Rail corrugation: characteristics, causes, and treatments

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Abstract: Rail corrugation is a phenomenon of great diversity but appears now to be substantially understood. This review proposes some differences in classification of the phenomenon to take account of work undertaken since a widely cited review was published by Grassie and Kalousek in 1993, it attempts to fill holes in an overall understanding of the problem, and answers questions that remained open in 1993 and several that have arisen since. All types of corrugation that have been documented to date are essentially constant-frequency phenomena. By treating the vehicle/track system in its entirety, treatments are proposed that impinge upon track and vehicle design as well as upon the wheel/rail interface where corrugation appears. There is no neat solution to rail corrugation, but it can be treated comprehensively and in many cases also prevented by using products that are already commercially available. Since the frequency of common wavelength-fixing mechanisms varies roughly in the range 50–1200 Hz, trains travelling at different speeds can produce corrugation of substantially similar wavelength by different mechanisms in different locations. Although historical data can no longer be checked, this is the most likely explanation of the belief that rail corrugation was a substantially constant-wavelength phenomenon.

Keywords: rail corrugation, rail corrugation measurement, measuring equipment, vehicle–track interaction, wheel–rail interface, vehicle dynamics, rails, rail fastenings, friction modification

1 INTRODUCTION

Irregularities on wheels and rails give rise to noise, ground-borne vibration and more general dynamic loading, which increases damage of components of both vehicle and track. Both wheels and rails are prone to develop quasi-sinusoidal irregularities, which are known as corrugation when their wavelength is less than about a metre. Longer wavelength irregularities are usually known as ‘waves’ when they occur on rails or ‘out-of-roundness’ on wheels. Although the effects of irregularities are substantially the same whether they occur on wheels or rails, the mechanism by which most types of irregularities occur differs in significant respects. Consequently while this article is relevant in several respects to irregularities on both wheels and rails, it concentrates on rail corrugation. Excellent references on wheel irregularities are the review paper by Nielsen and Johansson [1] and the proceedings of a workshop held at the Technical University of Berlin in 1997 [2].

The overall mechanism by which corrugation arises is illustrated in Fig. 1, which first appeared in this form in reference [3], although a similar feedback loop has been widely used. The initial longitudinal rail profile excites a so-called ‘wavelength-fixing mechanism’, which represents the dynamic behaviour of the vehicle/track system. This mechanism ‘fixes’ not only the wavelength but also the position of the eventual corrugation along the track. Other parameters, particularly the tangential forces between the wheel and rail (‘traction’) and the allowable limit of these forces (‘friction’) have some effect on this dynamic mechanism. For example, if a corrugation arises from periodic slip of the wheel on the rail, this is more likely to occur when the tangential force is close to the limit that can be sustained by friction. The dynamic force acts as the input to a so-called ‘damage mechanism’, which results in a change in the initial longitudinal rail profile.

The most common ‘damage mechanism’ on almost all types of railways is wear. Other damage mechanisms are plastic bending of the rail, which occurs when the rail is bent beyond its yield point (rather like a wire coat hanger) and plastic flow. Rolling contact fatigue (RCF) is exacerbated by corrugation, but (contrary to what is stated in reference [3]) does not itself appear to be a damage mechanism of the same form as wear or plastic flow, which change the profile of a
surface in the manner represented in Fig. 1. The influence of RCF on corrugation and vice versa is discussed further in section 5.

The dynamic force that is output from the wavelength-fixing mechanism may be normal to the wheel/rail contact or tangential, or indeed both. For those types of corrugation for which the damage mechanism is wear, a useful sub-classification can be made into those types in which there is a periodic variation in force normal to the wheel/rail contact and those in which the significant variation is longitudinal. A relatively simple, quasi-analytical treatment of the former category of corrugation, in which the wavelength-fixing and damage mechanisms are modelled independently, is given in reference [4]. Evidence from the field suggests that lateral dynamic behaviour gives rise to corrugation in only a few cases where there is a pronounced resonance (section 8).

This contribution summarizes significant characteristics of rail corrugation of different types, provides photographs and measurements of corrugation to help identify different types of corrugation from their appearance, suggests relatively simple methods that have helped to identify specific types of corrugation, and states treatments that have been either shown to work or that should work. Although basic background material is provided for all types of corrugation, it concentrates on work that has been done since 1993. The article also unashamedly reflects the author’s own interests since 1993, which have been more in the area of understanding and providing practical solutions of this problem than in modelling it.

Corrugation tends to be more prevalent in curves. It is sometimes more severe on the high rail, sometimes more severe on the low rail, and occasionally of similar severity on both rails. The reason for this difference is explained here and provides a treatment that may in some cases also be a solution.

2 CLASSIFICATION OF CORRUGATION

The most common types of corrugation that have been documented in the literature can be classified according to their wavelength-fixing and damage mechanisms, as shown in Table 1. The approximate frequency

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength-fixing mechanism</th>
<th>Where?</th>
<th>Typical frequency (Hz)</th>
<th>Damage mechanism</th>
<th>Relevant figures</th>
<th>References</th>
<th>Treatments¹</th>
<th>Should be successful</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pinned–pinned resonance</td>
<td></td>
<td>400–1200</td>
<td>Wear</td>
<td>2–6</td>
<td>[5–23]</td>
<td>Hard rails, control friction</td>
<td>Increase pinned–pinned frequency so that corrugation would be &lt;20 mm wavelength</td>
</tr>
<tr>
<td></td>
<td>(‘roaring rails’)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reduce applied traction in curving, improve curving behaviour of vehicles, dynamic vibration absorber</td>
</tr>
<tr>
<td>2</td>
<td>Rutting</td>
<td></td>
<td>250–400</td>
<td>Wear</td>
<td>2, 7–11</td>
<td>[5, 6, 24–36]</td>
<td>Friction modifier, hard rails, reduce cant excess, asymmetric profiling in curves</td>
<td>Reduce applied traction in curving, improve curving behaviour of vehicles, dynamic vibration absorber</td>
</tr>
<tr>
<td>3</td>
<td>Other P² resonance</td>
<td></td>
<td>50–100</td>
<td>Wear</td>
<td>3, 6, 17, 18</td>
<td>[4, 24, 37]</td>
<td>Hard rails, highly resilient trackforms</td>
<td>Reduce unsprung mass</td>
</tr>
<tr>
<td>4</td>
<td>Heavy haul P² resonance</td>
<td></td>
<td>50–100</td>
<td>Plastic flow in troughs</td>
<td>10, 12–14</td>
<td>[38–40]</td>
<td>Hard rails</td>
<td>Reduce cant excess when corrugation is on low rail</td>
</tr>
<tr>
<td>5</td>
<td>Light rail P² resonance</td>
<td></td>
<td>Straight track or curves</td>
<td>50–100</td>
<td>Plastic bending</td>
<td>15, 16</td>
<td>Increase rail strength and EI</td>
<td>Reduce unsprung mass</td>
</tr>
<tr>
<td>6</td>
<td>Trackform-specific Trackform specific</td>
<td>Straight track or curves</td>
<td>-</td>
<td>Wear</td>
<td>19, 20</td>
<td>[24, 42]</td>
<td>Hard rails, friction control</td>
<td>Avoid ‘peaky’ resonances, improve steering</td>
</tr>
</tbody>
</table>

Note: ¹Grinding or reprofiling more generally is a treatment for all types of rail corrugation. Irregularities in general, such as from welds and joints, should also be reduced as far as possible.
range associated with the wavelength-fixing mechanism is tabulated since it is now clear that all types of corrugation are essentially constant-frequency phenomena. Their wavelength at a particular location is accordingly

\[ \lambda = \frac{v}{f} \]  

where \( v \) is the speed of those trains that give rise to the corrugation and \( f \) is the frequency of the pertinent wavelength-fixing mechanism. Identification of this frequency is a powerful instrument in determining the type of corrugation at a particular location. For example, in a project undertaken in the USA in the mid-1990s a simple measurement was made at each site with a ruler of the average corrugation wavelength and this was used with the line speed for that section of track to give the effective corrugation ‘frequency’ for the site [5, 6]. Frequencies of possible wavelength-fixing mechanisms, which were found from dynamic testing on track and vehicles, were shown on the same graph. An example of this simple analysis is shown in Fig. 2. At three of the six sites the corrugation ‘frequency’ corresponds to the frequency of the second torsional resonance of driven wheelsets (which is the case for the so-called ‘rutting’ corrugation, section 4), it is close to the pinned–pinned resonance frequency at one site (section 3), and lies slightly above the frequency of the second torsional resonance at two sites. At one of these two sites there was a trackform that had been associated with corrugation on this metro and others (section 8).

Treatments that have been demonstrably successful or that should be successful are summarized in Table 1, relevant figures in this article are shown, and references are provided. The majority of references are for work that has been undertaken since 1993. The principal exceptions to this are for those areas in which relatively little work has been done in the intervening years: heavy haul, light rail, and trackform-specific corrugation (sections 6–8). For the first two types of corrugation, this largely reflects the fact that a good understanding already existed in 1993, from which a solution had been developed that the railways found satisfactory.

3 ‘ROARING RAILS’ OR ‘PINNED–PINNED RESONANCE’ CORRUGATION

3.1 Characteristics

‘Roaring rails’ or ‘pinned–pinned resonance’ corrugation occurs primarily in straight track and gentle curves, where curving is undertaken with minimal flange contact. It is more likely to occur on the high than on the low rail in curves and is associated also with track carrying relatively light axle load traffic, i.e. <20 tonne. Examples from a metro system and from the UK main-line railway are shown in Figs 3 and 4.

If there is a so-called ‘white phase’ in the running band on the head of a rail, one of the first signs of

Fig. 2 Correlation of corrugation frequency and frequency of possible wavelength-fixing mechanisms (from reference [5])

Fig. 3 ‘Pinned–pinned resonance’ and ‘P2 resonance’ corrugation on the same rail
corrugation is a periodic constriction in the band of white phase. (Development of ‘white phase’ is not discussed here since it is not fundamental to corrugation development. This material is an extremely shallow (50 μm), hard, martensitic layer that apparently develops as a result of rapid heating and quenching of the rail surface during wheel slip \([43–45]\).) The corrugation shown in Fig. 4, which is typical of ‘roaring rails’ seen on the UK main-line railway system, would first have appeared as a periodic constraint of one of the two bright running bands that lie along the rail. In some circumstances the corrugation is very much clearer over and on the approach to sleepers (Fig. 4).

Corrugation measurements for the same rail on a metro system, before and after grinding, are shown in Fig. 5. This illustrates the effect of modulation not only at sleeper pitch (~0.9 m) but also, to a lesser extent, by a \(P2\)-resonance corrugation at a wavelength of ~300 mm. The filtered displacement in the 30–100 mm wavelength range and the one-third octave spectra (in the format prescribed in reference \([46]\)) are shown.

The irregularity shown in Fig. 5 is <100 μm (0.1 mm) deep but is nevertheless an extremely severe pinned–pinned resonance corrugation. A short wavelength corrugation of this amplitude would be sufficient for there to be loss of contact in the corrugation troughs for all but the lowest speed traffic, so that a wheel would hammer along the track contacting only the corrugation peaks. The magnitude of impacts in such cases can be several times the static wheel load. It is unsurprising that such corrugation is often known as ‘roaring rails’ and is associated with rapid deterioration of ballast, sleepers, and fastening components.

When the speed of traffic is closely controlled, there is a clear peak in the corrugation spectrum. This is the case for the metro in Fig. 5, for which the pinned–pinned resonance corrugation has a wavelength of

![Fig. 4](image-url) 'Pinned–pinned resonance’ corrugation with modulation over sleepers

![Fig. 5](image-url) Measurements of corrugation before and after grinding: filtered displacement (30–100 mm wavelength) and one-third octave spectra
rail corrugation: characteristics, causes, and treatments

∼40 mm. However, if speeds vary there is a correspondingly broad peak in the spectrum, as was noted in early measurements of corrugation from the British main-line railway [15].

When reprofiling is undertaken to a high standard, as has been done with the ground rail in Fig. 5, irregularities are not only extremely small but also show no trace of the periodicity of the original corrugation. The small periodic irregularities at 10 and 20 mm, which result from a slowly moving grinding train, are of a similar length to the contact patch between a train wheel and the rail, and are rapidly removed by traffic.

3.2 Cause

At its pinned–pinned resonance the rail vibrates as if it were a beam that was almost pinned at the sleepers (or periodic rail fastenings). The frequency of this resonance is

$$ f = \frac{\pi}{2L^2} \sqrt{\frac{EI}{m}} \left[ 1 - \frac{1}{2} \left( \frac{\pi r_g}{L} \right)^2 \left( 1 + \frac{2(1 + \nu)}{K} \right) \right] $$

where $m$ and $EI$ are the rail’s mass per unit length and bending stiffness, respectively, $L$ is the sleeper spacing, $r_g$ is the radius of gyration, and $K (~0.34)$ is the shear constant of the cross-section. Clearly the corrugation wavelength is longer the greater the sleeper spacing and the lower the rail stiffness. A typical frequency is about 770 Hz for 56 kg/m rail and a 0.7 m sleeper spacing or 1200 Hz for 60 kg/m rail and 0.6 m spacing. The 40 mm corrugation wavelength in Fig. 5 corresponds well to the predominant speed of about 65 km/h and a 460 Hz resonant frequency for rail at about 0.9 m spacing, and is similar to the wavelength of corrugation on main lines where speeds are very much higher.

Corrugation is worse over sleepers (Figs 4 and 5) because the support appears dynamically stiff and vertical dynamic loads are correspondingly greater.

The damage mechanism for pinned–pinned resonance corrugation is wear. It can be shown from relatively simple dynamic models of the track and vehicle (e.g. reference [47]) that dynamic loads at the frequencies of interest are high on corrugation peaks and low in the troughs. This behaviour encourages slip and wear of the troughs. A simple analytical method to calculate the corrugation growth rate in such circumstances is given in reference [4]. This analysis suggests that where vertical dynamic loads are similar, corrugation would be more severe the greater the steady-state wear rate. This corresponds to the evidence that pinned–pinned resonance corrugation in curves is usually more severe on the high rail.

It was proposed in reference [3] that resilient rail-pads should be effective in reducing this type of corrugation, but modelling suggests instead that they have relatively little effect on dynamic loads associated with the pinned–pinned resonance [10]. This has also been found in practice. For example, Fig. 6 shows the filtered profile of corrugation in the 30–100 mm wavelength range and the one-third octave spectra for two sections of track with supports of very different resilience. These sections of track are <500 m apart between the same stations on the same metro line, they are in curves of similar radius, and are both ground routinely at about the same time. Although the severity of pinned–pinned resonance corrugation is very similar (RMS amplitudes are 13.8 and 14.8 μm in the 30–100 mm wavelength range shown), there is a significant difference in longer wavelength corrugation, for reasons that are explained in section 5.

![Fig. 6 Corrugation on resilient (dark) and stiff (light) trackforms: filtered displacement (30–100 mm wavelength) and one-third octave spectra](image)
The pinned–pinned resonant frequency is significantly higher than the frequency of other wavelength-fixing mechanisms and accordingly gives the shortest wavelength for a given train speed. An extremely practical question that arises is why corrugation is seldom measured with a wavelength of <30 mm and extremely rarely with a wavelength of <20 mm. The answer to this question is found in the influence of contact mechanics between the wheel and rail. This essentially as a filter that attenuates wavelengths of <20 mm [7, 12].

4 RUTTING

4.1 Characteristics

‘Rutting’ was identified as a specific type of corrugation in reference [3] and there has since been a wealth of work in this area, e.g. [4, 5, 21–36]. This type of corrugation occurs primarily on the inside rail in curves, e.g. Figs 7 and 8, although it may also occur in straight track where traction or braking is particularly severe. Discrete irregularities such as welds and joints (e.g. Fig. 7) are common ‘triggers’ for corrugation and often fix the position of corrugation along the rail. Rutting usually has an extremely uniform wavelength and appearance and can develop quickly to a depth of tenths of a millimetre. Wear debris is sometimes apparent to the naked eye, which is seldom if ever the case for other types of corrugation. Plastic flow can occur on a well-developed corrugation (Fig. 8).

4.2 Cause

In a broad study of corrugation on North American transit systems, it was found that rutting of the inside rail in curves was not only the most common corrugation mechanism but was also associated with the second torsional resonance of driven wheelsets, e.g. Fig. 2 [5, 6]. The first and second torsional resonances are illustrated in Fig. 9. The frequency of the second torsional resonance is commonly about 250–400 Hz. A frequency of 250 Hz corresponds to a corrugation wavelength of 50 mm for vehicles at 45 km/h, which is a common speed for metro vehicles.

Rutting occurs where the traction ratio (the ratio of tangential to normal force) on one wheel is close to the friction limit, so that this wheel slips and drives the opposite wheel in the wheelset in a roll–slip oscillation. It is usually the wheel on the leading wheelset in a bogie on the high rail that slips, since the tangential force from curving is greatest on this wheel and the coefficient of friction is often less (because the gauge face of the high rail is lubricated to reduce wear, and there is often some migration of lubricant). Applied traction increases the tangential force on the outer leading wheel and reduces it on the lower leading wheel, thereby increasing the difference in tangential force across the wheelset and exacerbating the stick–slip oscillation. These influences are illustrated in Fig. 10 [31, 32], which shows the traction ratio at both wheels on leading and trailing axles of a bogie as a function of curve radius and for two values of applied traction. The traction ratio shown comprises
components from both curving and applied traction ($T/N = 0$ for a coasting vehicle; $T/N = 0.28$ for a locomotive or metro vehicle with half the axles motorized). A conventional vehicle suspension and wheel/rail profiles were modelled, and the coefficient of friction was assumed to be 0.4 at all contacts. The trailing wheelset 'steers' well for all cases, so there is a relatively low traction ratio at both outer and inner wheels ('high rail' and 'low rail' wheels, respectively). For the leading wheelset under coasting conditions ($T/N = 0$), the traction ratio from curving alone causes slip at the outer wheel for curves of less than about 600 m radius, in which the modulus of the traction ratio is limited by the coefficient of friction of 0.4: these would be conditions to initiate roll–slip oscillations in such curves. If the applied traction ratio were as great as 0.28, conditions for roll–slip oscillation exist even in curves of $>1000$ m radius.

The damage mechanism for rutting is clearly wear, which is quasi-periodic with high peaks corresponding to the slip phase of a roll–slip oscillation. The importance of longitudinal slip is illustrated by the longitudinal scuffing marks in Fig. 11, which shows the low rail of a 200 m radius curve on a suburban railway that had been treated with the so-called 'friction modifier' to reduce both corrugation and other rail damage (section 9). Because the friction modifier affects the slip phase of the roll–slip oscillation, it has been a particularly effective treatment of rutting [28–30, 35].

In the German language there is an interesting distinction between ‘Schlupfwellen’ ('slip waves'), which occur in curves, and ‘Riffeln’ ('ripples'), which occur in straight track. German research in the last 20 years has concentrated on ‘Riffeln’ and there has been very little work on ‘Schlupfwellen’.

5 OTHER P2 RESONANCE CORRUGATION

5.1 Characteristics

Tassilly and Vincent associated the $P_2$ resonance with longer wavelength corrugation on the rapid transit...
system (RATP) in Paris, although only as a factor that exacerbated the effect of the fundamental torsional resonance of wheelsets [24]. Evidence from field measurements and observations undertaken over the last 15 years indicates that the $P_2$ resonance is significant not only in heavy haul and light rail corrugation (sections 6 and 7) but also as one of the most prominent and frequent causes of corrugation on a wide variety of railways. For example, the longer wavelength corrugation in Fig. 3 has resulted from excitation of the $P_2$ resonant frequency, and this is the source of corrugation at 300–400 mm in the measurements (from the same railway) shown in Fig. 6. Also, while it was proposed in reference [3] that corrugation on tramways (Fig. 12) resulted from excitation of the fundamental torsional resonance of axles, this appears instead to be caused by the $P_2$ resonance. In both ballasted and non-ballasted track the $P_2$ resonance can cause long wavelength corrugation that is clear when enhanced artificially by rail grinding (e.g. Fig. 13), but is otherwise difficult if not impossible to see with the naked eye. The difficulty of both seeing and measuring such long wavelength corrugation may well have led to its relative neglect.

The frequency of both the $P_2$ resonance and the first torsional resonance of wheelsets is commonly in the range 50–100 Hz, so it is unsurprising that severe corrugation can result where both resonances are excited. This can occur in tight curves in metro systems, as noted by Tassilly and Vincent [24]. Corrugation that has arisen from a resonance in this frequency range is a particular problem on metros because the relatively low-frequency ‘rumble’ is transmitted well into buildings and occasional amplified by structural resonances that occur at similar frequencies.

5.2 Causes

The $P_2$ resonance is, by definition, the wavelength-fixing mechanism for this type of corrugation and wear is the damage mechanism. If there are circumstances in which the fundamental torsional resonance can be excited and if the resonant frequencies coincide, this exacerbates the effects of the $P_2$ resonance alone.

Empirical evidence from five transit systems cited in reference [6] suggested that corrugation resulting from the $P_2$ resonance on ‘direct fixation’ fastening systems was absent if the track support stiffness was less than about 30 MN/m per fastening assembly. This has been supported by subsequent measurements. For example, the measurements of Fig. 6 show that $P_2$-resonance corrugation is pronounced on a trackform in which timber sleepers embedded in concrete are the main resilient layer, but is essentially absent on a commercially available trackform (‘Pandrol Vanguard’) whose support stiffness is $\sim$5 MN/m per assembly.
6 HEAVY HAUL CORRUGATION

‘Heavy haul’ corrugation is the term introduced in reference [3] to describe the type of corrugation that had been found to exist on so-called heavy haul railways. Summary information for this type of corrugation is given in Table 1 and a typical example is shown in Fig. 14.

The dearth of literature in this area in the last 15 years strongly suggests not only that the problem is satisfactorily understood but also that the treatments proposed have been similarly satisfactory. The treatment adopted is the use of hard rail to resist plastic flow combined with routine rail grinding to reduce irregularities that excite the $P_2$ resonance.

Heavy haul corrugation is associated in the literature with straight track and the ‘high’ rail in curves. There is evidence that corrugation occurs by substantially the same mechanism on the low rail of over-canted curves on mixed traffic railways that carry significantly lower axle loads than on heavy haul railways (Fig. 15). The reason for this is that plastic flow occurs more readily the higher the traction ratio and normal contact stress [48]. For a vehicle curving at balance speed the traction ratio is greater at the high rail than on the low rail for almost all circumstances (Fig. 10). It is accordingly reasonable to expect that plastic flow would occur more readily on the high rail in these conditions, as in Fig. 14. However, when a bogie curves with cant excess, the traction ratio on the low rail wheel increases significantly because the trailing wheelset moves in towards the low rail and the leading wheelset moves towards the high rail, thereby increasing the angle of attack. There are high lateral loads on the leading, low rail wheel and also high contact stresses, because contact tends to occur towards the field side of the wheel, which is often slightly convex. The direction of plastic flow, towards the inside of the curve (Fig. 15), is consistent with lateral forces arising from the angle of attack of the leading wheelset.

Where corrugation occurs by this mechanism on the low rail of mixed traffic lines, it is often because track has been canted for a few high-speed passenger trains, whereas the more damaging traffic is higher axle load, lower speed freight trains.

An example is shown in Fig. 16 of spalling that has developed from RCF in the trough of a corrugation. It appears more likely that RCF is a consequence of the high loads in the trough of such a corrugation rather than its cause, as was suggested in reference [3].

7 ‘LIGHT RAIL’ CORRUGATION

Corrugation that bears many similarities to that experienced on heavy haul railways was identified in the 1980s on track that is now operated by Australian Rail Track Corporation [41] but is also present elsewhere. The corrugation propagates from welds and has a wavelength in the range 500–1500 mm (Fig. 17). As with heavy haul corrugation, the absence of recent literature in this area suggests that the problem is not only well understood but also that the treatments adopted for it are substantially satisfactory. Accordingly only summary information is provided in Table 1.
The principal difference between light rail and heavy haul corrugation is that the damage mechanism for the former is plastic bending of the rail, so that corrugation is measurable on both railhead and railfoot. The treatment that has been adopted is to straighten welds and joints, thereby reducing the main irregularities that excite the $P_2$ resonance, and to grind rails to eliminate existing corrugation. Modern rail steels and more robust rail sections have a sufficiently high bending strength to resist damage by this mechanism.

8 TRACKFORM-SPECIFIC CORRUGATION

Some trackforms are associated with rapid corrugation formation, while corrugation on others occurs less quickly. An example is shown for 20 m of track in Fig. 18, where there is a different trackform to the left and right of a weld. In some cases a trackform performs quite acceptably in some circumstances, if not indeed in most, but corrugates quickly in other circumstances.

Both Tassilly and Vincent [24] and Ahlbeck and Daniels [42] noted that corrugation occurred relatively rapidly on the low rail in curved track on a trackform comprising sleepers mounted in resilient boots. Such trackforms are often used in metro systems to reduce ground-borne vibration. Guidance was given in references [24] and [42] as to how to reduce the severity of such corrugation, including lubrication in curves. However, these measures do not guarantee that such corrugation is avoided.

A different non-ballasted trackform has given rise to the corrugation in Fig. 19. The wavelength-fixing mechanism in this case is the lightly damped resonance of a large, resiliently supported baseplate on the resilience of the railpad, at a frequency of $\sim 400$ Hz. Relatively stiff non-ballasted trackforms corrugate from excitation of the $P_2$ resonance (section 5).

A common characteristic of trackforms on which corrugation occurs preferentially in some if not all circumstances is a pronounced resonance. In the case of

Fig. 17 Profile of light rail corrugation, showing propagation from the rail ends (about 15 m rail length)

Fig. 18 Trackform-specific corrugation: different trackform to the left and right of the weld at 15.725 km

Fig. 19 Corrugation (25–30 mm wavelength) resulting from resonance of baseplate on railpad
‘booted sleeper’ trackforms, the significant resonance is one for lateral excitation at the railhead [24, 42], whereas in others (e.g. for P2-resonance corrugation and the trackform in Fig. 19) the resonance is one in which there is a high vertical dynamic load.

9 CORRUGATION MEASUREMENT

The ‘CAT’ or corrugation analysis trolley (Fig. 20), which has been developed in the last 15 years, has provided consistent, reliable corrugation measurements that enable conditions on different systems to be compared, e.g. Figs 5, 6, and 18. This instrument has been widely used to measure both corrugation and acoustic roughness [4, 19, 22, 33, 49]. It is possible to make long measuring runs (limited only by the stamina of the user and storage on the computer) at a walking speed of $\sim 1$ m/s [51]. This equipment, which is a development of Harrison’s trolley profilometer [23], is robust, reliable, and used by main-line and metro railway systems, universities, consultancies, and grinding contractors worldwide. Equipment such as this is essential in order to reliably demonstrate that rail has been reprofiled to the requirements of the European Standard for reprofiling of rails [50] or that the rail is ‘smooth’ to the requirements of ISO 3095 [46] or the evolving ‘technical specifications for interoperability’.

10 CORRUGATION TREATMENT

Table 1 lists treatments of different types of corrugation. The success of some treatments has been demonstrated, while in other cases the success of the treatment should follow from the explanation of cause that is given here. Whether or not a treatment is a preventive measure, a cure of an existing problem, or simply a means of reducing the severity of corrugation depends on several factors, including particular circumstances, the type of corrugation, and whether the treatment is applied in isolation or as one of several measures. To take the simplest example, the classical treatment of corrugation is rail grinding, which is regarded by many as a palliative rather than a cure. However, if corrugation is initiated by railhead irregularities (as is manifestly the case with heavy haul and light rail corrugation, e.g. Fig. 17), removal of existing irregularities will often delay recurrence of corrugation sufficiently to be considered in practice as an extremely satisfactory treatment even if it does not eliminate the underlying mechanism that causes the corrugation. This underlying mechanism does indeed exist on all tracks. It is also clear that corrugation does not occur everywhere that trains curve with cant excess, but where it does there is excellent evidence that reduction of cant would greatly reduce if not eliminate corrugation.

10.1 Reprofiling and removal of corrugation

It is clear from the basic mechanism that gives rise to any type of corrugation (Fig. 1) that reduction of railhead irregularities is a basic treatment of all types of corrugation. In the case of heavy haul and light rail corrugation, where the damage mechanism involves exceedence of some threshold (the shakedown limit to cause plastic flow or yielding of the rail in bending), removal of irregularities may itself be sufficient to prevent the recurrence of corrugation. Where the damage mechanism is wear, reprofiling is more of a treatment than a cure, albeit an extremely successful one if it is administered satisfactorily.

An example of grinding that has satisfactorily removed corrugation is shown in Fig. 21(a), whereas a rail on which grinding has left a severe, periodic, quasi-transverse ‘signature’ is shown in Fig. 21(b). The distance between grinding scratches in the latter case is simply $L = v/f$, where $v$ is the speed of the grinding train and $f$ is the rotational frequency of the motors (typically 50 or 60 Hz). Corrugation would recur relatively slowly on the rail with minimal roughness and periodicity, but can grow particularly quickly if the grinding signature excites a possible wavelength-fixing mechanism. A European standard now exists that states objective limits on the longitudinal irregularities that should remain on a rail after reprofiling [50]. Measurements taken using the instrument shown in Fig. 20 demonstrate that major rail grinding companies routinely grind rail to this standard, in Europe and elsewhere.
An alternative method for controlling the longitudinal profile is in principle offered by ISO3095, which is intended to standardize the method of measuring rolling noise from rail vehicles [46]. This standard states limits on rail roughness that can exist at a site where vehicle testing is undertaken.

It is also important to reduce discrete irregularities at welds that ‘trigger’ corrugation. Rails of 80 m length are now common, with which there are many fewer welds than with rails of 15 m length, such as those in Fig. 17. A reasonable requirement for welds is that they should be finished to an irregularity of <1.5 mrad, i.e. <0.4 mm under a 1 m straight edge.

10.2 ‘Hard’ rails

Hard rails are a treatment of all types of corrugation. Insofar as the yield strength of these rails is high, they resist plastic flow and are therefore a treatment of heavy haul corrugation, while a high bending strength resists light rail corrugation. If the threshold for plastic flow or plastic bending is raised sufficiently, corrugation by these mechanisms may be eliminated entirely simply by satisfactory rail selection.

It was proposed in reference [3] that hard rails should alleviate those types of corrugation for which wear is the damage mechanism. Although no evidence existed at the time that this was the case, the success of the treatment has since been demonstrated in tests on main-line track in Germany in which corrugation developed at about two-thirds of the rate on 350BHN rail as on 260BHN rail [16]. The reduced corrugation propensity of open hearth rail steel, e.g. references [3] and [13], remains unexplained, and is now slightly academic since open hearth rail steel is rarely if ever produced.

10.3 Control of friction

Friction is potentially significant for all types of corrugation in which wear is the damage mechanism, insofar as the higher the coefficient of friction the greater the potential wear rate. If the railhead friction coefficient can be controlled to a value of about 0.35, this is sufficient for vehicle traction and braking while limiting damage from plastic flow and wear. Rain, rust, and a generally moist atmosphere are often sufficient to maintain friction to modest levels. However, in a dry environment, particularly in dry tunnels, the friction coefficient can approach 0.6, with severe consequences for wear.

So-called ‘friction modifiers’ are commercially available to control the coefficient of friction to levels of about 0.35. These offer a demonstrably successful means of controlling all types of corrugation for which wear is the damage mechanism [28–30, 35]. The treatment is particularly effective in treating ‘rutting’, which results from a roll–slip oscillation of the wheel on the rail since these substances limit the reduction of friction with sliding speed, thereby eliminating the potential instability associated with a falling friction characteristic.

Although some control of railhead friction can be obtained by judicious adjustment of gauge face lubrication, this should be used only with great care. Too much oil or grease on the railhead can lead to trains being unable to brake satisfactorily.

10.4 ‘Improved steering’ and reduction of tangential loads

Curves are particularly prone to corrugation as a result of the high tangential forces that arise from steering, particularly in combination with applied traction. There are several ways of reducing these forces by design of the track, the vehicle or the wheel and rail profiles, as well as by controlling friction itself (section 10.3).
Curving forces are particularly damaging when there is excessive cant. Reducing cant not only gives more similar tangential forces on opposite wheels in a wheelset [31] but also reduces the tangential force on the low rail. This reduces stick–slip oscillation, and thereby rutting, and heavy haur tail corrugation where this occurs on the low rail. Reduction of cant is also inherently safer since it reduces the angle of attack of the bogie and thereby also the potential for flange-climb derailment.

Wheel and rail profiles that increase rolling radius difference are an effective method of reducing curving forces on an existing railway, and demonstrably successful in reducing corrugation in curves. Profiles that increase rolling radius difference encourage contact along the gauge shoulder and gauge corner of the rail, thereby increasing contact stresses. Consequently, such profiles are best designed judiciously as one component of a wheel/rail interface strategy that considers vehicle dynamic behaviour as well as wheel and rail damage.

Applied traction causes stick-slip oscillation to occur in less severe curves. Consequently, if corrugation was considered at an early stage in the design of a railway system, it would be desirable to place curves far from stations.

Differences in wheelset diameter and misalignments of wheelsets within a bogie should be strictly controlled in order to minimize the resulting tangential forces and thus the propensity for wheels to slip. Mono-motor bogies should be avoided for this reason.

10.5 Trackform

Classical ballasted track provides a combination of resilience and damping that fortuitously avoids unnecessary resonances and reduces the effect of those that do exist. One of several reasons that corrugation is associated with metros is that non-ballasted trackforms are common and there is little guidance as to how corrugation might be avoided on such trackforms.

In order to reduce the potential for corrugation, a trackform should have a low $P_2$ resonance, and high damping of any resonant behaviour that cannot be avoided. The trackform in Fig. 6 for which there is no long wavelength peak in the one-third octave spectrum has excellent characteristics in this respect.

‘Roaring rail’ corrugation appears to be an unavoidable consequence of track that is supported periodically and on which trains travel sufficiently quickly that the resulting corrugation is longer than the contact patch. However, roaring rail corrugation tends to be shallow, so that it can be relatively easily controlled by routine rail grinding. In principle a continuous support should reduce the severity of roaring rail corrugation. However, continuously supported track tends to be relatively stiff, thereby increasing the likelihood of $P_2$-resonance corrugation. It is also more difficult to control track geometry during construction. Introduction of an artificial aperiodicity in support spacing appears intuitively attractive. However, the likely effect for any practical aperiodicity is that the pinned–pinned resonance and anti-resonance would move to those frequencies corresponding to the mean support spacing, and the modulation of contact force would decrease slightly. The severity of corrugation would decrease slightly but maintenance would be significantly more expensive.

It was suggested in reference [3] that resilient railpads were a possible panacea for several types of corrugation. Experience in the meantime indicates that corrugation is affected relatively little by the railpad except where this provides the principal resilience of the track support.

10.6 Wheelsets

When corrugation results from the torsional resonance of solid axles, modification of this dynamic behaviour may significantly reduce the problem if not solve it entirely [5, 6]. There is some evidence that rutting is greatly reduced when the wheelset is torsionally resilient, as occurs with some types of resilient coupling of driven axles. High torsional resilience of non-driven axles is rare. The opportunity still exists to develop a torsional dynamic vibration absorber for an operating vehicle to attenuate rutting corrugation, as proposed in reference [6].

10.7 Traffic

All types of corrugation whose cause has been explained to date are substantially constant-frequency phenomena. Consequently, the more consistent the speed of trains and the less varied the traffic, the more consistent the wavelength of any corrugation that results from excitation of a particular wavelength-fixing mechanism. Consistency is the bane of any dynamic problem and variety can be at least part of the solution. Measurements have demonstrated that pinned–pinned resonance corrugation resulting from trains travelling at one speed can actually be worn out by changing the train speed, and re-established at a different wavelength [22]. A true mixed traffic railway, with a mix of both vehicle type and train speed, is an ideal antidote to corrugation formation, but is increasingly uncommon.

11 CONCLUSIONS

A review of rail corrugation by Grassie and Kalousek in 1993, which has been widely cited in the subsequent literature, proposed that the phenomenon could be categorized by different ‘wavelength-fixing’
and ‘damage’ mechanisms. Six different types of corrugation were thus identified at that time. In the intervening years there has been relatively little published work in the areas of light rail and heavy haul corrugation, from which it could reasonably be concluded that these are not only well understood but also that satisfactory treatments have been developed and are being implemented. Those treatments are primarily routine repolishing of the rails, minimization of irregularities at welds, and the use of hard rails (for heavy haul corrugation) or rails with greater bending strength (for light rail corrugation).

Evidence of heavy haul corrugation on the low rail of curves on mixed traffic railways is examined here. Such corrugation occurs when curves are over-canted for lower speed, heavier freight traffic. A high angle of attack results from poor steering, causing leading wheelsets to run in contact with the field side of the low rail. High contact stresses result from these contact conditions and high tangential loads from poor steering. Together these cause plastic flow. If curves were instead canted for lower speed traffic, this would reduce both corrugation and other types of damage that occur on the low rail in curves. This would also be inherently safer since the lower angle of attack decreases the risk of flange climb derailment.

With hindsight it is clear that most research on corrugation from the 1970s until the late 1990s was on roaring rails. This research has demonstrated conclusively that roaring rails are a constant-frequency phenomenon whose wavelength-fixing mechanism is the rail’s pinned-pinned resonance. Although this wavelength-fixing mechanism is unavoidable to the extent that it is desirable for track to be supported periodically, both hard rails and control of friction are treatments for this type of corrugation. Where roaring rails occur on the high rail in curves, they can be reduced by any measure that improves curving and reduces wear of the high rail.

Since the mid-1990s there has been a wealth of research worldwide on rutting. This has demonstrated conclusively not only that rutting is a roll–slip oscillation associated with differential tangential force on the two wheels of a wheelset but also that the wavelength-fixing mechanism is the second torsional resonance of the wheelset. Rutting occurs preferentially on the low rail in curves because the curving force on the outer leading wheel of a bogie is higher than on the inside wheel, thereby causing the outer wheel to slip and drive a roll–slip oscillation on the inner wheel. Applied traction on driven axles causes the outer wheel to slip in curves of greater radius.

The trackform has a more significant effect on corrugation than was recognized in 1993, and there are several trackform-specific types of corrugation. Resonant behaviour should be avoided as far as possible and those resonances that do exist should be well damped. Damage from the P2 resonance can be minimized by ensuring that a trackform has adequate resilience and damping.

Although it was thought in 1993 that RCF could be a distinct damage mechanism, it appears more likely that RCF is a consequence of high loads that result from corrugation rather than being the means by which the rail is initially damaged.

Considerable advances have been made that enable corrugation to be treated and in many cases prevented. Substances that modify the coefficient of friction between the wheel and rail have been deliberately developed as a method of reducing corrugation. These have been widely and thoroughly tested, and are extremely successful treatments, particularly of the roll–slip oscillation that gives rise to rutting. It has been demonstrated that hard rails reduce corrugation for which the damage mechanism is wear, as well as being one of the principal components of the successful treatments of heavy haul corrugation. P2-resonance corrugation has been essentially eliminated on at least one commercially available, highly resilient non-ballasted trackform that was developed primarily to reduce ground-borne vibration. Wheel and rail profiles offer a means for reducing corrugation, particularly in curves, but should not be considered in isolation as profiles that improve curving behaviour can exacerbate other problems. It remains the case that any other method of reducing curving forces, such as the use of self-steering bogies, should also reduce corrugation in curves but demonstration of this remains a challenge for the future.

Rail grinding remains the most widely used treatment of rail corrugation and will continue to be essential even if treatments are found that reduce the rate of corrugation development. Although many railways have developed their own grinding specifications, a European standard has been developed in the last 15 years that can be applied to control the quality of rail grinding in an objective and readily quantifiable manner. Equipment has been developed with which a continuous measurement can routinely be made of tiny amplitudes of corrugation over essentially an unlimited distance. This equipment can be used not only to control grinding but has also provided a widely used tool in corrugation research.

For decades it was thought by many (including the author) that corrugation was a phenomenon in which the wavelength varied relatively little with speed. This belief was based on a substantial volume of circumstantial evidence, such as that shown in Fig. 22, which contained data from a Midland Railway survey in 1911, observations from Harrison’s doctoral research on British railways in the 1970s, and from Vancouver Skytrain in the 1980s. It is no longer possible to examine whether all these data arose from a single corrugation mechanism, but there is convincing evidence for an alternative explanation, summarized here in Table 1. This is essentially that corrugation...
at lower speeds results largely from lower frequency wavelength-fixing mechanisms, whereas at higher speeds results from higher frequency wavelength-fixing mechanisms. To take some examples given here, roaring rail corrugation could result at a wavelength of 40–60 mm on a metro line with vehicles at 65 km/h and a pinned–pinned resonance at 460 Hz, on a British main-line with vehicles at 160 km/h and a pinned–pinned resonance at 770 Hz, and on a German main-line with vehicles at 250 km/h and a pinned–pinned resonance at 1200 Hz. Rutting could occur at roughly the same wavelength on a metro with vehicles travelling at 45 km/h from the second axle torsional resonance at 250 Hz. The data in Fig. 22 demonstrate the effect of what Prof Knothe has termed ‘non-steady-state contact mechanics’ in ensuring that almost no corrugation is measured with a wavelength of <20 mm [12].

There may exist a single, all-encompassing theory that explains all corrugation, and perhaps also explains neatly why corrugation occurs from different mechanisms in different places. This contribution provides guidance but no such neat solution. It instead surveys developments in the area of rail corrugation from the viewpoint of a practitioner and railwayman, whose interests lie more in providing solutions that have a sound theoretical basis and whose effects are thoroughly documented and understood than in perfecting the theory. The success in both explaining and treating rail corrugation would not have been achieved without accepting not only that both theory and observation have contributed immensely to this area, but also that each has its limitations.

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Q1 Reference 51 appears before reference 50. This is against the Journal style; hence please re-number the reference to maintain the order.