Improving track geometry alignment to reduce rolling contact fatigue (RCF)

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Abstract
In the UK, research into rolling contact fatigue (RCF) over the last ten years has resulted in the development of models to predict the initiation of RCF and an understanding of some of the factors which influence its formation, such as wheel/rail profiles and cant deficiency. The object of the research described in this paper was to understand the relationship between short-wavelength lateral track geometry quality and the formation of RCF, and whether track maintenance standards could be improved to reduce the risk of RCF initiation.

The research was undertaken through application of vehicle dynamics simulations of a range of vehicle types interacting with different track alignment faults on a range of curves. The results showed that the risk of RCF depends on the combination of track alignment, curve radius and cant deficiency; but also the vehicle primary suspension characteristics and wheel/rail conicity. Vehicles operating with lower wheel/rail conicity values were found to be less sensitive to variations in track alignment and were therefore less likely to result in RCF initiation. The sensitivity of RCF to track alignment was also dependent on curve geometry with tangent track and curves at higher cant deficiency able to tolerate larger track alignment variations without developing RCF.

One important finding was that the risk of RCF initiation was a function of not only the magnitude of the lateral track alignment but also the wavelength of the alignment variation. This was an important finding which influences the way track geometry is measured and analysed since existing track maintenance standards are based only on the amplitude of the lateral alignment and not on its wavelength.

Introduction
The development of rolling contact fatigue (RCF) cracks in rails presents an increased risk to the safe operation of the railway and incurs significant maintenance costs and activities which reduce the availability and capacity of the network. Understanding the causes of RCF and implementing new management techniques which control or prevent the initiation of RCF is therefore key to improving the safe operation and reliability of the rail network.

In recent years a number of studies have utilized detailed site investigations and vehicle dynamics simulations of vehicles running over the sites to correlate wheel/rail interaction forces with observed locations of rail surface damage. This has increased understanding of the forces and mechanisms responsible for different forms of RCF damage [1-3] and resulted in the development of a model to predict RCF [4, 5].

As a result of these studies it has been possible to conduct studies to determine the parameters (for both the vehicle and track) which can influence the initiation of RCF damage [6, 7]. On the whole, it has been found that two different mechanisms are responsible for generating RCF: quasi-static forces generated during curving are generally responsible for RCF on moderate radius curves (1000-1500m radius), and dynamic forces resulting from lateral track misalignments tend to be responsible for RCF on shallow radius curves and tangent track. This can lead to the formation of RCF cracks in regular groups or ‘clusters’. Very often the track alignment at these locations is within the maintenance limits, suggesting that although some of our current track standards are adequate for preserving passenger ride comfort and safety against derailment, they may not be fully appropriate for preserving asset life. The work described in this paper describes some recent findings about the relationship between track lateral alignment quality and RCF formation, and suggests how track measurement and maintenance standards may need to be revised in the future if RCF is to be better controlled.

RCF crack initiation
The model of RCF crack initiation which was used in this study of has been developed from detailed modeling of sites with RCF [1-5] is a function of the energy generated in the contact patch (usually described by the parameter $T_f$ (often referred to as the ‘wear number’ or ‘wear index’ as it has also
been used to correlate wheel or rail wear) when computed in vehicle dynamics simulations. The RCF crack initiation model is based on a relationship between $T_γ$ and RCF initiation risk which is shown in Figure 1. This shows that there is a $T_γ$ threshold above which there is a risk that RCF cracks will initiate. Below this threshold there is insufficient energy to initiate RCF, and at high values of $T_γ$ the increase in energy is such that the dominant form of surface damage is wear rather than crack initiation. Contact patch energy in this range is most common during wheel flange contact which gives rise to significant levels of rail side wear if not mitigated with flange lubrication.

![Figure 1: RCF crack initiation function](image-url)

Experimental evidence has also identified that RCF cracks can only initiate if the shear force generated in the contact patch is acting on the rail in a traction direction (i.e. the force experienced by the rail is in the opposite direction to the direction of travel of the wheel). If this is the case then fluid can become trapped within the nascent crack as the contact patch passes over it. Under the resulting compressive load from the wheel the fluid pressurises the small crack, which forces the crack open and causes it to grow by fatigue. On the low rail of curves, where the wheel/rail interaction forces are very similar to those on the high rail but their action is opposite, fluid cannot become trapped in the same manner so that cracks cannot form. This is why RCF tends to form on the high rail of curves and not on the low rail. Hence, to assess the risk of RCF crack initiation it is necessary to consider the magnitude of the energy generated (Figure 1) and the direction of shear force within each contact patch.

As a result of recent UK research the roles of curve radius and applied cant, primary yaw suspension and wheelset conicity in controlling the wheel/rail tangential forces, and their consequent impact on RCF are now well accepted [6, 7]. The UK industry has also been host to a number of trials and initiatives to seek to reduce RCF through changes to these parameters [8]. With regard to the effects of track geometry, work [2, 4, 6] has shown that RCF is more sensitive to lateral alignment quality than vertical alignment, and that RCF due to poor lateral track quality is more likely on shallow radius curves and tangent track than tighter curves; indeed, on tangent track or through S&C lateral alignment (including gauge variations) are usually the main drivers behind the generation of RCF. However, there is no clear understanding of the relationship between vehicle parameters, track alignment and the resulting RCF risk, nor how these can be related to existing track maintenance standards. Indeed, it is observed that RCF can be present on many pieces of track where the geometry is within the Network Rail line standard for both standard deviation and discrete faults.

**Methodology**

To determine to what extent track lateral alignment can influence RCF, how it depends on vehicle characteristics, and whether existing track alignment standards are adequate for controlling RCF, and to what extent we should expect regular maintenance activities to effectively manage track to reduce or eliminate RCF, a series of vehicle dynamics studies have been undertaken.

These studies used the Vampire vehicle dynamics simulation software to predict the behaviour of vehicles running over sections of track consisting of a sinusoidal lateral alignment variation. Analyses were conducted to investigate the effects of:

a) irregularity wavelength (from 2 to 50m)
b) lateral alignment amplitude
c) wheel/rail profile (conicity)
d) vehicle primary yaw stiffness (PYS)
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e) vehicle speed
f) track gauge
g) curvature

The results of the tests were assessed by determining the maximum value of $T_\gamma$ generated through each track alignment shape and converting this to a measure of RCF damage using the function shown in Figure 1. The choice of the maximum $T_\gamma$ value, rather than an alternative measure such as the average value, reflects the desire to know from the simulations the conditions which would lead to the development of the first clusters of RCF rather than the ‘average’ level of damage generated on a piece of track.

Results

A typical set of vehicle responses to different track alignment inputs on tangent track are shown in Figure 2. This shows the maximum contact patch energy (or wear number, $T_\gamma$) generated in the contact patch as a function of the wavelength of the simulated lateral alignment defect, for a range of alignment magnitudes. Figure 2a shows the results for a vehicle with a low conicity wheel/rail profile, and Figure 2b shows the results for the same vehicle with a moderate conicity wheel/rail profile (the UK P1 and P8 wheel profiles, respectively). As would be expected the results show that as the magnitude of the alignment defects increase then, for any given alignment wavelength, the wheel/rail forces and contact patch energy increases. The results also highlight that the forces generated are sensitive to particular wavelengths of lateral alignment, and that some combinations of lateral alignment wavelength and amplitude will result in the generation of forces which exceed the RCF damage threshold (which is indicated on the graphs by a dotted line), resulting in the initiation of RCF cracks.

What is also clear from the graphs in Figure 2 is that the different conicity wheel profiles cause the vehicle’s response to the track alignment features to be sensitive to different wavelengths of lateral alignment in the track; and that the wheel/rail profiles with the higher conicity result in the generation of much higher wheel/rail forces. The lower conicity wheel profiles (Figure 2a) appear to be sensitive to lateral track alignment with a wavelength between 20 and 30m and require alignment defects of the order of 4-5mm at these wavelengths to initiate RCF on straight track. In comparison, the higher conicity wheel profiles (Figure 2b) are sensitive to shorter wavelengths in the track alignment (7-20m); they also require smaller alignment defects at these wavelengths (approximately 2mm alignment) to initiate RCF, and can generate significantly higher forces and more RCF damage with alignment defects up to 5mm than with a lower conicity wheel profile. In fact, a 4mm alignment defect at a wavelength of 10-15m is predicted to initiate RCF after 100,000 axle passes (according to the damage function in Figure 1 which has been tested against experience in the field) for a moderate conicity wheel/rail profile, whereas track with similar alignment, but with a wavelength of 30m, and a lower conicity wheel/rail profile would have a life in excess of ten times that, before RCF was initiated.

Wheelset behaviour

To illustrate how the vehicle/track interaction forces vary for different alignment wavelength inputs Figures 3 and 4 show the movement of the wheelset relative to the track. For six different wavelengths of track alignment the figure shows the variation in position of the left and right rails (which drive the vehicle response) relative to the ground, and the position of the centre of the
wheelset relative to the ground. All six plots are for the same amplitude of track lateral alignment. Figure 3 shows the results for the low conicity situation, whereas Figure 4 shows the same results, but for the moderate conicity situation.

![Figure 3: Motion of the wheelset and track relative to the ground for a low conicity wheel/rail profile running over track with a) 2.5m, b) 5m, c) 10m, d) 20m, e) 30m and f) 40m wavelength lateral alignment defects](image1)

![Figure 4: Motion of the wheelset and track relative to the ground for a moderate conicity wheel/rail profile running over track with a) 2.5m, b) 5m, c) 10m, d) 20m, e) 30m and f) 40m wavelength lateral alignment defects](image2)

Figures 3 and 4 show that, for short wavelength track alignment features the wheelset oscillates with a very small amplitude about the track centerline. This is because, for both the low (Figure 3) and moderate (Figure 4) conicity wheel/rail profiles, the variation of position of the track is occurring faster than the rate at which the wheelsets can respond to it, so the frequency of oscillation of the track is almost invisible to the wheelset. However, as the wavelength of oscillation of the track increases then the wheelset starts to oscillate more as it seeks to ‘steer’ around the variation in track position. For wavelengths of 10-20m for the moderate conicity wheel/rail profiles (Figure 4) and 20-30m for the low conicity wheel/rail profiles (Figure 3) the steering effect induced in the wheelset is approximately 180°
out of phase with the position of the track, such that the wheel and the rail always appear to be moving towards each other. This causes a large variation in the contact patch position, resulting in the generation of larger rolling radius differences and high contact patch forces. At longer wavelengths (40m), in both Figures 3 and 4, the wavelength of the track position is sufficiently long that the wheelset can ‘steer’ its way along the track, completely in phase with movement of the track, generating lower wheel/rail forces and resulting in less RCF damage.

These results show that the response of the vehicle to track alignment variations appears to be strongly linked to both the wavelength of track alignment variation and the conicity of the wheel/rail profiles, with some combinations causing high wheel/rail forces if the wheelset is unable to steer its way through the alignment. This is of concern in track maintenance since current standards for maintaining track depend only on the amplitude of the track alignment variation, whereas this data suggests that the wavelength of variations in track alignment are important to understand if rail surface damage is to be minimized.

Wheelset frequencies of oscillation
The characteristics of the behaviour of the wheelsets seen in Figures 3 and 4 suggests that the higher wheel/rail forces are the result of wheelsets oscillating at a characteristic frequency which is related to the conicity of the wheel/rail profile. The natural frequency of oscillation of an unconstrained wheelset was first demonstrated by Klingel [9], and shown to be a function of wheelset conicity and independent of lateral alignment and vehicle speed. To investigate the characteristic behaviour of the wheelset further an eigenvalue analysis of the vehicle model was undertaken using different conicity conditions to determine the natural frequency of oscillation of the yaw displacement (i.e. the ‘steering’ moment behaviour) of the wheelset, and relate that to the characteristics observed in Figures 1-4.

Figure 5 shows the results from this analysis, showing the variation in the natural wavelength of oscillation of the wheelset with conicity for different values of the vehicle primary yaw stiffness and vehicle speeds. Also shown is the relationship between the natural frequency of oscillation and conicity of an unconstrained wheelset (according to the ‘Klingel’ relationship), which shows a very close correspondence with the natural frequency of the wheelsets in the vehicle model. These results show that the natural wavelength of oscillation does not depend on vehicle speed, and is weakly dependent on the primary yaw stiffness of the vehicle. Also shown on Figure 5 are the ‘low’ and ‘moderate’ conicity values used in the analyses of Figures 1 and 2. This shows that the natural wavelength of oscillation for these conicities should be approximately 30 and 15m, respectively, which agree very well with the data from Figures 1 and 2 for the wavelengths where most energy (and therefore rail surface damage) is being generated when excited by lateral track alignment features.

Figure 5: Relationship between the natural wavelength of oscillation of the wheelsets with equivalent conicity for different vehicle primary yaw stiffnesses and operating speeds

Influence of primary yaw stiffness and vehicle speed
An alternative presentation of the data, which more clearly shows the sensitivity to alignment of the vehicle’s response to different wavelength inputs is shown in Figure 6. In this case, the data is presented as the amplitude of alignment which is required to generate a given $T_f$ (or RCF damage
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index) value at different alignment wavelengths. The results are presented in Figure 6 for a $T_\gamma$ of 15J/m; the energy value above which RCF initiation is expected to occur (Figure 1). The plots include results for vehicles with different primary yaw stiffness (PYS) characteristics and operating speeds, as well as variations in wheel/rail conicity values.

Also shown in Figure 6 are the existing line standards for discrete faults. Three limits are shown: the limit on alignment faults at installation; the limit at which a maintenance activity is triggered; and the maximum allowable limit that a fault is permitted to reach.

*Figure 6: Variation of alignment amplitude required to initiate RCF damage for different conicity, vehicle yaw stiffness and speed, as a function of lateral alignment wavelength*

This shows that variations in vehicle speed have very little impact on the results: very similar results are obtained irrespective of the chosen speed. This supports the observation that the vehicle’s response to a particular alignment feature is driven purely by the natural kinematic motion of the wheelset (the ‘Klingel’ wavelength), which is purely wavelength driven and independent of vehicle speed (and therefore frequency of oscillation). The response of the vehicle is also only weakly dependent on the primary yaw stiffness of the vehicle: the dominant characteristic which dictates whether RCF damage is likely on a particular piece of track as a result of lateral alignment variations is the wheel/rail equivalent conicity.

Figure 6 also clearly shows that track which is maintained within acceptable maintenance limits is capable of containing alignment defects which could trigger RCF at most wavelengths; and for wavelengths shorter than 20m the higher conicity profiles are significantly more sensitive to alignment. Indeed, with a moderate conicity wheel profile even track installed to the installation standards is capable of containing alignments which could trigger RCF, if they occur at wavelengths shorter than approximately 20m. For lower conicity wheel profiles track maintained to the installation standard should not contain alignment faults which are capable of initiating RCF, irrespective of their wavelength.

**Effect of track gauge**

In general, widening track gauge reduces equivalent conicity for a given wheel/rail pair, and tightening track gauge increases equivalent conicity. It would therefore be expected that tightening track gauge would make the response of the wheelset more responsive to shorter wavelength alignment defects, and wider gauge would be less sensitive. Figure 7 shows how variations in track gauge, with a low and moderate conicity wheelset affect the size of alignment defects which are necessary to cause RCF. As would be expected, widening track gauge, particularly for the wheel/rail profiles which are more likely to generate higher conicity values, makes the wheelset less sensitive to track alignment, increasing slightly the required magnitude of a alignment amplitudes required to initiate RCF and also making them more sensitive to longer wavelengths in the track.
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**Figure 7:** Variation of alignment amplitude required to cause RCF to initiate with variations in track gauge

**Effect of curvature**

Some analyses have also been undertaken to investigate the sensitivity of vehicles to different alignment wavelengths on constant radius curves. Figure 8 shows the results for a 2400m radius curve where rail grinding has taken place, which reduced the equivalent conicity. Figure 8 shows the results for a new wheel/ground rail profile combination when applied to straight track; and on a 2400m radius curve, with vehicles running at 8 and 80mm of cant deficiency. The results show that both the curve radius and cant deficiency can have a big impact on the alignment amplitude required to generate RCF. This is partly due to the curvature, which causes the generation of quasi-static forces which the vehicle generates to be able to negotiate the curve, and which therefore reduce the allowable amplitude of alignment fault that can be tolerated before the wheel/rail forces rise to such a level to initiate RCF damage. However, increasing cant deficiency reduces the quasi-static forces on the leading wheelset, due to the increased rotation of the bogie reducing the angle-of-attack of the leading wheelset, which means that larger alignment variations can be tolerated without generating RCF. What is also evident is that the wavelength at which the greatest sensitivity to alignment amplitude is reached also reduces when applied to a curve. This may be related to the change in effective conicity as the wheelset’s quasi-static position relative to the track moves so that it can negotiate the curve.

**Figure 8:** Variation of alignment amplitude required to cause RCF to initiate with variations in curvature and cant deficiency

**Discussion**

The results of the analyses reported here have shown how variations in track alignment can initiate RCF, and that this depends not only on the amplitude of the track alignment but also its wavelength and the characteristics of the equivalent conicity generated by the wheel and rail. However, if RCF
due to track alignment is to be reduced through changes to track maintenance it is important to know if maintenance techniques can:

a) correct alignment at the wavelengths which are most prone to generating RCF, and

b) move the track within the tolerances required to sufficiently reduce the dynamic forces.

Figures 2 and 6 show that the wavelengths which need to be addressed are generally in the 10-30m range and that alignment amplitudes in some cases may need to be reduced to less than 2mm to eliminate RCF. Figure 9 shows a typical tamping/lining transfer function, from Esveld [10], which indicates that track machines should be most effective at removing the wavelengths around 10-20m. However, to completely prevent the formation of RCF it may be necessary to ensure that track is maintained with alignment amplitudes less than 2mm, for moderate and high conicity wheel/rail profiles. An additional problem is then to determine how well the track will retain this desired position, or whether it will revert to its previous alignment due to ‘ballast memory’ effects.

However, despite these uncertainties, it is clear that attention to track geometry, particularly alignment variations in the wavelengths close to those associated with the natural kinematic motion of the wheelset (i.e. the equivalent conicity) will be most important for reducing RCF, and that larger alignment variations at wavelengths further from these sensitive wavelengths can be tolerated.

The results from these analysis suggest that it may be possible to review existing line standards such that track can be better maintained to preserve asset life, as well as maintaining safety standards and passenger comfort, by considering the wavelength of the alignment. However, this would also require changes to the way that track geometry is measured and analysed since consideration is not currently given to the wavelength content of the track. This should be the subject of further research, to better understand whether such analysis could improve the efficiency and reduce the cost of track maintenance by focusing on those wavelengths which are most sensitive to variations in track alignment.

![Figure 9: Typical transfer function for tamping & lining, from “Modern Railway Track”, C. Esveld [10]](image)

**Conclusion**

Studies of vehicle response to different track alignment wavelength and amplitude have shown that:

- Higher conicity profiles are more sensitive to shorter wavelength alignment faults than higher conicity profiles,
- Higher conicity profiles are also more sensitive to smaller variations in track alignment than lower conicity profiles: for a typical moderate level of conicity an alignment variation of 2mm may be sufficient to initiate RCF, if it is at the most sensitive wavelength
- The wavelengths to which the vehicles are most sensitive are driven by the natural kinematic wavelength of the wheelset (the ‘Klingel’ wavelength),
- Increasing vehicle primary yaw stiffness can increase the sensitivity of the vehicle to alignment amplitude, although it has little effect on the wavelength response.
On curves, the steady-state curving forces generated to steer a vehicle round the curve mean that it is also more sensitive to variations in track alignment, although increasing cant deficiency can reduce this sensitivity by reducing the quasi-static steering forces.

The wavelengths at which the greatest sensitivity exists should be those which tamping/lining operations can have the biggest impact on correcting, but it is not clear to what extent they can reduce the alignment faults that are causing RCF.

References