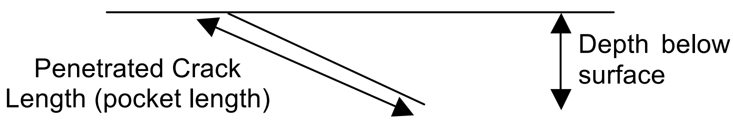


Figure 22: Difference between crack depth and penetrated crack length

The most important point to be drawn from Figure 20 is the difference between the ratios of crack length to crack depth for R220 and R260. The surface crack lengths at which crack depths become greater than 5mm are between 25 and 30mm for R260 compared to 17mm for R220. Thus the results show that there is some evidence to support the theory that harder rail steels, having the same surface crack length as softer ones, have lower crack depths. One railway network in Europe uses this theory to prioritise their grinding strategy[12]. The very limited results for R370CrHT also provide further evidence for this.

As well as detailed information on the growth of RCF cracks; track monitoring has also revealed information on the initiation of RCF cracks. This is reported in Figure 23 as the period to initiation and is the amount of traffic carried before RCF cracks were observed. Distinction has been made between new rail and ground rail as well as between the different rail steels. The results are in accordance with the crack growth rate measurements in that the areas most susceptible to RCF, i.e. have the lowest period to initiation, are curves with radii between 700 and 3000m and the least susceptible is tangent track. Interpretation is difficult because of the variability in results but in general there is some trend of higher periods to initiation for harder rail steels although there are only limited results for curves at 800 and 2000m. There is also some evidence to suggest that RCF initiates earlier on track that has been ground in comparison to that which has not.

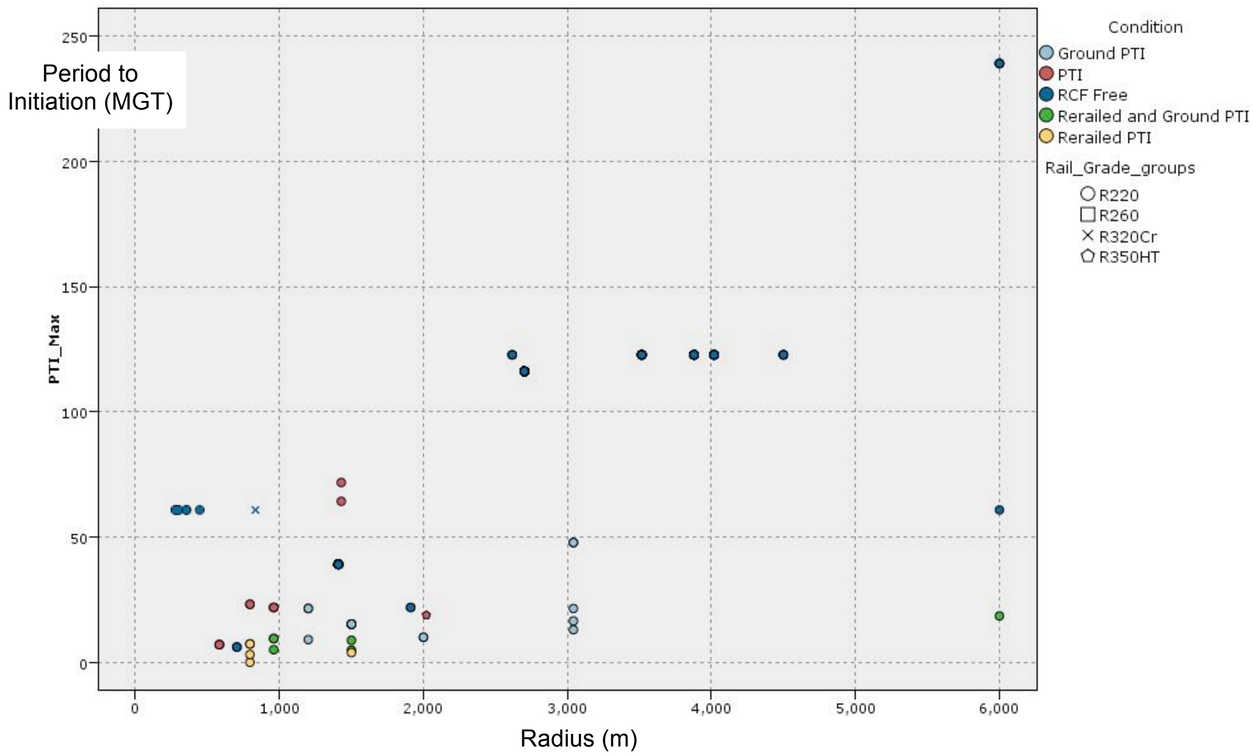


Figure 23: Period to initiation of RCF cracks

8. Application of Algorithms to Track

The rail degradation algorithms derived in the previous section from data measured on short track monitoring sites have been used to provide an understanding of the degradation of longer sections of track. It is only by application over a reasonable length of track that an understanding of the significance of the different factors involved in rail degradation and rail grade selection can be understood.

A 118km section of mixed traffic railway, with predominantly commuter traffic, has been segmented based on track curvature and amount of traffic using the approach described in D1.2.5[26]. The curvature of the route is plotted in Figure 24 as radius against distance; curves with a radius greater than 6000m, along with tangent track are plotted at a radius of 6000m. The change in traffic along the route is also shown with almost four times as much traffic at the start of the route than at the end. A summary of the radius ranges and the proportion of transitions are given in Figure 25. The degradation of the transition curves have been calculated using the minimum radius for the associated curve and are therefore representative of the most severe wear encountered.

The only things taken into account in this analysis is the degradation and life of the rail. Not taken into account is the life of the other track components, such as sleepers and ballast, as information on degradation has not been recorded during the site monitoring projects. It is important to take into consideration these factors when carrying out life cycle cost calculations on the rail grade selection. Also not included is the effect of other rail degradation mechanism other than wear and head checks. One important life-determining factor is corrosion this can be accelerated in localised areas, such as tunnels or level crossing, to such an extent that it becomes the life determining factor of the rail. In these locations consideration should be given to other solutions such as coated rails.

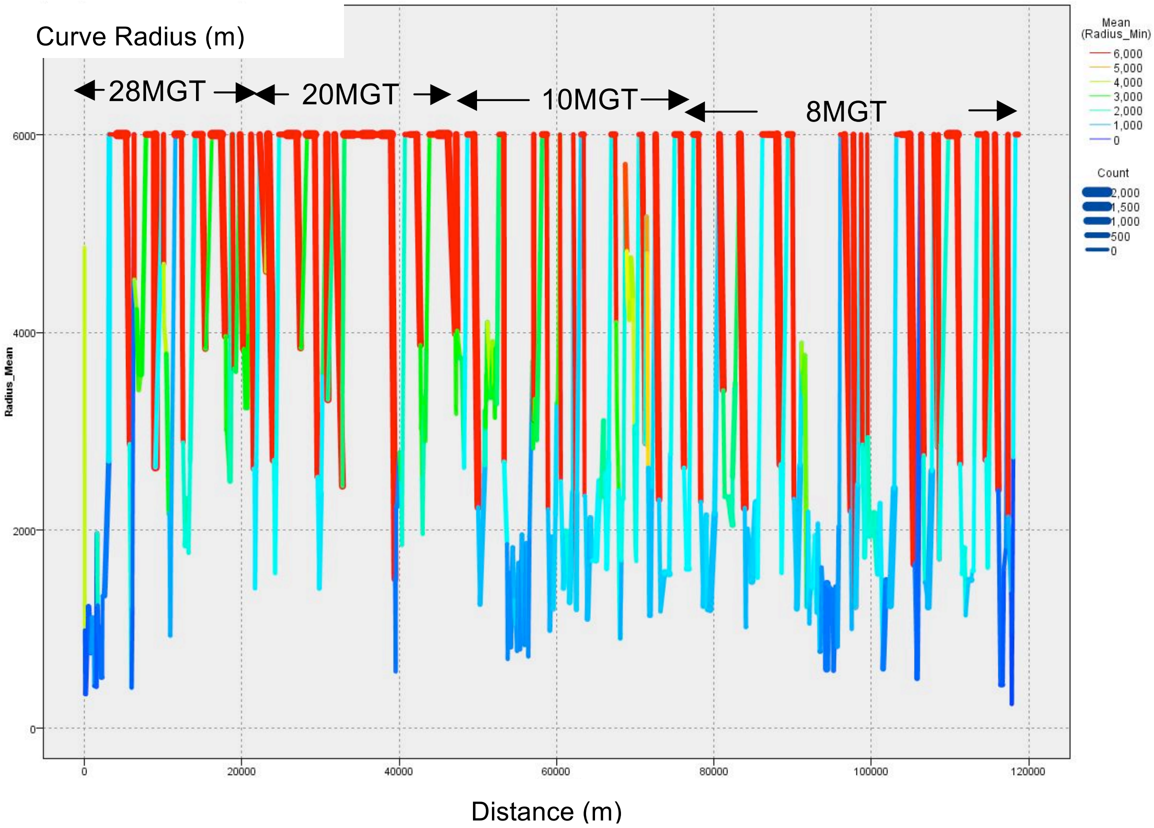


Figure 24: Radius profile of route (tangent track drawn at a radius of 6000m)

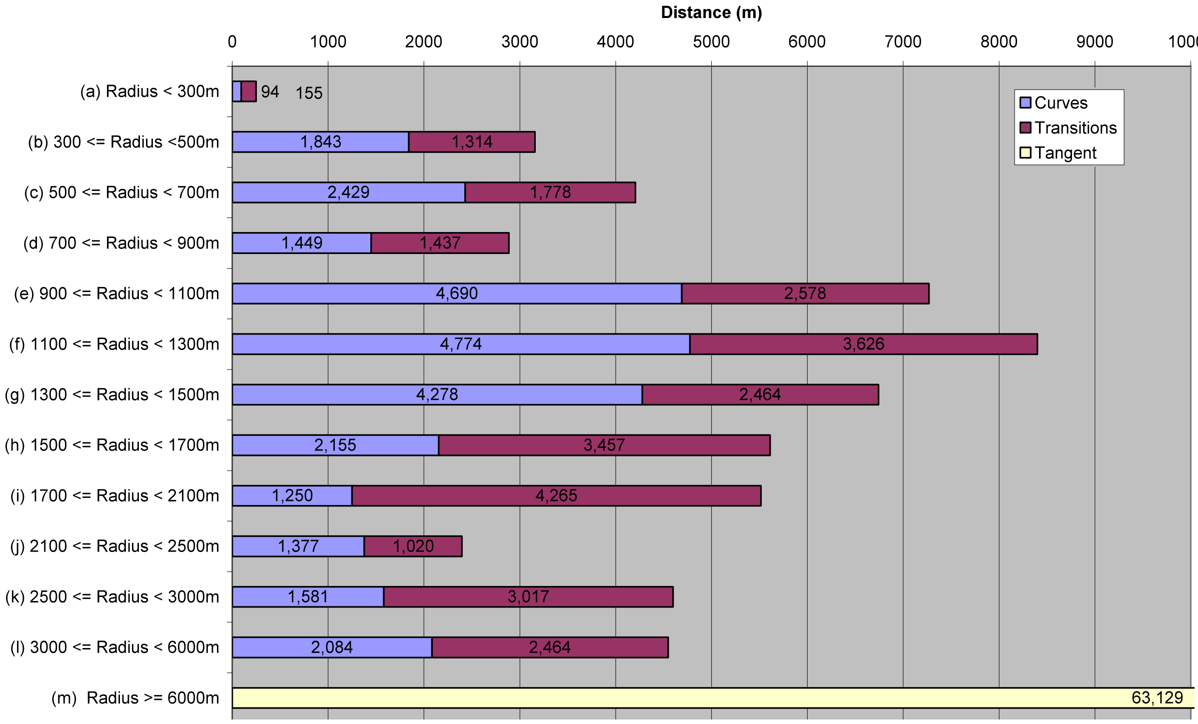


Figure 25: Summary of Radius Ranges

8.1 Wear

As mentioned in Section 6 there is insufficient data to be able to derive degradation algorithms for side wear and hence an approximation has been made using the 45º wear data, Equation 10.

$$\text{Side wear} = 45° \text{ wear} \times \text{cosine}\,(45°) \qquad (10)$$

Figure 26 plots the predicted (vertical, side and 45°) if the route were laid solely with grade R220 rail along its full length. The amount of traffic per year along the route is also given. Vertical wear is between 0.2 and 0.75mm/year and is dependent on both the radius and traffic. For the majority of the route (75%) this is the life determining factor. It is only the sharper radius curves where side wear becomes significant and the very tight radius curves, less than 500m, where side wear becomes the life determining factor. With a vertical wear limit of 14mm, a wear rate of 0.5mm/year is equivalent to a rail life of 28 years for R220. The algorithms derived above indicate that for the majority of the route there will only be a small increase in life with a move to R260.

To understand the benefits, in terms of 45° wear, of changing from R220 to R260 grade and also from using premium grade rail steels (R370CrHT) an analysis of the predicted wear rates for curves of different radius ranges has been carried out. The wear rates have been converted to rail life using a 45° wear limit of 11mm (equivalent to a side wear limit of 8mm using equation 10).

Table 2 shows the effect of changing rail grade on the amount of rail (as a percentage) with different expected life spans. As an example for R220 91.5% of rails will last longer than 30 years while 1.6% will last less than 5 years. This only predicts the life based on 45° wear, whereas the maximum rail life for 75% of the route where there is little side wear, will be approximately 28 years based on vertical wear. Using the middle values for the rail life ranges (and 30 years for those predicated to be greater) allows a prediction of average rail life for the route, demonstrating a 2.2% improvement when moving from R220 to R260.

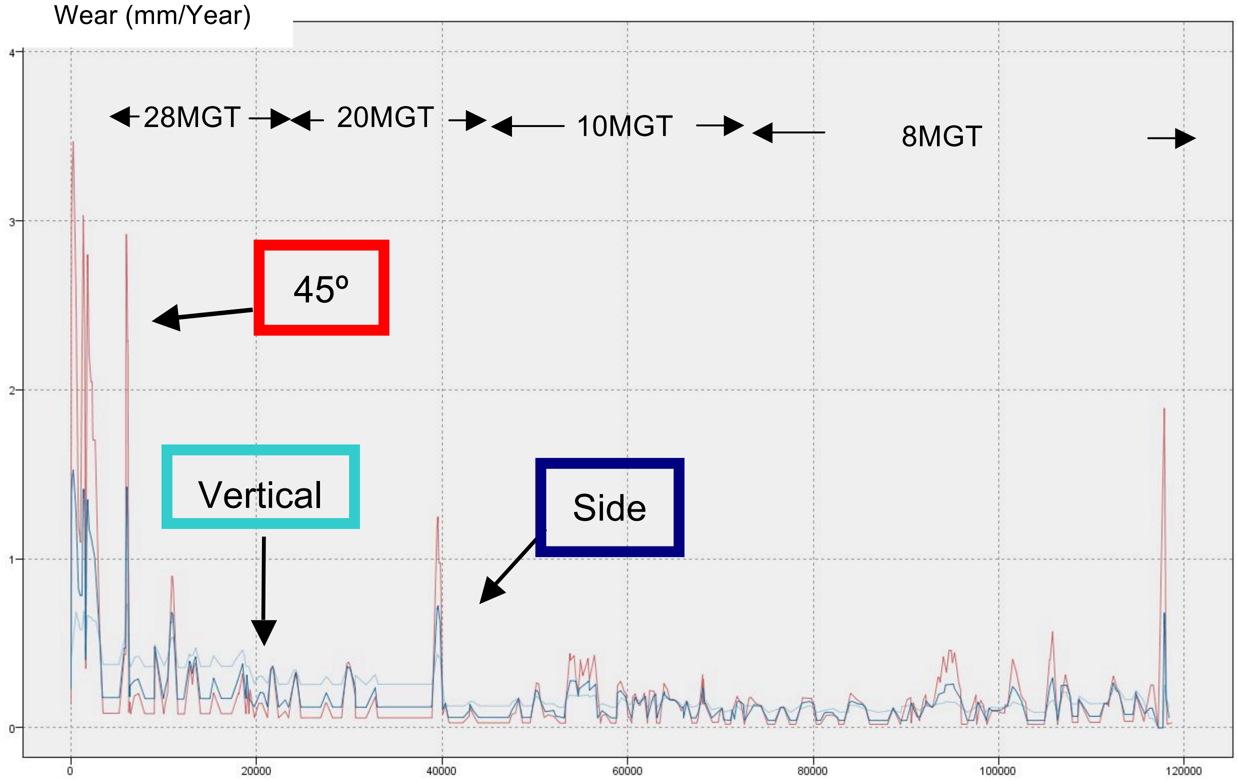


Figure 26: Comparison of predicted wear for full route (based on R220)

Percentage of track with average rail life, L (%)						Average Rail life	% Improvement over R220	% Improvement over R260
Rail Life (years)	L≥30	22≥L>30	11≥L>22	5≥L>11	L<5			
R220	91.5	4.3	1.5	1.5	1.6	28.94		
R260	96.3	0.6	0.9	1.8	0.6	29.30	2.2	
Premium < 300m	96.3	0.6	1.1	1.7	0.6	29.32	2.3	0.0
Premium < 500m	96.7	0.2	1.7	1.5		29.41	2.6	0.4
Premium < 700m	96.7	0.5	1.8	1.0		29.49	2.8	0.6
Premium < 900m	96.7	0.8	1.4	1.0		29.52	2.9	0.7
Premium < 1100m	96.8	0.8	1.3	1.0		29.53	3.0	0.7
Premium < 1300m	96.8	0.8	1.3	1.0		29.53	3.0	0.7
Premium < 1500m	96.8	0.8	1.3	1.0		29.53	3.0	0.7
Premium < 2000m	96.8	0.8	1.3	1.0		29.53	3.0	0.7

Table 2: Prediction of rail life for total route as a function of rail grade base on 45°wear

A similar analysis can be carried out for premium grade rail steels to understand which curves would benefit from fitting of rail steels with greater wear resistance than standard grades. This is expressed as a rail grade selection strategy where the premium grade steels will be fitted to curves below a certain radius to allow the optimum locations to be found. This shows there is an improvement in increasing average rail life over R260 by fitting premium grade rails to curves up to 900m, but there is no additional benefit in fitting them to curves of greater with radii greater than 900m. Furthermore, the additional benefit between 700m and 900m is small. It should be emphasised that these observation apply only to wear, RCF will be considered separately later.

Fitting premium grade rails to all curves of less than 700m requires 7.7km of premium rails (high rail of curves only; there may be an additional benefit to fitting them to the low rail to resist plastic deformation and flow), which is approximately 6.5% of the network including transitions. The effect of this is to reduce the number of areas where frequent rail replacement is required. For R260 grade 0.6% of the track (700m) has to be replaced every 5 years while 1.8%(2km) has to be replaced at a minimum every 10 years. Replacing these locations with premium grades results in only 1%(1.2km) requiring replacement at least every 10 years. The locations where the premium grades are required are shown in Figure 27. The higher cost of the premium grade rail steels has to be balanced against the repetitive replacement costs for these areas, as rail material costs are only a small part of the total renewal costs.

The limitations of rail grade selection based solely on radius ranges can clearly be seen. For example installing premium grade rails in all curves of radius less than 700m equates to 6% of the network while only improving the life significantly in 2.6% of locations. One reason for this is the change in traffic along the route, with a greater amount at the start and decreasing amounts towards the end. This factor also has to be taken into consideration when considering rail grade selection rules, Table 3.

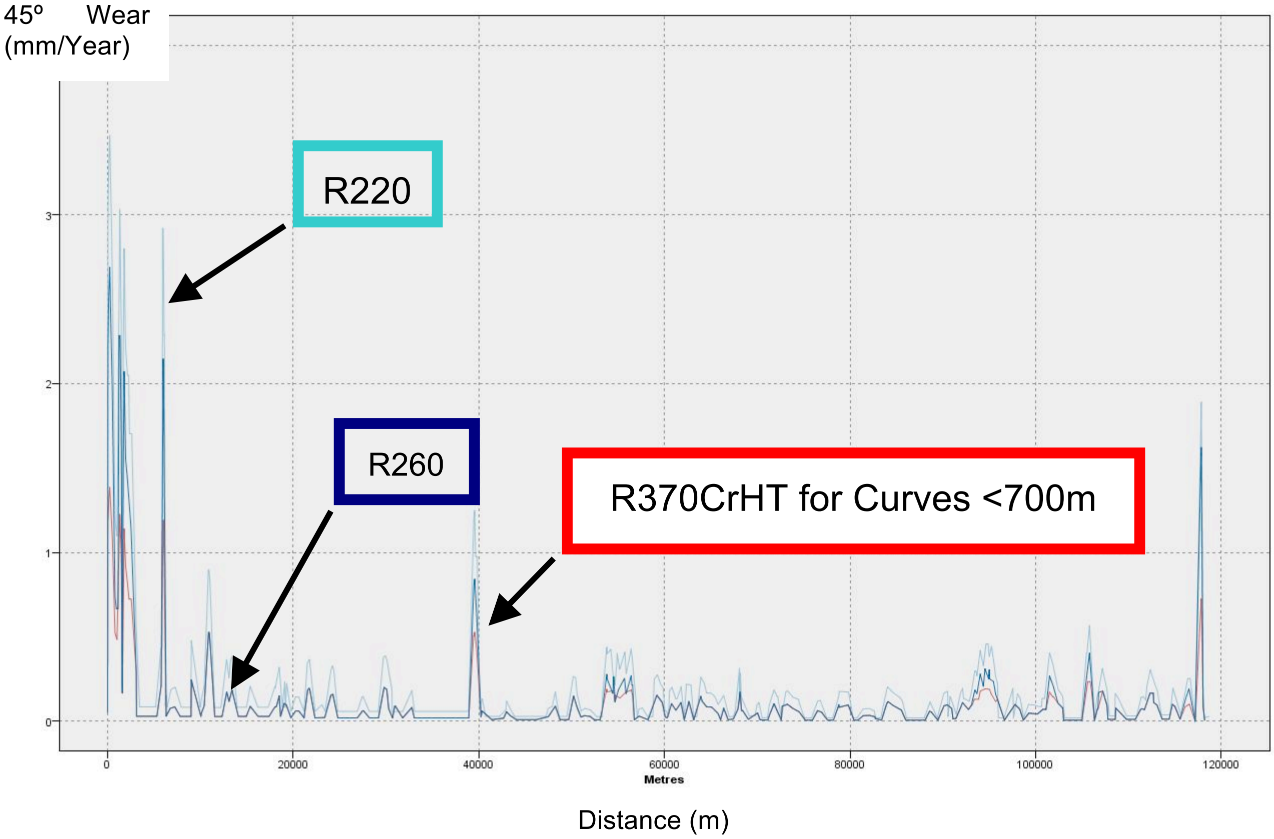


Figure 27: Effect of Premium Grade Rail Steels on Wear

Table 3 gives the percentage of the route with the expected rail life broken down into the amount of traffic carried, showing that almost 50% of the route has less than 10MGT per year for which the life will be greater than 30 years. This has been done for the whole route fitted with R260 and for premium grade rails fitted to curves of less than 700m. The colours indicate the change in each category between the different grades, green is a decrease in amount for R370CrHT compared to R260 while yellow is vice versa.

Rail Life	Traffic, T	Percentage of track with average rail life, L (%)	Total	Track with

(years)	(EMGTPA)	Percentage of track with average rail life, L (%)					Track (m)	Increased Life	
		L≥30	22≥L>30	11≥L>22	5≥L>11	L<5		Metres	%
R260	All	96.88	0.79	0.62	1.53	0.17			
	0 ≤ T < 5	1.52	0.00	0.00	0.00	0.00			
	5 ≤ T < 10	48.65	0.00	0.06	0.08	0.00			
	10 ≤ T < 20	16.03	0.12	0.00	0.00	0.00			
	20 ≤ T < 30	29.79	0.67	0.56	1.28	0.17			
	30 ≤ T < 40	0.89	0.00	0.00	0.18	0.00			
Premium < 700m	All	97.19	1.18	1.46	0.17	0.00	7734	3125	
	0 ≤ T < 5	1.52	0.00	0.00	0.00	0.00	892	0	0
	5 ≤ T < 10	48.65	0.14	0.00	0.00	0.00	3880	163	4
	10 ≤ T < 20	16.15	0.00	0.00	0.00	0.00	140	140	100
	20 ≤ T < 30	29.98	1.05	1.28	0.17	0.00	2612	2612	100
	30 ≤ T < 40	0.89	0.00	0.18	0.00	0.00	210	210	100

Table 3: Effect of traffic on rail life for R260 and premium grade rails

The results show that the benefits of premium grade rail steels are largely limited to curves where the amount of traffic is greater than 10EMGTPA; there is also a small section of track in the 5-10 EMGTPA category that would also benefit, but the majority, 96%, would not.

The UIC guidelines on rail grade selection advise fitting “hard” rail steels to curves of less than 700m for a minimum amount of traffic of 5MGT for curves where premium grade rail should be fitted[19]. Therefore for this section of route, 7.7km of premium grade rail steels would require to be fitted according to these guidelines. This is in contrast to predictions of the wear based on historical data, which demonstrates that premium rail steels should only be used in 3.1km of track where the life would be significantly improved.

8.2 Rolling Contact Fatigue (RCF) – Head Checks

Route analysis has been carried out for RCF in a similar manner to that for wear in terms of looking at the benefits of introducing premium grade rail steels to curves of different radii and studying the effects on the RCF crack depth growth rates along the total length of the route. Unfortunately the limited data for grade R260 has meant that it is not possible to use it as a comparison. Therefore the standard rail steel has been assumed to be R220. Note that the crack depth growth rates for R220 seem high and may reflect the data on sites where RCF is well developed, but this is the only grade for which a substantial quantity of data is available.

The crack depth growth rates can be calculated over a year to account for the traffic pattern, Figure 28. Alternatively grinding regimes are often based on intervals of specific periods of traffic and therefore the growth can also be reported between grinding interventions. Figure 29, demonstrates this principle based on an interval of 15 MGT.

When crack growth is based on the annual traffic the areas with the most significant growth are those with the most traffic. In contrast with degradation based on 15MGT grinding intervals, the part of the route with lower annual amounts of traffic has the greater crack growth because their are more curves with radii which are susceptible to RCF than those on the busier section.

The use of premium grade rail steels demonstrates a significant reduction in the growth as demonstrated above in the discussion on the derivation of algorithms. The effect of this on the route can be seen in Figures 28 and 29. Also plotted in these figures is the effect of using premium grade rail steels on curves of different radii. The greater the radius the less amount of track with higher growth rates and therefore more track which is more resistant to rolling contact fatigue which requires less grinding.

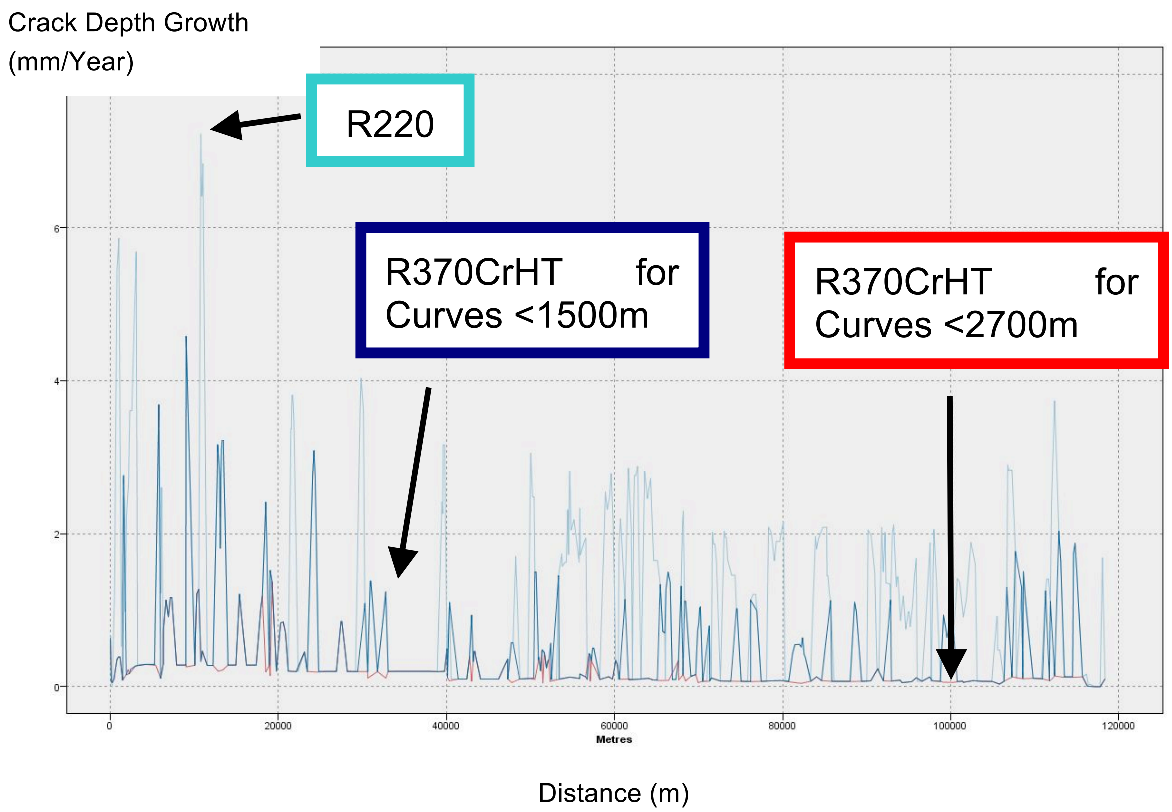


Figure 28: Premium Grade Rails and RCF crack depth growth per year

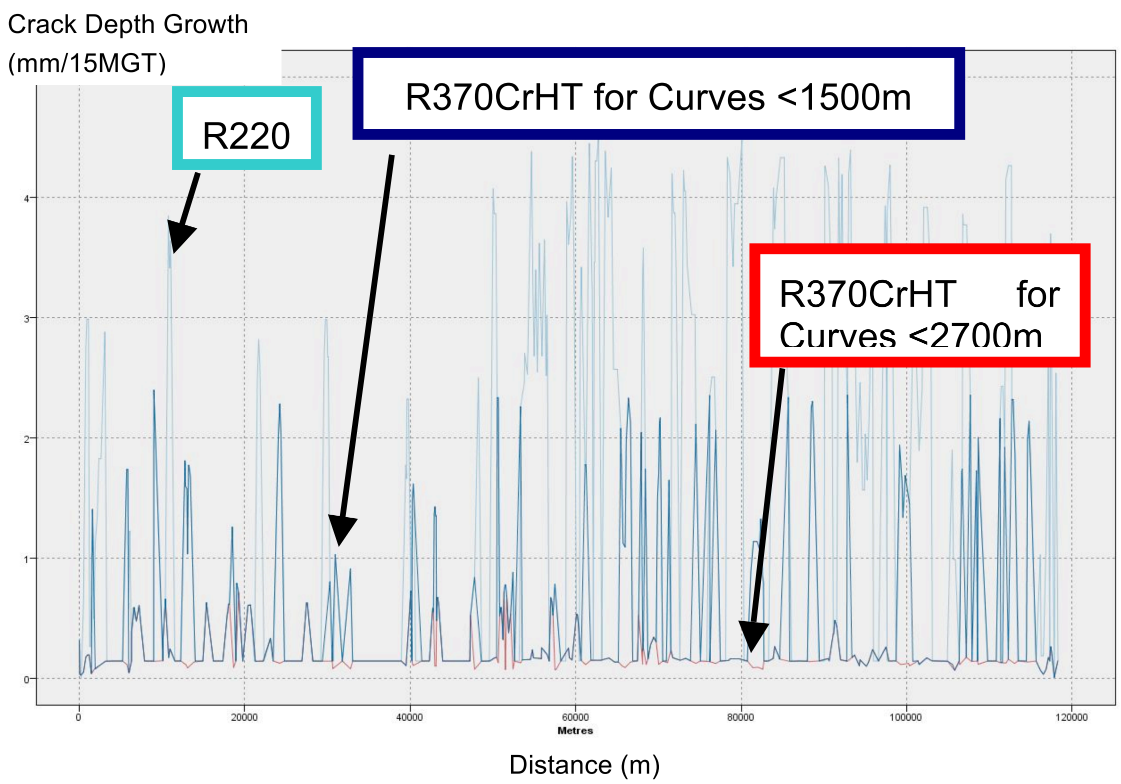


Figure 29: Premium Grade Rails and RCF crack depth growth per 15MGT

Table 4 attempts to quantify the benefits of applying premium grade rail steels to different track radii by calculating the percentage of track within a range of crack depth growth rates in mm/year. Also calculated is the amount of rail replacement with premium grade rail required. The amount of track requiring premium grade rails is plotted in Figure 30 against the proportion of the route with crack growth rates per annum greater than certain amounts. This demonstrates that as more of the route is fitted with premium grade steels there is a reduction in the amount of track with the higher crack growth rates. Once curves of less than 2500m (39% of total route) have been fitted, the higher crack growth rates (greater than 2mm/year) are reduced to almost zero and therefore it becomes much easier to control RCF by grinding.

This example demonstrates the possibilities of using rail degradation algorithms and uses R220 as a standard grade. Using R260 as standard in place of R220 rail will result in a reduction of crack growth for the whole route and will probably result in the requirement of premium grade rail being reduced as it will be targeted at the areas most susceptible to RCF. It can also be seen that there is little effect of premium grade rail steels on RCF growth at the lower radius curves as there is little RCF growth since wear is the dominant degradation mechanism.

% of Track in Category		Crack Depth Growth (mm/Year)										Track (m)	Track (%)
		0<D≤0.25	0.25<D≤0.5	0.5<D≤1	1<D≤2	2<D≤3	3<D≤4	4<D≤5	5<D≤7	6<D≤7	D>7		
R220		46.2	12.7	8.0	18.0	10.3	3.1	0.5	0.8	0.2	0.1		
Premium Grade for curves:	< 300m	46.2	12.7	8.0	18.0	10.3	3.1	0.5	0.8	0.2	0.1	249	0
	< 500m	48.1	12.3	7.7	17.4	9.8	3.1	0.5	0.8	0.2	0.1	3406	3
	< 700m	51.7	12.3	5.9	16.5	9.6	2.3	0.5	0.8	0.2	0.1	7613	6
	< 900m	53.5	12.7	5.9	14.9	9.4	2.3	0.5	0.4	0.2	0.1	10499	9
	< 1100m	59.2	13.0	5.9	12.0	6.6	2.2	0.5	0.4			17767	15
	< 1300m	66.3	13.0	5.9	10.8	1.4	1.6	0.5	0.4			26167	22
	< 1500m	71.6	13.4	5.9	6.6	1.3	1.0	0.2				32909	28
	< 1700m	76.1	13.7	5.4	3.2	0.8	0.9					38521	32
	< 1900m	79.1	13.9	4.4	2.1	0.6						44036	37
	< 2100m	80.7	13.9	3.4	2.0								
	< 2300m	82.3	13.9	2.1	1.8								
	< 2500m	82.7	13.8	1.9	1.6							46433	39
	< 2700m	83.9	13.6	1.2	1.3								
	< 2900m	85.1	12.8	1.2	1.0							51031	43
	< 3100m	87.2	12.3	0.5	0.1								
	< 3500m	88.8	10.9	0.2									
	< 4000m	89.0	10.8	0.2									
	< 5000m	89.2	10.8										
	< 6000m	89.2	10.8									55579	47

Table 4: Percentage of track with crack growth rates for application of premium grade rails

An alternative approach to looking at premium grade rail steels and RCF is the amount of growth that occur between successive grinding cycles to try to optimise the frequency of grinding. This is demonstrated in Figure 31 for grinding intervals of 15 and 45MGT for grades R220 and R370CrHT (applied to curves of less than 2700m). The difference between the growth rates for the two grinding intervals for both rail steels will be the same i.e. a factor of 3. However the actual crack dimensions will be different due to the lower growth rates for the R370CrHT. It is this performance characteristic of premium grade steels that allows their use to be combined with a reduction in the frequency and magnitude of grinding, hence reducing maintenance costs. For the sections of track with the maximum crack depth growth, the growth between grinding interventions of 15MGT will be ~4mm for R220 and 0.8mm for R370CrHT. However by moving to grinding interventions of 45MGT the crack growth for premium grades will be ~2mm, in contrast for R220 it will be greater than 12.5mm. For the sections of track most prone to RCF with the highest growth rates then it may not be possible to use intervals of 45MGT and more frequent grinding may be required. However, for the majority of curves, grinding intervals of 45MGT will result in crack depth growth rates of less than 1mm between interventions when fitted with premium grade rails steels. In contrast for the same curves with R220 the growth would be greater than 5mm. This would be impossible to control by grinding and thus a more frequent grinding regime would be required.

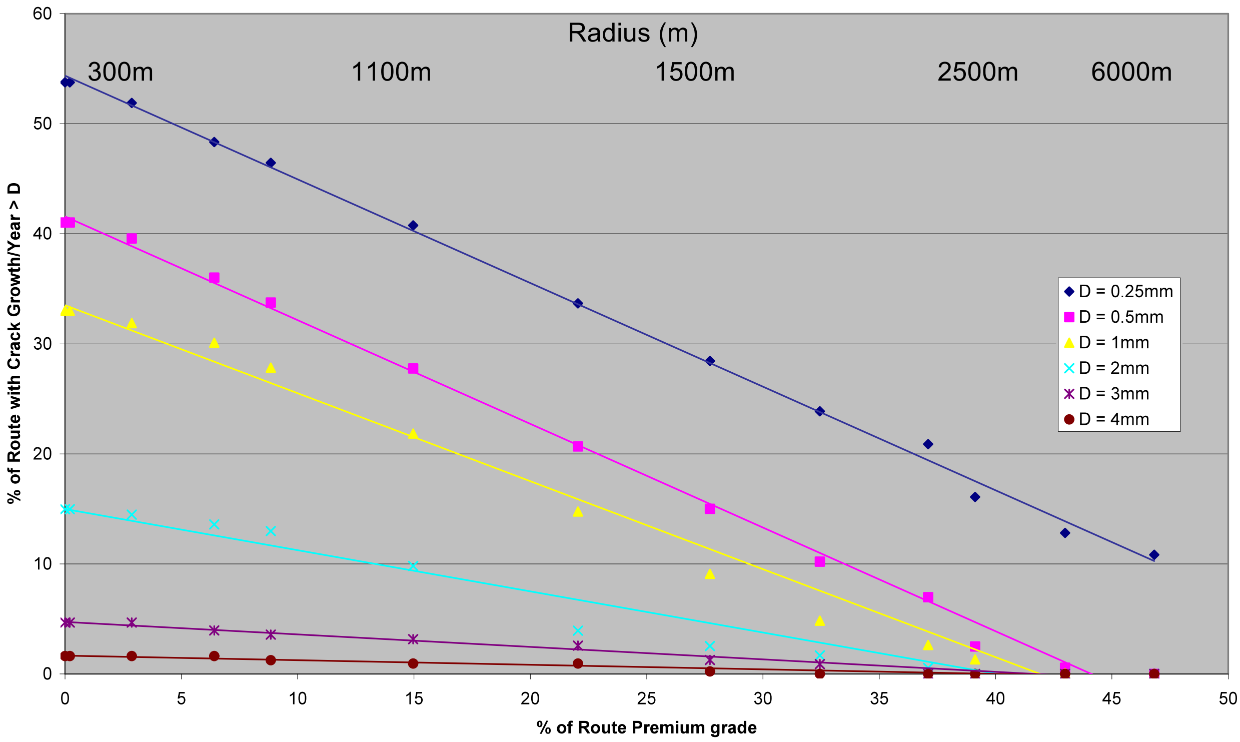


Figure 30: Effect of premium grade on extent of RCF

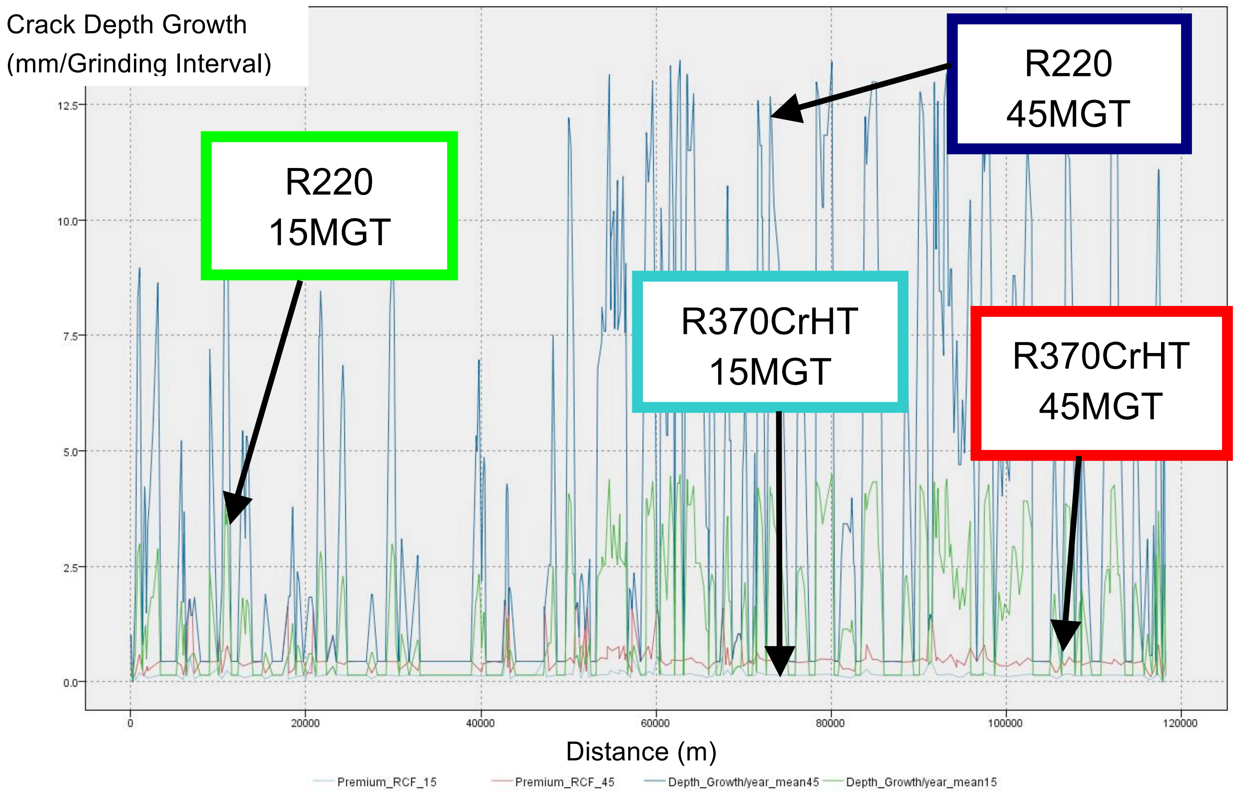


Figure 31: Effect of grinding interval on depth of RCF crack, premium grades applied to curves of <2700m

9.0 Conclusions

Detailed site monitoring allows an understanding of the performance of current and new rail steels, but the variability in results makes it difficult to compare behaviour for different rail steels installed on different curves with different traffic patterns. Therefore, for more effective track investigations, consideration should be given during the design stage to installing a comparative grade in addition to the grade of interest on the same curve in order to minimise variability in experimental conditions. Consideration should also be given to understanding, if possible, the parameters outlined in section 4.2.

The collated data is only a small sample of all track monitoring data collected by the IM's but by adding further data, both historic and new, to the database the accuracy of the rail degradation algorithms will be improved. In recent years laser profiling of the rail has been adopted by various IM's to measure wear along long sections of route and the analysis of this data will allow validation of the wear algorithms as well as the potential to give much more accurate predictions.

The collated data have demonstrated that it is possible to investigate trends in rail degradation for both wear and rolling contact fatigue. Furthermore, and in spite of the considerable observed variability in the results, the studies have confirmed the findings of previous investigations, in terms of:

- Wear increases with increasing rail curvature (decreasing radius), with a greater effect for 45° wear than for vertical wear.
- The wear rate of harder premium grade rail steels is lower than for standard rail steels on the same curve types.
- Rolling contact fatigue, in the form of head checks, is most prevalent on curves of 700-3000m radii.
- Premium grade rail steels are more resistant to RCF initiation and growth.
- For a given surface crack length the depth of the associated crack is less for harder rail steels than for standard grades.

These effects have been quantified in the current report furthermore rail degradation algorithms have been developed that demonstrate many of these points in the form of mathematical equations as a function of curve radius and traffic.

Segmentation of a section of a mixed traffic railway has been carried out and the rail degradation algorithms have been applied to predict the degradation of each segment. This procedure has been carried out in order to understand the relative importance of the different contributory factors and to demonstrate how the algorithms can be used to aid the development of rail grade selection criteria, the key conclusions of which are highlighted below.

Wear

- The life determining factor for the majority of the route will be vertical wear with a maximum rail life of approximately 30 years
- Curves with radii of less than 1000m exhibit significant amounts of 45° (and side) wear, with the amount of wear increasing with decreasing radii.
- There is no benefit of installing premium grade rail steels in curves of greater than 900m with respect to wear.
- In respect to the section of track that has been analysed. The fitting of premium grade rail steels to curves of less than 700m curves requires 6.5% of the track to be fitted while improving the life significantly for only 2.5% of the total route.
- Rail grade selection criteria should be based on the known degradation mechanisms and rates and not solely on track radii and the amount of traffic carried.

Rolling Contact Fatigue

- The use of premium grade rail steels result in lower RCF crack growth rates with magnitudes of improvement depending on the curvature and amount of traffic.

- The proportion of the route with higher growth rates is reduced as the premium grades are applied to curves with increasing radii, up to a maximum radius of 3000m.
- The proportion of the route to be fitted with premium grade rails will depend on the amount of grinding capacity available and a life cycle cost analysis. The latter requires the correct balance between the higher material costs and a reduction in maintenance costs resulting from an increase in the interval between grinding operations, which in turn is a result of the lower crack depth growth rates of premium rail steels.

The work carried out has demonstrated the benefits of re-interpreting historic track monitoring data and applying the results to allow an understanding of rail degradation. The rail degradation algorithms have been developed using data from several different European Railways. However, one of the reasons for the observed spread in results is the fundamental difference between the railways (such as track construction, maintenance regimes, vehicle type etc.). Therefore to allow accurate predictions of rail degradation for each individual railway, as an aid to rail grade selection, it is recommended that each IM undertake calculations based on data collected from their own system and applies it to their whole network.

In the future the greater use of automated inspection technologies for both wear and RCF should further enhance the understanding of rail degradation, thereby aiding selection of where premium grade rail steels would best be employed in place of standard R220 and R260 grade rails.

9. Bibliography

1. Ekberg, A., Kabo, E., *Rolling contact fatigue of railway wheels and rails: an overview*, Proceedings of the 6th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems Chalmers University of Technology, Gothenburg, Sweden 2003, A2, p11-24
2. *Wheel/rail interface handbook*, Ed's. Lewis, R. and Olofsson, U., Woodhead Publishing, UK, 2009
3. D4.1.1 *Interim database for actual and new rails/joints*, Lead partners: Corus and voestalpine, Innotrack Deliverable, 2008
4. D4.1.2 *Interim Rail Degradation Algorithms*, Lead partners: Corus and voestalpine, Innotrack Deliverable, 2008
5. D4.1.5GL *Definitive guidelines on the use of different rail grade*s, Lead partners: Corus and voestalpine, Innotrack Guideline 2009
6. Jaiswal, S., *Rail metallurgy and the rail/wheel interface*, in: Wheel/rail Interface Management, Mayfair, London, 2003
7. D4.2.4 *Improved model for loading and subsequent deterioration due to squats and corrugation,* Lead partners: TUDelft and Chalmers, Innotrack Deliverable, 2009
8. Grassie, S. L. and Kalousek, J., *Rail corrugation, characteristics, causes and treatments*, Proceedings of the I.Mech.E: Part F, Journal of Rail and Rapid Transit, 207, p57-68, 1993
9. Grassie. S.L., *Rail corrugation: characteristics, causes, and treatments,* Proceedings of the I.Mech.E: Part F, Journal of Rail and Rapid Transit, 262, p581-596, 2009
10. D173, Report No. 1: *Review of rolling contact fatigue in rails,* Office for Research and Experiments of the International Union of Railways, Utrecht, The Netherlands, 1990
11. Takikawa, M., Iriya, Y., *Laboratory simulations with twin-disc machine on head check*, Wear 265, p1300–1308, 2008
12. D4.2.6GL *Recommendation of, and scientific basis for minimum action rules and maintenance limits*, Lead partner: Chalmers, Innotrack Guideline 2009
13. Greenwood Engineering website, http://www.greenwood.dk/miniprofrail.php, accessed on 15/10/2009
14. Esveld, C., *Modern Railway Track*, MRT Publications, Duisburg, Germany, 2nd Edition, 2001.
15. Clark, S.L., Dembosky, M.A., Doherty, A.M., *Dynamic wheel/rail interactions affecting rolling contact fatigue on the British railway system,* The World Congress on Railway Research, WCRR 2003, Edinburgh, Scotland, UK, p392-399, 2003
16. Cannon, D.F., Edel, K-O, Grassie, S., Sawley, K., *Rail defects: an overview*, Fatigue and Fracture of Engineering Materials and Structures, 26 (10) p 865-886, 2003
17. prEN13674-1:2009, *Railway applications - Track – Rail - Part 1: Vignole railway rails 46 kg/m and above*, CEN: European Committee For Standardization, Brussels, 2009
18. Tolley K.H., *Rail wear and associated problems,* Fourth R.I.A. Track Sector Course, p4.6.4/1-4.6.4/11,1992
19. Leaflet 721, *Recommendations for the use of rail steel grades*, UIC, Paris, 2005
20. Steele, R.K., Reiff, R.P., *Rail: its behaviour and relationship to total system wear*, Proceedings of the 2nd International Heavy Haul Conference, Colorado, USA, p227-276, 1982
21. Griffin, K.J., Rosval, G.W., *In -track assessment of premium and intermediate grade rail steels,* Canadian Mining and Metallurgical Bulletin, 81(914), p117-124, 1988
22. Ringsberg, J.W., *Shear mode growth of short surface-breaking RCF cracks*, Wear, 258(7-8), p955-963, 2005
23. Burstow, M., *What we now know*, Vehicle/Track Systems Interface Committee Annual Seminar 2009, RSSB, London, UK, Presentation available at
http://www.rssb.co.uk/pdf/vtsic_presentations/2.%20What%20we%20now%20know%20M%20Burstow.pdf; (Accessed 23/12/09)
24. D1.3.3, *The Root Causes of Track Problem Conditions and Priorities for Innovation*, Lead partner: Network Rail, Innotrack Deliverable, 2008

25. *Rolling contact fatigue in rails: a guide to current understanding and practice*, RT/PWG/001, Railtrack, London, UK, 2001

26. D1.2.5 *Methodology for Generic Track Segmentation Approach,* Lead partner: Corus, Innotrack Deliverable, 2008