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A CASE STUDY ON THE EFFECT OF SPEED VARIATION ON THE GROWTH OF WEAR-TYPE RAIL CORRUGATION

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Abstract

The transportation noise phenomenon known as wear-type rail corrugation is a significant problem in railway engineering, which manifests as an undesirable periodic wear pattern on the contact surfaces of the rail. This variation from a flat profile induces unwanted vibrations, noise and other associated problems. Currently the only reliable solution to corrugation is removal by grinding at significant expense to the railway operator.

Recent research by the current authors has theoretically shown that uniformity in pass speed enhances corrugation growth rate and that broadening the probabilistic pass speed distribution may be a possible method of mitigating corrugation growth.

To further test these results and to quantify the expected performance, in this paper, field measured data from a site with recurrent corrugation is used to tune and validate a theoretical model that predicts the growth rate of the phenomenon. The effect of changing the field measured pass speed distribution is then investigated and results quantifying the expected reduction in corrugation growth rate are presented and discussed.

1. INTRODUCTION

Rail corrugation is a significant problem for the railway industry worldwide. It is a periodic irregularity that is observed to develop on the running surface of the rail and is characterised by long (100-400mm) and short (25-80mm) wavelengths (Sato *et al.* [1]). The formation and growth process of rail corrugations is analogous to corrugations developing on unsealed roads. A conceptual model of corrugation formation can be seen in Fig. 1, where a feedback process occurs over multiple wheelset passes due to the interaction of vehicle/track vibration dynamics I, contact mechanics II and a damage mechanism III, initiated by an initial rail profile irregularity. This irregularity grows in amplitude as a function of the number of passes, until typically removal by grinding is required to ameliorate the excessive noise, vibration and associated problems caused by the corrugated rail. The type of corrugations, on which this paper focuses, is characterised by wear as the damage mechanism III and is a particular concern to industry as no reliable alternative cure to regrinding affected surfaces exists. Because the problem has become so entrenched, a periodic preventative rail grinding schedule is often enforced in order to avoid the occurrence of rail corrugation. This palliative costs the Australian industry alone in the order of AU$10 million per annum and will continue to become more costly with the predicted growth of rail traffic and freight unless an alternative reliable cure is developed.

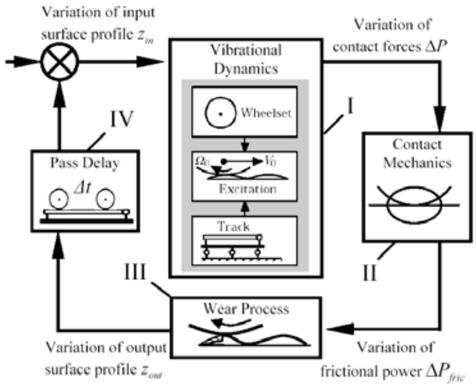

Figure 1. Feedback model for corrugation formation.

Grinding costs have motivated much recent research effort on methods of corrugation mitigation throughout the world. A variety of control techniques have been proposed and developed, unfortunately with unreliable success under varying conditions (see reviews of [1,2,3]). The most renowned methods include railhead hardening or hardfacing, lubrication of the rail with friction modifiers and vibration damping of the vehicle and or track. Hardening of the rail contact surface has long been proposed as a cure as it provides resistance to wear and therefore supposedly also variations in wear. Latest field tests of HSH rails[4] versus conventional rails at the exact same site confirm these results although there is still much debate as to whether this is valid for all conditions and types of corrugations. Arguably the most promising solution for rail corrugation at present is friction modifiers. These are specialized lubricants applied to the wheel-rail contact that effectively control the coefficient of friction to approximately 0.35 [5]. In typically high tractional conditions, this lower coefficient of friction lowers traction and wear. Friction modifiers also produce a positive sloped traction-creep curve under full sliding conditions to eliminate stick-slip instability that can occur under dry conditions. In practice the lubricant has been shown to reduce the occurrence of some types of corrugations, however further field testing is still required to understand and overcome the uncertainty of performance. Also top of rail lubrication has been difficult to control in the field. Tuned vibration dampers/absorbers on railway tracks and wheels have been proposed and tested recently to reduce wayside noise in Germany [6]. These devices have mainly been developed for the purpose of noise control as opposed to corrugation suppression. Also the present cost is excessive for practical application. Wheelset torsional vibration absorbers have also been proposed for corrugations associated with cornering on metro systems [2], however, this has not been pursued as of yet.

Perhaps the unreliability of proposed solutions for corrugation arises partly due to an incomplete theoretical understanding of the mechanisms of corrugation growth. Over the past few decades, much international research progress has been achieved towards overcoming this. For example, the research of Hemplemann and Knothe [7], Igeland and Ilias [8] and Matsumoto *et al.* [9] amongst many others has resulted in the development of numerical models for simulating the characteristic behaviour of corrugation formation. Powerful insight has also been gained from simpler analytic models which overcome excessive computational expense with closed form solutions. These have been used to identify fundamental growth mechanisms and to investigate parametric trends that may reduce corrugation formation. Recent examples of this research include Muller [10], Nielson [11], Meehan *et al.* [12] and Bellette *et al.* [13]. In [10] and [11] analytical predictions showed that certain wavelength ranges of corrugation were promoted due to a wavelength based contact filtering effect, however the effects of dynamic wheel/rail contact forces were ignored. In [12], system stability of the interaction between structural dynamics and contact mechanics over multiple wheelset passages revealed the characteristic exponential growth of corrugations and a closed form analytic expression for this growth rate was obtained. Subsequently in [13], the effect of variable pass speeds was investigated, and theoretical results revealed that a wide distribution of pass speeds may result in large reductions of the corrugation growth rate.

To further examine the hypothesis in [13], a test site with a recurrent corrugation problem has been selected on a suburban line in Australia for field investigation. In this paper the model developed in [13] will be tuned to match the field conditions at this site, so that predictions can be made of what changes in corrugation growth rate are expected in response to an altered pass speed distribution.

2. FIELD SITE MEASUREMENTS

The field site investigated, is a corrugated section of suburban track occurring on a curve with a 242 metre radius, a recommended speed of 50 km/h and a cant of 60mm. The traffic is composed of 3 to 6 carriage Electrical Multiple Unit (IMU/SMU) trains, half of which will have stopped at the previous station and half will have run express through the previous station with a recommended speed of 60 km/h.

As part of an ongoing study into corrugation growth at various sites around Australia (see Daniel *et al.* [14]) measurements of the rail profile at this site have been recorded over a period of 3 years using a Corrugation Analysis Trolley [2]. A profile measurement of the corrugated section just prior to grinding can be seen in Fig. 2.

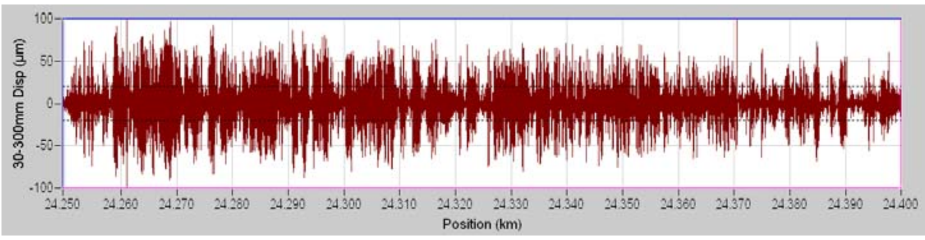

Figure 2. Measured profile of corrugated test section after Bandpass Filtering between 30 and 300mm.

In Fig. 3 the corresponding Fast Fourier Transform (FFT) and Third Octave Spectrum of this profile can be seen, showing a peak corrugation wavelength at approximately 110mm.

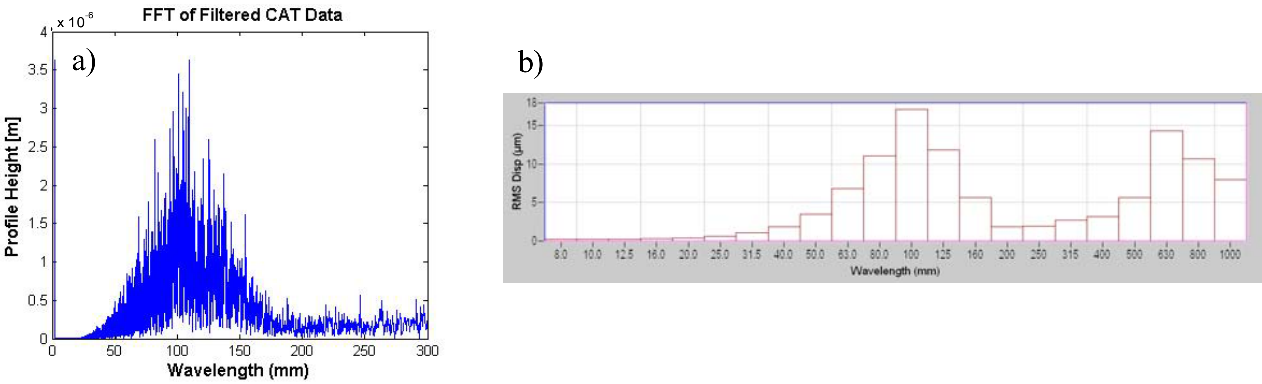

Figure 3. Wavelength spectrum of corrugated test section; a) FFT analysis, b) Third Octave analysis.

By measuring the profile, performing an FFT and recording the peak height at different stages of corrugation evolution, an estimate of the field measured corrugation growth rate, G_r, can be developed as defined by [12] as,

$$G_r = \left\| \frac{Z_n}{Z_{n-1}} \right\|_\infty - 1 . \qquad (1)$$

Here, Z_n is the n^{th} pass worn profile. This is shown in Fig 4, where it should be noted that the theoretical prediction of exponential growth is seen to occur (see for example [12]).

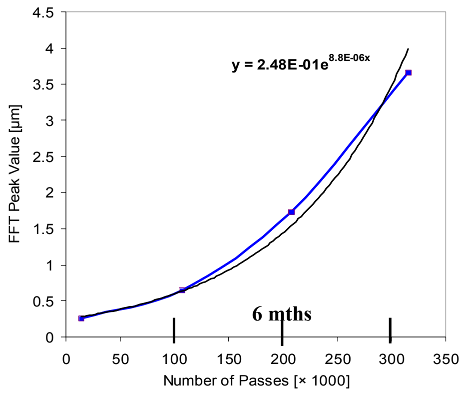

Figure 4. Growth of FFT Peak. (▪) 109mm Peak Wavelength Value and (-) Trendline

It can be seen from the exponential fit to this data that the field measured corrugation growth rate is approximately given by $G_r = 8.77 \times 10^{-6}$. Performing a similar analysis to the third octave spectrum yields a growth rate in approximate agreement of $G_r = 8.45 \times 10^{-6}$.

From a limited sample of speeds taken at the site, the approximate distribution of pass speeds was constructed using non-parametric density estimation techniques, which is shown in Fig 5.

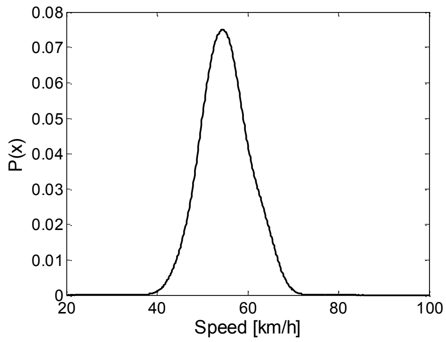

Figure 5. PDF of Speed Distribution

For ease of analysis and due to the limited number of samples taken this distribution can be approximated as a normal distribution with a mean speed of 55.2 km/h and a standard deviation of 4.7 km/h.

3. TUNING OF THE MODEL TO FIELD DATA

In recent research [13], a model was developed that predicts how pass speed distribution affects the growth rate of corrugations. It was shown that when one mode of vibration dominates the response of the combined wheel/rail system, substantial reductions in corrugation growth rate may be realised by having a wider distribution of pass speeds. It was shown that the expected frequency response of the n^{th} pass worn profile to the initial rail profile is given by,

$$\left|\frac{Z_n}{Z_0}(i\omega)\right| = \alpha^n \sqrt[n]{\exp\left[\int_{-\infty}^{\infty} \ln\left(\frac{\left(\omega_i^2 - x^2\omega^2 - \frac{K_b K_{c_i}}{\alpha}\right)^2 + (2\xi_i\omega_i x\omega)^2}{\left(\omega_i^2 - x^2\omega^2\right)^2 + (2\xi_i\omega_i x\omega)^2}\right) p(x)dx\right]}\ , \tag{2}$$

where

$$\alpha = 1 + K_b\ , \tag{3}$$

Z_0 is the initial profile, K_b represents the sensitivity of wear variations to wheel/rail contact deflection variations [12], K_{ci} represents the modal sensitivity of the wheel/rail relative displacement to a change in input longitudinal profile [12], n is the number of wheel passes, ξ_i is the modal damping ratio, ω_i is the modal natural frequency, ω is the angular frequency for the frequency domain, x is the ratio of the current speed to the mean speed and $p(x)$ is the probability distribution of x. From this expected frequency response the growth rate defined by eq. (1) can be calculated by finding the n^{th} root of the peak of eq. (2), denoted,

$$G_r = \left\| \frac{Z_n}{Z_{n-1}} \right\|_\infty - 1 = \sqrt[n]{\max_\omega \left| \frac{Z_n}{Z_0}(i\omega) \right|} - 1. \tag{4}$$

Using the known speed distribution, the corrugation growth rate and the corrugation wavelength, estimates of the unknown parameters in Eq. (2) can be made. These estimates, based on field measurements, are summarised in Table 1.

Table 1. Corrugation Parameter Estimates from Field Data

K_b	2.01×10^{-6}	ω_i [rad/s] (at 55km/hr)	783.8
K_{ci} [N/mkg]	5.67×10^{5}	ξ_i	0.0019

If these simulation parameters are used in the numerical model described in Meehan et al. [15], along with the initial profile obtained from field measurements, the development of corrugation seen in Fig. 6a) can be observed. If the FFT of this profile is taken and the peak value plotted against pass number, as shown in Fig. 6b), the same profile growth as the field results presented in Fig. 4 can be seen.

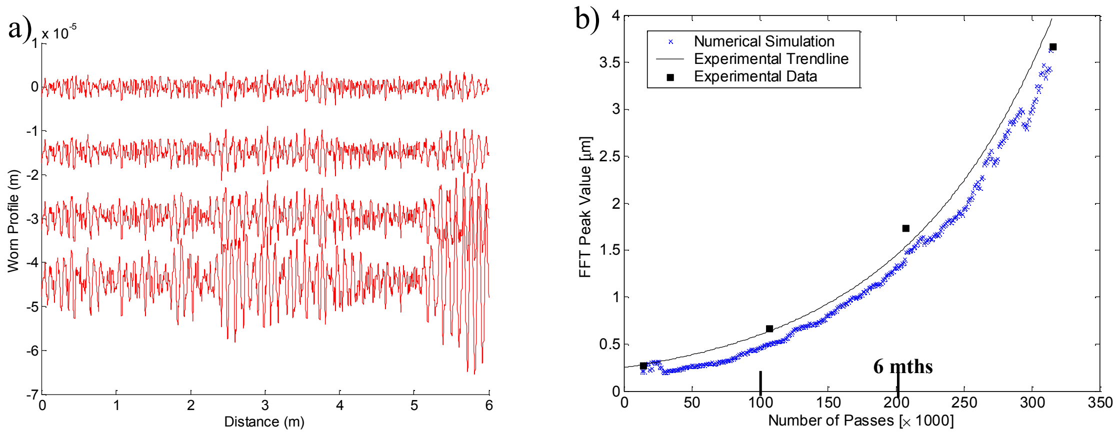

Figure 6. Measured and Simulated Profile Evolution. a) Initial measured profile and subsequent simulated profiles at 90,000 wheelset pass intervals, b) comparison of FFT corrugation peak growth.

In the subsequent Section the tuned model is used to predict the effect of changing the wheelset pass speed distribution.

4. EFFECT OF CHANGING SPEED DISTRIBUTION ON CORRUGATIONS

As noted previously, if the speed distribution is broadened it should be possible to cause a reduction in growth rate, thus lengthening the time between regrinds and reducing the associated costs. As an example, the effect of changing the measured speed distribution to a normal distribution with the same mean speed of 55.2 km/h and twice the standard deviation (= 9.4 km/h) was investigated using the field conditions of Section 2. Under these conditions, the expected corrugation growth rate calculated using Eqs. (1) to (4) drops to $G_r = 4.7 \times 10^{-6}$. Plots of numerical simulations of comparison of profile growth between the controlled and existing speed conditions, is shown in Fig. 7.

This decrease in growth rate would result in the optimum time between regrinds to be increased by a factor of approximately 1.9. Based on the costing analysis detailed in [14], this represents a substantial grinding cost saving of approximately 45 to 50%. There are however other possible undesirable effects associated with a change in pass speed distribution that could occur. These are investigated in the subsequent Section.

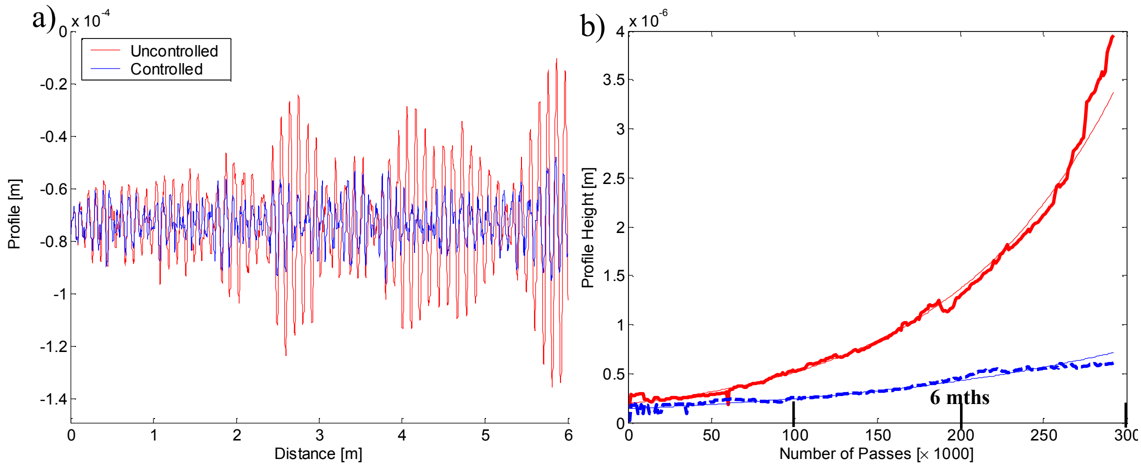

Figure 7. Comparison of corrugation growth under existing and controlled speed distributions; a) predicted profiles after 9 mths growth, b) FFT corrugation peak growth.

5. POSSIBLE UNDESIRABLE EFFECTS

Two possible issues that may occur when broadening the speed distribution are; 1) an increase in the traction on the track prior to the corrugated section, due to increased braking and accelerating, and 2) a lack of driver compliance with the suggested new speed range. The implications of these scenarios will be discussed in the following.

5.1 Increased Traction

Increased traction on the previous section of track is a concern because any increase in traction will cause an increase in growth rate (according to [12]), which may cause corrugations to develop on a section of track where they previously did not occur. For instance, it is possible that the corrugated section may just shift to a different position when an increase in speed variation is introduced.

To quantify the possible extent this increase in speed variation will have on traction, an approximation of the average absolute value of the acceleration, a, on the section prior to the variable speed board will be calculated in the uncontrolled condition and compared to the absolute value when speed variation is introduced. As acceleration is related to traction this will give an estimate of the possible effects on corrugation growth rate and mean wear.

In the controlled conditions the trains will leave the station at the suburban site and the train requires a distance, d, to adjust to the desired controlled pass speed. In the uncontrolled case the driver will see a fixed speed sign of 50 km/h and have the same distance to adjust their speed. Now note that half of the trains stop at the station and half will be running express with a recommended speed of 60 km/h. If it is assumed that the acceleration is constant then the absolute value of the acceleration will be given by,

$$|a| = \sqrt{\left(\frac{v^2 - u^2}{2d}\right)^2}, \tag{5}$$

where v is the speed over the corrugated section and u is the speed at the station. Now u and v will be random variables with associated probability distributions given by $P_1(u)$ and $P_2(v)$. From Eq. (5) the average absolute value of the acceleration can be calculated from

$$\langle |a| \rangle = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sqrt{\left(\frac{v^2 - u^2}{2d}\right)^2} P_1(u) P_2(v) du dv . \quad (6)$$

In the uncontrolled case $P_2(v)$ will be given by the measured speed distribution (fig. 4) and in the controlled case will be given by the controlled distribution presented in Section 4. $P_1(u)$ will be given by a combination of the distribution of the express trains about 60km/h and a distribution of speeds about a small speed representing those that stopped at the station. It is assumed that these distributions will be similar to the measured distribution about the mean speed in the corrugated section.

Numerically integrating Eq. (6), under the measured site conditions including the extreme value, d=70m, shows that the average acceleration over the section of track before the variable speed board will increase by less than 1% in the controlled condition, making minimal difference to the growth rate. It is therefore not expected that any substantial increase in track wear or corrugation formation will occur in the section of track prior to the corrugated section. In addition, the extra variation in speed distribution on this track section will be expected to substantially reduce the likelihood of any corrugation growth in line with the predictions of Section 4.

5.2 Driver Compliance

Another possible issue is that as there may be a reliance on driver compliance to modify the speed distribution at the site. It is useful to quantify the effect that driver compliance will have on the expected growth rate reduction. To do this it is assumed that a certain percentage of drivers will achieve the desired pass speed according to the target controlled speed distribution, whilst other drivers will not and therefore accord to the existing measured speed distribution. This will result in a probability distribution given by the sum of the controlled and uncontrolled distributions, each scaled by the ratio of how many passes are controlled over the total number of passes.

If the distribution constructed from the percentage of driver compliance is used in Eq. (2) then the corrugation growth rate, G_r, can be calculated as a function of driver compliance using Eqs. (3) and (4) as shown in Fig. 8.

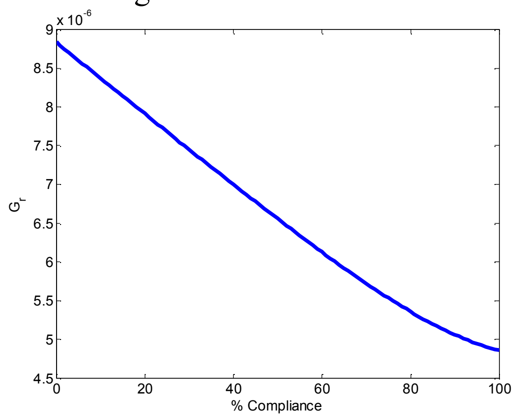

Figure 8. Corrugation Growth Rate for Different Levels of Driver Compliance.

Inspection of figure 8, shows that even if only 50% driver compliance is achieved, then the growth rate will still be reduced substantially to 6.7×10^{-6}. This would result in a factor of increase in the optimum time interval between grinds of 1.35, which is still a substantial cost saving of approximately 25 to 30%. Note, at the extremes, 100% driver compliance will result in the maximum reduction in corrugation growth rate calculated in Section 4 while no driver compliance results in no reduction to the uncontrolled growth rate shown in Section 2.

6. CONCLUSIONS

The results of field measurements have been applied to a theoretical model for the corrugation growth rate reduction due to a wider distribution of pass speeds. This model shows that a substantial reduction in corrugation growth rate may be achieved at this site, such that the time interval between grinds is expected to increase by a factor of 1.9.

Possible undesirable complications arising from the introduction of speed variation have been shown to exert a minimal effect in worst-case situations.

A possible limitation of this modelling is the limited amount of data on speed and acceleration that is currently available from this site. Experimental equipment to record and modify the speed distribution at this site is currently being installed and will allow more fine tuning of the model and later provide data for field validation of the effect of speed distribution on the growth of corrugation.

7. ACKNOWLEDGEMENTS

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