Rail corrugation: characteristics, causes and treatments

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Corrugation is a phenomenon which has excited the interest of railwaymen for more than a century, but for which there often does not appear to be a cure. It has generally been realized that there are in fact different corrugation mechanisms, and that some types of corrugation can indeed be prevented. The present paper draws upon both the literature and the authors' experience to categorize corrugation according to two mechanisms: that damaging the rail (wear, plastic flow etc.) and that fixing the corrugation wavelength. Six types of corrugation are thus identified and described by the following proposed terminology: 'heavy haul', 'light rail', 'booted sleeper', 'contact fatigue', 'rutting' and 'roaring rails'. Both mechanisms are well understood for all but the last type of corrugation, for which a convincing and well-validated wavelength-fixing mechanism has yet to be demonstrated. Despite the absence of this understanding, satisfactory treatments of, and in many cases also means of preventing, all six types of corrugation have in fact been developed. Excitation of the vehicle's unsprung mass on the track stiffness is the most common wavelength-fixing mechanism.

1 INTRODUCTION

Corrugation of rails occurs in one manifestation or another, and often in several, on nearly every railway system. Its removal by grinding provides work for several international grinding companies and already cost the industry world-wide in the order of at least US $10^6 per annum in the early 1980s (1). The phenomenon is a more or less periodic irregularity of the running surface which is often visible to the naked eye, and gives rise to high dynamic loads between wheel and rail, degradation of the ballast and other track components, and noise. The latter is particularly annoying with the short-wavelength corrugations which excite vibration in the audible frequency range. Corrugation is therefore a phenomenon of great practical concern to the railway industry: substantial savings could in principle be made if it could be prevented rather than simply treated, and if there existed a few guidelines which could be followed to make corrugation less likely on new railway lines. The purpose of this paper is to review the topic of rail corrugation in this light, and particularly to consider what has been learned from work which has been done in this area in the last 20 years. Six different types of corrugation with significantly different characteristics are identified, the mechanism giving rise to each type of corrugation is discussed, and recommendations are made as to what has been done or could be done to treat the malady most effectively, and where possible prevent it.

It is fundamentally important to appreciate that 'corrugation' is not a single phenomenon with a single cause and a single solution or treatment: considerable confusion can otherwise arise. This may be apparent from a bibliography on rail corrugation which was compiled by the Research Department of the then British Railways (BR) in 1961 (2) which contains references from almost every year in the period 1904-1960; the flow of literature has not abated since. Considerable contradiction apparently exists, particularly in the early literature, regarding possible causes or contributory factors: for example, some investigators believed that 'soft' rails were responsible whereas others thought the opposite; in some places wear was held to be the cause whereas elsewhere the cause was thought to be 'flow' of the rail. As early as 1922 a paper appeared which was optimistically entitled 'How to avoid or overcome rail corrugation' (3); had this indeed been possible, the present paper would be unnecessary.

Since BR's bibliography appeared, the structured approach which has developed to understand the phenomenon has borne fruit in the realization that corrugation is a family of phenomena with superficially similar features: primarily the periodically irregular running surface at roughly similar wavelengths. Although some differentiation is often adopted between 'long' and 'short' wavelength corrugation (usually about 200-300 mm and 25-80 mm respectively), it is shown here that classification by wavelength alone is insufficient. Corrugations differ in the detailed appearance of the rail, the root cause, and consequently also in the treatment which can most effectively be adopted. All of these factors are discussed in this paper and areas are identified in which further work is most required.

Although this paper primarily draws together work which has appeared in the literature, some gaps have tentatively been filled by the authors where a full understanding based on published material is incomplete. Some of these gaps have also been filled by identifying similarities between corrugation observed and investigated in different places.

The paper has developed in part from a less detailed review by one of the authors which appeared in 1990 (4).

2 CLASSIFICATION OF CORRUGATION BY MECHANISM

The mechanism of corrugation formation can usefully be regarded as comprising two features: a wavelength-
fixing mechanism and a damage mechanism, as illustrated in the basic feedback loop of Fig. 1. The rail is initially uncorrugated, but the profile has components of roughness at all wavelengths, and inevitably some irregularities are larger than others. This initial roughness in combination with other factors such as traction, creep and the friction characteristic at the wheel/rail contact excites dynamic loads which cause damage of some type, thereby modifying the initial profile. Provided that sufficient trains pass over the site at a similar speed, the wavelength at which the dynamic load varies is similar from one train to another, and corresponds to the specific wavelength-fixing mechanism. The same irregularities excite each train, and the damage caused by one train tends to exacerbate vibration of subsequent trains, leading to further damage at a specific wavelength. The dynamic loads may be either normal or in the plane of the wheel/rail contact. Typical damage mechanisms are plastic flow and wear.

By means of this classification by wavelength-fixing and damage mechanisms, it appears that there are essentially six common types of corrugation. These can be distinguished by names given in Table 1: 'heavy haul' and 'light rail' corrugation; corrugation on resiliently 'booted' sleepers; 'contact fatigue' corrugs in curves; 'rutting'; and 'roaring rails'. This nomenclature is intended to be useful while not substantially altering terms which may previously have been used more loosely: for example 'roaring rails' [a term which appears at an early date in BR's bibliography (2)] are probably most commonly known as 'short pitch corrugation', 'riffeln' in Germany, or the like, but it is clear from Table 1 that other types of corrugation have similar wavelength. Each of the six types of corrugation has a particular combination of wavelength-fixing and damage mechanisms. The following information is also tabulated:

(a) typical wavelength of the corrugation: for all except the roaring rail corrugation this is the quotient of the predominant vehicle speed \( v \) and a characteristic frequency \( f \), that is

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

(b) appropriate references to the corrugation in the literature;

(c) reference to relevant figures in this paper.

Almost all of the information tabulated has been derived from the appropriate references, but some reasonable deductions have also been made where insuffi-

![Fig. 1 Components of a general corrugation mechanism](image)

### Table 1 Types and characteristics of corrugation

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength mm</th>
<th>Wavelength-fixing mechanism</th>
<th>Damage mechanism</th>
<th>References</th>
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<td>1 Heavy haul</td>
<td>200–300</td>
<td>P2 resonance</td>
<td>Plastic flow in troughs</td>
<td>(5–7), (10)</td>
<td>Fig. 2</td>
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<td>2 Light rail</td>
<td>500–1500</td>
<td>P2 resonance</td>
<td>Plastic bending</td>
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<td>3 Booted sleepers</td>
<td>45–60 (RATP)</td>
<td>Sleeper resonance; flexural</td>
<td>Wear of troughs from lateral oscillation; plastic flow of peaks</td>
<td>(14–16)</td>
<td>Fig. 4</td>
</tr>
<tr>
<td></td>
<td>51–57 (Baltimore)</td>
<td>resonance of wheelset</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Contact fatigue</td>
<td>150–450</td>
<td>P2 resonance laterly</td>
<td>Rolling contact fatigue</td>
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<td>5 Rutting</td>
<td>50 (trans)</td>
<td>Torsional resonance of wheelset; peak vertical dynamic force, for example P2 resonance</td>
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<td>(14, 15), (27–30)</td>
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<td></td>
<td>200 (RATP)</td>
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<td></td>
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<tr>
<td></td>
<td>150–450 (FAST)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>6 Roaring rails</td>
<td>25–80</td>
<td>Unknown</td>
<td>Wear of troughs from longitudinal slip</td>
<td>(31–42)</td>
<td>Figs 9–11</td>
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</table>
cient published work has been found. Inadequacies in the present state of knowledge and further details of each type of corrugation are discussed further in the following sections of the paper.

3 HEAVY HAUL CORRUGATION

3.1 Characteristics

A type of relative long wavelength corrugation is associated particularly with heavy haul railways, where there are high wheel loads (in excess of 15 tonnes), unit trains and low, consistent speeds. An example is shown on the rail in the background in Fig. 2; the rail in the foreground is uncorrugated. Their cause (both the wavelength-fixing mechanism and the damage mechanism) was probably understood earlier than that of any other type of corrugation. Research into their cause and possible treatments was undertaken primarily in Australia, see for example (5-7). The corrugations propagate from welds, joints and other discrete railhead irregularities. Although they are not restricted to curves they do occur preferentially on the 'high' rail in curves (as in Fig. 2) regardless of track superelevation or operating speeds (6). The typical wavelength of 200–300 mm corresponds to a frequency of about 30 Hz for the low speeds of loaded heavy haul trains. There is gross plastic flow in the corrugation troughs and 'mushrooming' of the railhead. At corrugation sites the ballast around the sleepers is much disturbed, appearing like white pebbles recently swept up on the dark beach of the remaining ballast: this is a common feature of all types of corrugation on ballasted track, or indeed at any site where there are high dynamic loads and excessive sleeper vibration.

3.2 Cause

The pertinent damage mechanism is clearly gross plastic flow as a result of excessive contact stresses. The wavelength-fixing mechanism is resonance of the unsprung mass (in this case the unsprung mass of heavily loaded ore cars) on the track stiffness; this loaded track resonance gives rise to what are now commonly known as P2 forces, following British Rail's terminology, for example (8). The periodically high dynamic loads excited by railhead irregularities are superposed on the high static loads, giving rise to periodic plastic flow. When the wheel is in contact at the gauge corner of the high rail, the conformity is poor and normal contact stresses are correspondingly high: consequently plastic flow occurs preferentially on the high rail. Consistent types of vehicle (and hence resonant frequency) and consistent speeds of loaded trains give rise to a fairly constant corrugation wavelength.

3.3 Treatment

The only practical treatment for this type of corrugation is to select a sufficiently hard rail steel and to ensure that railhead irregularities are sufficiently small as to reduce the contact force below the level which can be borne by the rail. Accordingly the treatment most commonly adopted for existing corrugation is to grind the rail and straighten welds, thereby minimizing the initial roughness which excites vibration of the vehicle on the track stiffness and gives rise to high dynamic loads. In principle the dynamic loads could also be reduced using primary suspension on wagons and bogie-hung traction motors on locomotives to reduce unsprung mass, but these are expensive modifications with limited benefit. Typically rails are ground regularly to maintain low dynamic loads and allow high static loads to be carried.

Initially the rail should be selected with adequate yield and tensile strengths to resist corrugation for typical railhead irregularities. The photograph of Fig. 2, which was taken at a test site set up by BHP's Melbourne Research Laboratories, is an illustration of the success of this initial rail selection process: the uncorrugated rail in the foreground is made of head-hardened rail, whereas the standard carbon rail in the background is corrugated. Marich and Maass have tabulated the appropriate yield and tensile strengths (7), and a design method has been proposed to select rail accordingly for particular railhead irregularities (9).

Some difficulties can arise with aluminothermic welds and occasionally also with flash butt welds, particularly on head-hardened rail, because the welds are softer than the parent material; these soft areas can dip under heavy wheel loads (10). Improvements in welding are accordingly desirable to reduce this differential hardness.

4 LIGHT RAIL CORRUGATIONS

4.1 Characteristics

A corrugation which bears many similarities to that experienced on heavy haul railways was identified in the
1980s on track operated by Australian National Railways (AN) (11, 12), but is also present elsewhere. The corrugation propagates from welds and has a wavelength in the range 500–1500 mm; the profile of a badly corrugated rail is shown in Fig. 3. The typical wavelength of 700 mm again corresponds to an excitation frequency of about 30 Hz at predominant vehicle speeds (which are substantially higher than on heavy haul railways). Amplitudes of 1 mm or more are often measurable on both railhead and railfoot. The phenomenon is associated particularly with relatively light, 47 kg/m rail, although some is present also on older 53 kg/m rail; 60 kg/m rail has to date been unaffected. Gross plastic flow of the railhead is uncommon.

4.2 Cause

The wavelength-fixing mechanism for light rail corrugation is the same as that for heavy haul corrugation: resonance of the vehicle's unsprung mass on the track stiffness, excited primarily by irregular welds. In this case the critical vehicles were identified as locomotives, which had relatively high static wheel loads (about 11 tonnes) and high unsprung mass (12). The damage mechanism was shown to be the yield of the rails in bending, which gave rise to full section deformation (or 'rippling') of the rail. The rail steel used at that time for the 47 kg/m and 53 kg/m rails had a relatively high tensile and low yield strength, so that the load required to cause plastic bending was lower than that required to cause plastic deformation of the work-hardened surface layer. For most types of rail steel, plastic bending occurs at much higher loads than plastic flow. The relatively wide range of wavelengths arose from the different speeds and types of vehicle; where these were consistent, wavelengths are also consistent.

4.3 Treatment

The treatment which has been adopted by AN for this type of corrugation has been successful to date in eliminating existing corrugation and preventing its recurrence. The principal components of the treatment are the same as those for corrugation on heavy haul track: reduction of railhead irregularities, particularly at welds, to a sufficiently small level that the sum of dynamic and static loads is insufficient to yield the rail in bending (12). For the conditions on AN, it was sufficient to reduce the effective ramp irregularity to an amplitude of about 7 milliradians (13). To allow higher speeds to be attained, locomotives with a lower unsprung mass have been acquired, thereby reducing the P2 force for a particular irregularity. The rail steel now used has higher yield strength and greater flexural rigidity, which gives greater resistance to this type of corrugation.

5 CORRUGATION OF BOOTED SLEEPERS

5.1 Characteristics

Track has been laid in many places, primarily in metro systems, using monobloc or twin block concrete sleepers with resilient 'boots' to reduce ground-borne vibration from the track. Corrugation has occurred on several such systems on the low rail in severe curves with a radius of less than about 400 m. There is no corrugation on adjacent sections of track of different construction. Examples of this type on twin block sleepers in Paris (14, 15) and Baltimore (16) have been well documented, but essentially identical corrugations exist on resiliently booted monobloc sleepers on the Terminal 4 loop at Heathrow Airport on London Underground (Fig. 4). Corrugations of measurable amplitude have developed within days of grinding to remove all previous traces of corrugation (14, 16). Corrugation wavelengths of about 50 mm are similar at all sites.

On fully developed corrugation there is plastic flow forward and outward (towards the inside of the curve) on the corrugation peaks at an angle of about 30 degrees to the direction of traffic [Fig. 4 and (16)]. Microcracking commonly exists at the gauge corner of the high rail at corrugation sites. In Baltimore, corrugation was often found to be more severe on the run up to a sleeper (16).

5.2 Cause

The damage mechanism for this type of corrugation is initially differential wear of the corrugation troughs. The wavelength-fixing mechanism is the ill-damped flexural natural frequency of the resiliently booted sleepers...
(at 310–345 Hz in Baltimore and 250–350 Hz in Paris) which gives rise to an anti-resonance at the railhead and a maximum in the vertical dynamic contact force. There are also wheelset resonances in the same frequency range. Consequently variations in normal load brought about by railhead irregularities cause variations in traction at the same frequency, and large variations in slip and wear. The variations would be more severe if there were stick-slip, which appears to be present in Baltimore (16). The leading wheelset on each bogie, at which the gauge spreading forces are greater, is believed to be responsible for the corrugation in both Paris and Baltimore. Any modulation of the corrugation severity at sleeper pitch probably arises from excitation of the lateral ‘pinned-pinned resonance’ (which is typically at about 350 Hz); in these circumstances the contact force tends to be greater towards the sleeper than at midspan [as illustrated for the vertical pinned-pinned resonance in (17)]. As the corrugations develop, variations in the normal load become more severe. Plastic flow in a well developed corrugation probably arises from these high dynamic loads combined with the high traction between poorly steering wheelsets and the rail; whereas at low frequencies the phase of contact force on corrugation is such as to promote plastic flow of the troughs (as with heavy haul corrugation, Section 3), at higher frequencies the contact force is greater on the peaks of the corrugation (exacerbating plastic flow) and less in the troughs (exacerbating plastic flow and wear) (17). For this type of corrugation excitation by the railhead profile alone is insufficient. High lateral creep in a curve at the leading wheelset of a ‘soft’ bogie is also required in order to encourage differential slip of the more lightly loaded inner wheel.

5.3 Treatment
Several successful treatments of existing corrugation have been developed. In both Paris and Baltimore, resilient railpads have been introduced: these decouple the sleeper from the rail and slightly reduce the anti-resonant frequency of the track, thereby reducing the vertical dynamic contact force and separating the track’s anti-resonant frequency from the wheelset’s resonant frequency. In Baltimore, the corrugation growth rate was significantly reduced by lubricating the gauge corner of the high rail: this reduced both friction and wear. In both cases grinding was used to remove existing corrugation.

With regard to prevention of such corrugation on new track, it is clearly desirable to avoid using sleepers with ill-damped, resilient ‘boots’, whether they be monobloc or twin block sleepers. It is particularly important to avoid using such sleepers in curves. A similar wavelength-fixing mechanism may exist with track laid on individual, lightly damped, resiliently supported concrete blocks. Some improvement should be possible if bogies were steered better (for example, with higher concavity wheel profiles), and if the rails were asymmetrically profiled to improve steering: there is, however, a limit to what can be achieved with an existing bogie design in a 400 m curve. Interlinking wheelsets to improve steering would be beneficial. Microcracking at the gauge corner of the high rail might be reduced by grinding to increase the gauge corner radius and reduce contact stresses. A friction modification agent such as that used on the railhead of the Vancouver Skytrain system (Section 8) would reduce the propensity for stick-slip vibration of the wheel and rail. Since dry wear is the initial damage mechanism, wear-resistant head-hardened or alloy rails may be beneficial, as has been found with the rutting corrugation which occurs in curves on north American freight lines (Section 7).

6 CONTACT FATIGUE CORRUGATIONS IN CURVES

6.1 Characteristics
This type of corrugation has been documented primarily in well lubricated curves on Canadian freight railways and has a wavelength in the range of 150–450 mm which is often irregular at any one site, as shown in Fig. 5 (18–20). The depth is typically 0.5 mm and can reach 2 mm. Where corrugation occurs the rail surface is always flaked. Flakes at the gauge corner of the outer (or high) rail easily break off and form what are known as ‘shelly spots’. The area where the size of flakes, intensity of the shelly spot or density of associated surface cracks is greatest becomes the corrugation trough. Plastic deformation and flow, which are primarily towards the inside of the curve, are also most pronounced in the troughs. Corrugation typically appears first on the inside (low) rail if the track gauge is wide.

Fig. 5 Profile of (a) corrugation at FAST; (b) contact fatigue corrugation
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and on the outside (high) rail if the gauge is tight or if the rail head profile is relatively flat that is, the transverse radius of the crown is greater than about 300 mm. Although contact fatigue corrugation develops in a mild form on track with flange lubrication in a dry climate, it is greatly exacerbated by water, particularly in the form of monsoon rain or drifting snow. A well-developed contact fatigue corrugation is shown in Fig. 6.

6.2 Cause

The damage mechanism for this type of corrugation is evidently rolling contact fatigue (RCF). The rate of development of RCF is governed by two processes: the rate at which microscopic cracks appear at the surface and the speed at which they grow. The initiation phase has been investigated by Bower (21) and by Ghonem and Kalousek (22). Bower (23) and Bold et al. (24) have studied the propagation phase, while Kalousek (19) has examined the particular relevance to wear and RCF of rails. The micro-crack initiation process is accelerated both by the high wheel/rail normal contact stresses which exist with non-conformal wheel and rail profiles, and by high friction between dry wheels and rails which accelerates crack initiation from high tangential traction. Oil, grease and water, which lubricate the crack faces and pressurize the crack tip, are responsible for propagation of micro-cracks into fully developed RCF failures. Alternating wet and dry conditions lead to the most rapid development of corrugation by contact fatigue.

At first, because micro-cracks initiate randomly and relatively infrequently along the rail, the low spots correspondingly appear almost randomly. However, as the low spots develop they excite resonance of the unsprung mass on the track stiffness, that is the P2 resonance, so that corrugations subsequently appear preferentially at those spots where the normal force is a maximum. Therefore shallow RCF corrugation has an almost random and relatively long pitch, whereas well-developed RCF corrugation has a more constant pitch which corresponds to the quotient of the predominant vehicle speed and the P2 frequency: this is the case in Fig. 6. It may indeed be the case that micro-cracks and low spots initially occur preferentially at places where railhead irregularities give rise to high P2 forces, but this has not been examined to date.

6.3 Treatment

The successful treatment for this type of corrugation has been termed ‘preventive maintenance’ (18, 20) and essentially treats the damage mechanism. The treatment comprises two components. The first of these is good lubrication to reduce initiation of the fatigue cracks: these commonly start at sites where the rail surface is heavily sheared by the poorly steered wheelsets traversing the curve. The second is regular, light grinding to eliminate any fatigue micro-cracks before they propagate significantly. (A similar removal of the cracked surface layer is sometimes obtained by switching off lubricators in curves. The rate of metal removal is, however, difficult to control.) The success of preventive maintenance is enhanced if the rails are ground asymmetrically: this helps wheelsets to steer around the curves, thereby reducing traction forces, particularly when the rails are dry. It also improves conformity, thereby reducing contact stresses. The problem would also be mitigated with bogies which themselves steered better around curves than the present three-piece bogies: this would be achieved if bogies had steering linkages between the wheelsets. Such bogies may be economically attractive on extremely circuitous railways.

7 RUTTING AND AXLE WIND-UP

7.1 Characteristics

A type of corrugation which is extremely widespread has the characteristic appearance of shiny crests and dull, clearly worn troughs which run across the full width of the rail (Figs 7 and 8). In order to differentiate this type of corrugation from others discussed here, the authors propose that the term ‘rutting’ be used to describe the phenomenon as the corrugations appear similar, for example, to the transverse ruts which exist on corrugated dirt roads [which are discussed by Miso and Carson (25, 26)]. There is convincing circumstantial evidence that both the longer wavelength corrugation examined on track of the Paris Mass Transport Authority (the RATP) (14, 15) and that which has been investigated thoroughly in curves at the Facility for Accelerated Service Testing in Colorado (FAST) (1, 27, 28) are of this type. The latter are believed to be of the same type which occur widely on ‘revenue service’ track on north American freight lines (28). The superficial fea-
Fig. 7 'Rutting' on tram tracks

tures and circumstantial evidence strongly suggest that corrugations commonly found on tram tracks, on the inside rail in some tight curves on metro tracks (for example, the RATP) and more widely on metro systems with monomotor bogies (as is common with trams and on mass transit systems), are also rutting.

The wavelength of these corrugations on the RATP in Paris is about 200 mm (14, 15); at FAST the corrugation varied in the range 150–450 mm from one site to another (28), but was very consistent at any one site, as shown in Fig. 5. On tram tracks, where speeds are lower, the wavelength is more commonly about 50 mm.

Photomicrographs made of the rail surface at FAST (28) indicate that slip is predominantly longitudinal and is greater in the troughs of the corrugation than at peaks; gross sliding was, however, absent. This is consistent with the appearance of rutting at sites where there is high longitudinal traction, such as termini and curves, and with vehicles in which both wheelsets on a bogie are powered by the same traction motor. There was also significant longitudinal acceleration of the rail at the corrugation frequency.

7.2 Cause

The damage mechanism for this type of corrugation is differential wear caused by variations in longitudinal traction. This is demonstrated by metallurgical analysis of the rutted rail surface at FAST, by their measurements of longitudinal vibration of the rail, and by the theoretical analysis made of the corrugation formation mechanism on the RATP. Although a stick-slip mechanism does not appear to be responsible for corrugation at FAST, stick-slip would exacerbate differential wear. The wavelength-fixing mechanism identified for both the FAST and RATP corrugations is a coincidence of the wheelset's fundamental torsional resonance and a maximum in the vertical dynamic contact force. On the RATP the vertical dynamic force (at a frequency of about 55 Hz) arises from resonance of the vehicle's unsprung mass on the track stiffness, whereas at FAST a sleeper resonance at about 110 Hz gives rise to a maximum in the contact force.

In view of the wide variety of ballasted and unballasted track on which this type of corrugation occurs, coincidence of the frequencies of axle wind-up and a maximum in the vertical dynamic force may be unnecessary, but excitation of the torsional resonance is critical. This is supported to some extent by the findings at FAST that corrugation could not be initiated by an artificially severe railhead irregularity. The torsional resonance is excited where there is differential traction between the two wheels of a wheelset, and slip. It is accordingly reasonable to find rutting of the rail in curves, at braking sites and at termini, particularly if rotation of the wheelsets themselves is constrained by coupling to the same traction motor. Zahradka has shown that frictional forces vary at the frequency of
torsional resonance when excessive traction is demanded; possible implications for corrugation formation are not discussed (29).

7.3 Treatment
Grinding is necessary to remove this type of corrugation but does not by itself provide a means to prevent its recurrence. The most successful means identified at FAST of reducing the development of rutting on the low rail in curves was to lubricate the gauge corner of the high rail. Some benefits were also obtained using harder rail steels (28). On the RATP a test is in progress to ascertain whether a significant improvement is possible using sleeper soft pads in order significantly to reduce the vertical track stiffness (30).

It can be deduced by considering the mechanism of corrugation formation that it would be desirable to improve steering of vehicles in curves, with either more resilient yaw suspension or a steering bogie. Similarly, it would be desirable to use bogies in which wheel sets are not coupled through the traction motor. Only limited advantage is likely from asymmetric profiling of the rails in curves on metro and tram tracks as these are often extremely severe; some advantage may, however, be gained on less severe curves on freight track. It should be possible to mitigate any roll-slip oscillation using a friction enhancement agent in the wheel/rail contact: it has been demonstrated in Vancouver (Section 8) that such a substance controls roll-slip vibration by ensuring that the coefficient of friction between a sliding wheel and the rail is not less than the limiting static friction.

8 ROARING RAILS

8.1 Characteristics
The term 'roaring rails' is used here to refer to the type of corrugation which is now commonly associated with high-speed, main-line track with relatively light axle loads (that is usually less than about 20 tonnes: a 10 tonne wheel load). It occurs predominantly on tangent track or in gentle curves in which there is no contact between the wheel flange and the gauge side of the rail. Examples on British Rail (BR) and on Vancouver Skytrain are shown in Figs 9 and 10 respectively. Its wavelength varies little with train speed: a variation of about 25–80 mm is typical between sites where the predominant speed is in the range 10–50 m/s, as shown in Fig. 11 for roaring rail corrugations on BR (31) and in Vancouver (32). Although the latter occur on a mass-transit system, they appear similar in those respects which have been examined to date: in particular, the damage mechanism appears to be identical (that is wear of the corrugation troughs) and their wavelength varies similarly with speed, as shown in Fig. 11. They are accordingly assumed here to be the same phenomenon.

Corrugation on track of the Deutsche Bundesbahn (DB), which has long been afflicted with this type of corrugation, is typically of shorter wavelength than that on BR but is superficially similar. There are, however, no data such as those shown in Fig. 11 showing how the corrugation wavelength varies with predominant vehicle speed.

At any one site roaring rail corrugation appears quite uniform to the naked eye, but measurements indicate a rather broad spectrum of corrugation wavelengths (31). Well documented experimental evidence from field tests on BR indicate that typically a martensitic 'white phase' develops incrementally into one or two fairly continuous running bands on the railhead, and is then worn away periodically to leave the corrugations; these then appear as relatively bright peaks and rather dull troughs. Measurements of the running surface of corrugated rail on Vancouver Skytrain (32) show that slip between wheel and rail is predominantly longitudinal and is greater in corrugation troughs than on peaks: this is consistent with there being greater vertical force on the peaks and slip in the troughs.

It has been observed on BR and elsewhere that Acid Bessemer rail steel corrugates more quickly than Open Hearth rail steel (33); corrugations develop at an intermediate rate on the Oxygen rail steel which is now used on BR. No consistent variation has been detected in rates of corrugation formation on rails of different hardness (34). On BR's main lines, where the speeds are typically 160–200 km/h, the severity of corrugation often varies visibly at sleeper pitch, being more severe on the approach to sleepers than in between.

8.2 Cause
Observations made in the field indicate that the damage mechanism for roaring rail corrugations is wear. This is consistent with the fact that the vertical wheel/rail force is least towards the corrugation troughs: indeed, a corrugation depth of 0.1 mm is sufficiently severe to cause loss of contact.

Fig. 9 'Roaring rails' on British Rail
No satisfactory explanation is yet available for the wavelength-fixing mechanism, although many suggestions have been made. Among these are mechanisms involving primarily the lateral (35) and longitudinal (36) dynamics of the track; a combination of lateral and vertical dynamics (37), and primarily excitation of the pinned-pinned resonance by the initial railhead roughness (38). A difficulty with any mechanism which involves essentially excitation of a resonance at a single frequency is that it cannot easily explain the relatively small variation of wavelength with vehicle speed which is observed in practice (Fig. 11). Although analysis to date has shown that roll-slip oscillations are unlikely because vibration of the track is extremely well damped, circumstantial evidence from Vancouver Skytrain strongly suggests that these occur by a mechanism involving slip due to exceptionally high spin, which increases with increasing conformity between wheel and rail.

In view of the lack of field measurements of wavelength of DB corrugation and its variation with predominant vehicle speed, it is possible that the wavelength-fixing mechanism on DB is indeed excitation of the pinned-pinned resonance, as is strongly suggested by the work of Knothe et al. (38). Until further data are available from the field and from calculation, it may be prudent to hold an agnostic view on this question.

Roaring rail corrugation is exacerbated by factors which increase the propensity of the wheel to slip and wear those areas of the rail which become corrugation troughs. Such factors include high vertical dynamic loads and high lateral and longitudinal creep, such as occurs when wheelsets are misaligned in a bogie.

The periodicity of corrugation at sleeper pitch is explained satisfactorily by the track's vertical dynamic behaviour alone; if the corrugation excites the pinned-pinned resonance, the variation in dynamic contact

![Diagram of Corrugation Wavelength vs. Train Velocity]

**Fig. 11** Variation of wavelength of 'roaring rail' corrugation with vehicle speed
force is greater on the approach to sleepers than elsewhere (17). With regard to the effect of rail metallurgy, an investigation by BR of different rail steels has suggested that Acid Bessemer steel may be more prone to corrugate because it wears relatively quickly and is more resistant to plastic deformation under cyclic loading above yield (39).

8.3 Treatment

Grinding is the principal treatment for roaring rail corrugations. It has been shown on BR (40, 41) and on DB (34) that grinding new rail also significantly delays the onset of new corrugation, which is consistent with exacerbation of the corrugation by vertical vibration excited by railhead roughness. Insofar as high vertical dynamic loads are undesirable, resilient railpads should reduce the rate of corrugation formation by reducing vertical dynamic loads, particularly those caused by sleeper resonances and the pinned-pinned resonance of the rail. If the discrete support at sleepers, which gives rise to the pinned-pinned resonance was an essential component of the corrugation mechanism, it would be unusual to find roaring rails (although not necessarily other types of corrugation) on track with a continuously supported rail [such as is used in the Paved Concrete Track (PACT) system].

Whatever the detailed wavelength-fixing mechanism might be, it is desirable to reduce misalignment of wheels in bogies and thereby reduce the propensity of wheels to slip. Undoubtedly one of the reasons for the recent increase in roaring rail corrugation is that bogies on high-speed trains have relatively stiff in-plane suspension to achieve stability: this increases the likelihood of slip even on unmotorized wheels. In view of the different propensity of Open Hearth and Acid Bessemer rail to corrugate, there is in principle great potential to reduce corrugation formation by rail selection; however, this behaviour is not yet adequately understood.

The most comprehensive and apparently successful treatment of this type of corrugation is that which has been adopted on the Vancouver Skytrain system. This comprises the following three components:

(a) reduction of the misalignment of wheelsets in the bogies;
(b) grinding to remove existing corrugation and to re-profile the rails transversely: the latter is done both to reduce conformity between wheel and rail and to vary the effective gauge so as to change the contact point on the wheel, thereby giving more uniform wear;
(c) use of a proprietary substance on the railhead which modifies the friction characteristics between wheel and rail, in particular to make the sliding coefficient of friction greater than the limited static coefficient, thereby eliminating a fundamental requirement for stick-slip vibration.

The effectiveness of these treatments is consistent with what is agreed to date about the cause of roaring rails, even if a full understanding is not yet available. Although there is therefore every reason to believe that these treatments would also be successful elsewhere, there has not yet been a controlled test to demonstrate that this is so. A field test was set up on BR in 1981 to examine the effect of close conformity on corrugation formation (42), but no results have yet been published from this study.

9 CONCLUSIONS AND RECOMMENDATIONS

A wide variety of types of rail corrugation exists in practice. Two critical characteristics of a corrugation have been considered:

(a) the mechanism which gives rise to the periodicity (the wavelength-fixing mechanism), and
(b) the mechanism which causes the perceived damage (the damage mechanism).

By this means, six types of corrugation are distinguished and have been denoted by the terms heavy haul, light rail, booted sleeper, contact fatigue, rutting and roaring rails. The damage mechanism has been identified for all six types of corrugation.

For five of the six cases the wavelength-fixing mechanism appears to be excitation of a characteristic frequency by trains passing at a relatively small range of speeds: the corresponding wavelength is simply

$$L = \frac{v}{f}$$

where $v$ and $f$ are the appropriate train speed and resonant frequency respectively. Resonance of the unprung mass of vehicles on the track stiffness (the P2 resonance, Table 1) is the most prevalent wavelength-fixing mechanism, and it is accordingly critically important to reduce the unprung mass to as low a level as is practical in order to reduce the track’s propensity to corrugate by any one of a number of mechanisms.

Both the damage and the wavelength-fixing mechanisms are accordingly well understood for all but one of the six types of corrugation: heavy haul, light rail, booted sleeper, contact fatigue and rutting (Sections 3, 4, 5, 6 and 7 respectively). Both booted sleeper and rutting corrugations are similar to the extent that they involve the same damage mechanism, dry wear, and are associated with a resonant frequency, but they differ insofar as resonance involves primarily lateral and longitudinal forces respectively.

The most perplexing member of the corrugation family is roaring rails (Section 8). The damage mechanism and many features which exacerbate this type of corrugation are now well understood, but there is not yet a well validated theory which provides a convincing, physical explanation of the relatively small increase in corrugation wavelength with speed which has been documented on BR and in Vancouver. In view of the prevalence of this type of corrugation on main-line track, it will undoubtedly and rightly remain a topic for research, as a full understanding of the wavelength-fixing mechanism might reveal a means for prevention.

Treatments which involve some measure of prevention, rather than simply grinding away the irregularity and allowing it to recur, have been identified for all six types of corrugation. The possible treatments, which are summarized in Table 2, show that all types of corrugation are at least alleviated by grinding. More detail of the treatments of individual types of corrugation can be
found in the appropriate references (Table 1). Where excessive vertical dynamic loading is an essential feature of the corrugation mechanism (that is, heavy haul and light rail varieties), maintenance of a sufficiently smooth railhead profile is the only practical means for preventing corrugation on existing track. For heavy haul corrugation, improvements in welding procedure are required to minimize differential deformation of the weld and parent materials. Means are available to specify allowable irregularities for specified types of rail and traffic to prevent heavy haul and light rail corrugation.

Grinding is important in two other respects. It is an essential means of removing nascent fatigue cracks before they propagate into contact fatigue corrugations, and it can be used to profile rails transversely, thereby improving steering in curves and controlling conformity of wheel and rail.

Selection of an appropriate rail for new track helps to prevent corrugation. Sufficiently high flexural rigidity and yield strength are required to resist corrugation by plastic bending (light rail corrugation), and adequate yield and tensile strengths are required to resist corrugation by plastic flow (heavy haul corrugation). Hard rails mitigate formation of the corrugation which occurs in curves at FAST, and should accordingly reduce formation of rutting corrugation elsewhere, and possibly also corrugation on booted sleepers. The rail metallurgy influences roaring rail corrugation, but in a way which is not yet fully explained. It may be surmised that if the pinned-pinned resonance were fundamental to the formation of roaring rails, these could be substantially eliminated (in principle if not economically in practice) using a sufficiently heavy rail section and a sufficiently short sleeper spacing for the resonant frequency to be excited only by roughness whose corrugation was less than the length of the contact patch.

Resilient railpads have demonstrably helped to reduce formation of booted sleeper corrugation in curves, and should help in all cases where corrugation is exacerbated by high vertical dynamic loading at relatively high frequencies, for example, roaring rail corrugation.

Adequate lubrication of the gauge corner of the high rail is an important means of mitigating formation of all types of corrugation in curves. Control of friction between the wheel tread and the railhead to reduce the propensity for roll/slip oscillations is an important element in mitigation of roaring rail corrugation, and may also help to reduce rutting.

All types of corrugation which occur in curves are exacerbated by poor steering of bogies and would accordingly be less likely to form if steering were improved. In many cases this may be possible simply with more resilient yaw suspension, whereas elsewhere it may be beneficial to interlink the wheelsets in a bogie. Some field testing of these possibilities would be useful, even if the costs of a better primary suspension could not be justified by reduction of corrugation alone.

Two types of corrugation appear to be exacerbated by particular types of track or vehicle: dry wear corrugation on curved track with resiliently booted sleepers and rutting with vehicles having monomotor bogies. For this reason alone it may be unwise to use the former type of construction on curved track. The latter characteristic is a further reason to develop independently driven wheelsets, or indeed independently driven wheels.

For many practical purposes the types of corrugation described here are already sufficiently well understood for successful treatments to have been developed and accordingly for little further research to be required into their cause. Roaring rail corrugation is the most prominent exception, and research into its wavelength-fixing mechanism is indeed an active area of research at present. There are areas where understanding of the cause is a little tentative: for example, the wavelength-fixing mechanism for contact fatigue corrugation.

Further research into and demonstration of the efficacy of effective treatments is, however, particularly desirable for roaring rails, rutting and booted sleeper corrugations. At least one treatment has been identified for each of these and others are tentatively suggested here, but it would be attractive to have a range of possible treatments whose effectiveness has been convincingly demonstrated. Field testing is an essential component in demonstrating this effectiveness, but
laboratory testing and mathematical modelling are also highly desirable in order to improve understanding of possibilities and limitations.

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