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# The effects of passing speed distribution on rail corrugation growth rate

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*Abstract:* The transportation phenomenon known as wear-type rail corrugation is a significant problem in railway engineering, which manifests as a periodic wear pattern developing on the surface of the wheel and rail with use. Some field studies and recent theoretical results by the current authors have suggested that uniformity in pass speed causes an increase in corrugation growth rate. This paper presents the predicted change in corrugation growth rate and dominant wavelengths with change in passing speed distribution, based on state of the art cornering growth modelling techniques.

*Keywords:* cornering, rail corrugation, speed variation.

## 1 Introduction

Rail corrugation is a significant problem for the railway industry worldwide. It is a periodic irregularity that develops on the running surface of the rail with a characteristic wavelength in the range of 25-400 mm. This irregularity grows in amplitude as a function of the number of wheelset 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 corrugation on which this paper focuses is known as wear-type rail corrugation and is of particular concern to industry as no reliable alternative cure other than grinding exists. Because the problem has become so entrenched, a periodic preventative rail grinding schedule is often necessary to avoid the effects of high amplitude rail corrugation. Preventative grinding 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 unless an alternative reliable cure is developed. 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, but have unfortunately proven unreliable under varying conditions (see reviews of [1,2,3]).

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 made towards filling this gap in knowledge. For example, the research of Hemplemann and Knothe [4], Igeland and Ilias [5] and Matsumoto *et al.* [6] amongst many others has resulted in the development of numerical models for simulating the characteristic behaviour of corrugation formation. Recent examples of this research include Muller [7], Nielson [8], Meehan *et al.* [9] and Bellette *et al.* [10]. In [7] and [8] 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 [9], 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 [10] and [11] 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 [10] and [11], the site investigated in [11] has been monitored for train passing speeds and further simulations using a comprehensive cornering corrugation growth model in [12] have been performed. This paper presents the observed passing speed data and cornering simulation results for a varying speed distribution, focusing on changes in corrugation growth rate and the associated dominant wavelengths.

## 2 Modelling

The model used in this paper uses modal representations of key components of the dynamic system, combined with contact and wear models to predict dominant corrugation wavelengths and associated growth rates for a bogie travelling in steady state cornering, conceptually as shown in figure 1.

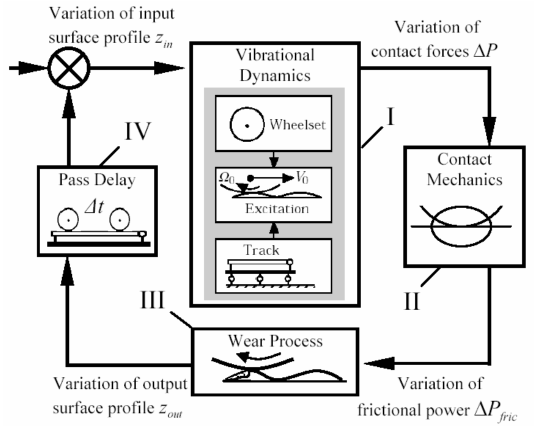


Figure 1 – Flow diagram of the modal cornering model

In the dynamics model (I), modal representations of the rail in on-sleeper and mid-sleeper positions are solved for and the model then interpolates between these positions to give the whole rail response. Methods of interpolation used to best simulate the passing over sleepers at a given spacing are detailed in [12]. Finite element models of the driven and undriven wheelsets created in [12] were also used to create modal descriptions of the bogies. A full 3-dimensional contact model is utilized for the cornering conditions (II), based on a combination of Shen *et. al.* [13] and Polach [17]. Parameters were chosen to represent dry contact conditions. Full lateral sliding of the wheel on the rail is permitted with peak and high creep coefficients of friction both chosen to be 0.4. The wear model used (III) is based on the assumption that the rate of material lost is proportional to the frictional power. Literature values of wear coefficient when severe wear is present range from $1.3\times10^{-9}$ kg/Nm to $14\times10^{-9}$ kg/Nm [16]. A mid-range wear coefficient of $4\times10^{-9}$ kg/Nm was chosen, based on the assumption that severe wear was occurring due to the cornering conditions. The amount of wear for a given wheelset pass is scaled up to represent a number of consecutive wheelset passes under the same conditions. The worn profile (IV) is then used as input for the system dynamics for the following bogie pass.

## 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 track cant of 60 mm. The traffic is composed of 3- and 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 at a recommended exit speed of 60 km/h. As part of this study, wheelset passing speeds have been measured and logged at the tested site over a period of approximately one month. From a sample of 25,874 measured bogie passes, the approximate distribution of pass speeds was constructed using non-parametric density estimation techniques, shown in Figure 2.

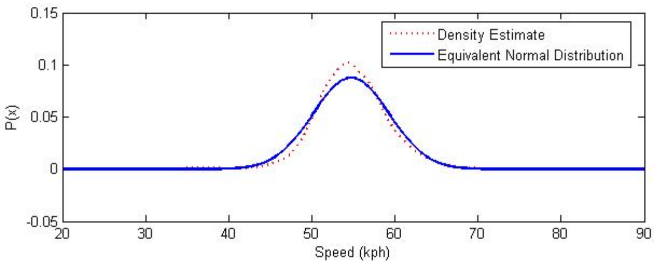


Figure 2 – Approximated passing speed distribution curve

Since the basic shape of the distribution curve is not expected to significantly change the corrugation growth behaviour (see [10]) a normal distribution was assumed, with an average speed of 54.66 km/h and a standard deviation of 4.55 km/h.

As part of an ongoing study into corrugation growth at various sites around Australia (see [11]) measurements of the rail profile at this site have been recorded over a period of 3 years using a Corrugation Analysis Trolley [2]. A three month old profile measurement was taken as input for the model to grow corrugations off of and a nine month profile measurement from the same regrinding period was taken to compare simulated results. The measured profile after three and nine months, and spectral and third octave plots after nine months are given in Figures 3 and 4.

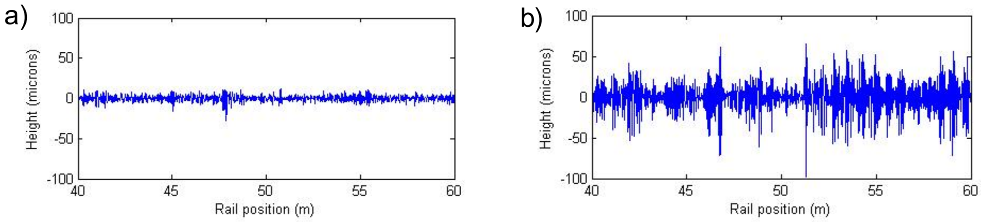


Figure 3 – Measured rail profile a) Three months after grinding b) Nine months after grinding

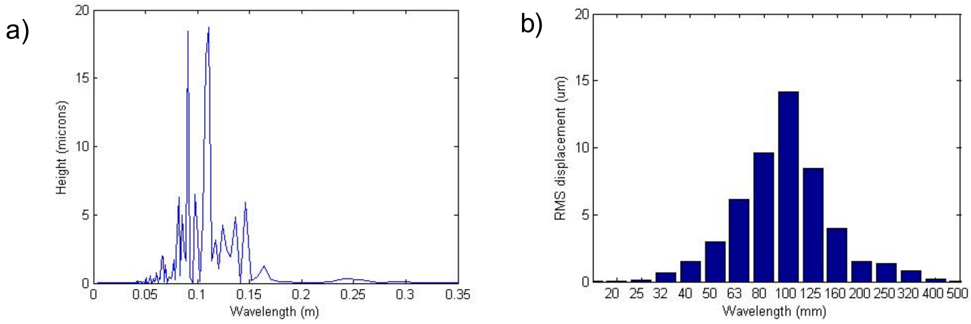


Figure 4 – Frequency spectra of nine month corrugation profile a) Spectral plot b) Third octave

## 3 Tuning of the model to field data

The model used is capable of producing an accurate spectral plot and dominant wavelengths throughout most stages of corrugation growth and showing changes to the growth curve with variation of input parameters. Modal representations of the wheel sets on suburban trains were already created in the development of the original model but the modal response of the rails is site-specific and needed to be tested for. In order to tune the model to the experimental site properties, a number of receptance tests were performed on the rail. Vertical and lateral receptance data sets were needed for positions at mid-sleeper spacing and directly above a sleeper in order to tune the model properly. A modal approximation was then developed using five modes of vibration for each data set. Figures 5 to 6 show the receptance plots at both on- and between-sleeper locations and their modal fits.

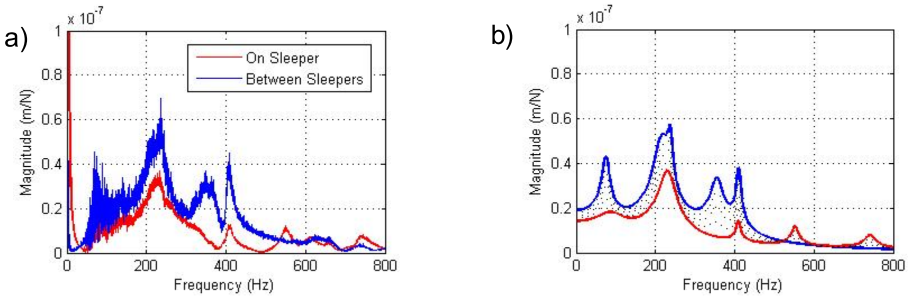


Figure 5 – Lateral rail receptance plots a) Experimental b) Modal fit

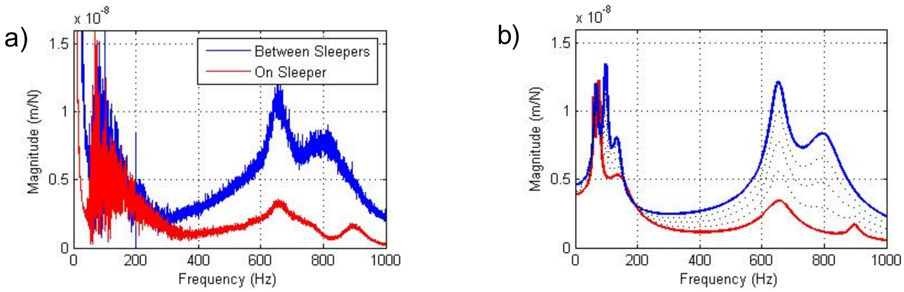


Figure 6 – Vertical rail receptance plots a) Experimental b) Modal fit

The model also required inputs of track cant, curve radius and train speed (see Appendix for input parameters). The model was run with a varying speed for each wheel pass generated randomly from a normal distribution, fit to the distribution curve taken from site measurements. A set of 100 bogie passes were simulated at the generated speeds with an accelerated wear factor of 900 to represent 180,000 wheelset passes, starting from the three-month existing profile in figure 2a). The resultant spectral curve plots and growth curve are given in figures 7 and 8.

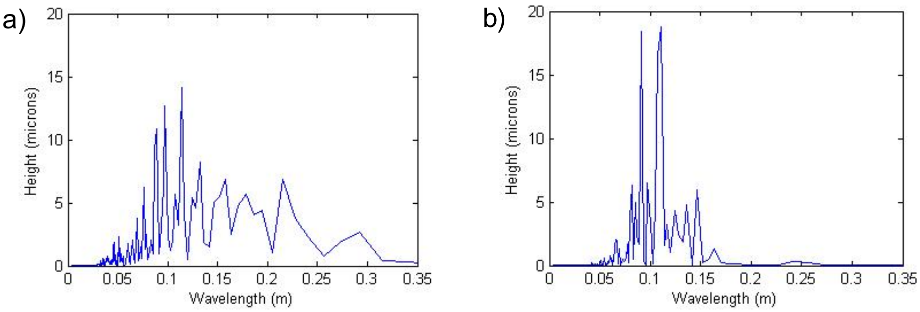


Figure 7 – Spectral plot of resultant rail profile a) Simulated b) Experimental

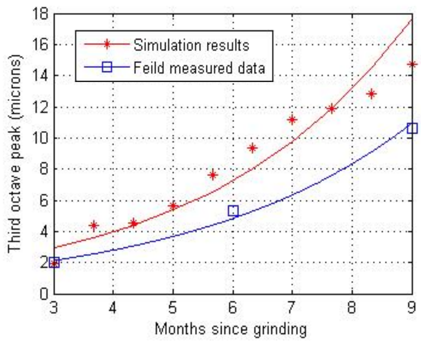


Figure 8 – Growth curves for simulation results and field measurements

Although the simulated spectral plot does not match the measured plot exactly, the dominant wavelengths can still be observed at the same locations as the measured profile. The returned corrugation height difference is reasonable for an exponential growth curve. In the subsequent section the tuned model is used to predict the effect of changing the wheelset passing speed distribution.

## 4 Effect of changing speed distribution on corrugations

As stated previously, an increased standard deviation of passing speed is expected to reduce the corrugation growth rate. The corrugation growth rate is taken to be the exponent for a corrugation height equation as a function of wheelset passes. The growth rate can be calculated between any two points on the growth curve by plotting them against a log of wheelset passes and measuring the slope. Outliers are ignored if the median growth rate is calculated instead of the mean. To investigate the effect of passing speed distribution on the corrugation growth rate the tuned model was run with both experimentally measured and twice experimentally measured standard deviations of speed and the results compared. Figure 9 shows the growth curves at the experimentally measured standard deviation and twice the experimental standard deviation and the spectral plot for twice measured standard deviation.

The median growth rate exponents observed for measured and twice measured standard deviation were $9.9\times10^{-6}$ and $6.1\times10^{-6}$ respectively. By comparison of the final third octave heights it can be seen that the change in standard deviation caused a decrease in final profile height from 14.75 to 5.09 microns. The simulation results are consistent with the estimated changes in the growth rate exponent as detailed in [11]. The overall expected height was slightly higher from simulation but only because of an unexplained numerical step observed midway through the first month of simulated growth.

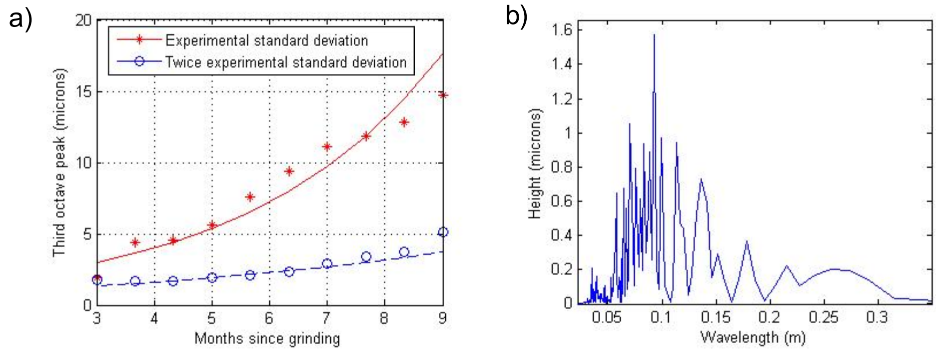


Figure 9 – Simulation results for doubled standard deviation a) Growth curve b) Spectral response

It has also been suggested that a change in speed distribution while maintaining the same average speed could change the dominant wavelengths measured on the corrugated profile. An investigation into the changes in dominant wavelength of corrugation with varying speed distribution has not been published to date. The peaks on the spectral plot in figure 9b) show the dominant wavelengths on the resultant profile for a doubled standard deviation and their associated heights. It can be seen that the locations of the peaks have not noticeably changed from those seen in figure 7a) but their heights have. What was previously the most dominant wavelength at 110 mm became the fourth highest peak and the second highest peak at 90 mm became the most dominant. The change in peak height is likely due to different modes of vibration being excited by a varying speed as discussed in [10].

Possible undesirable effects from increasing the speed distribution are outlined in [11] and are stated to be minimal.

## 5 Conclusions and Recommendations

The results of experimentally monitoring train passing speeds at a suburban test site showed a near normal distribution with a standard deviation of 4.66 km/h. Rail receptance tests were used to tune a corrugation growth cornering model to predict resultant corrugation wavelengths. The model was then tested with a speed distribution curve with doubled standard deviation and corrugation growth compared. The results compared well with those using a simpler model. The increased standard deviation caused a 38% reduction in corrugation growth rate and a 66% reduction in final corrugation height after six months. Although all dominant wavelengths were still present, the most dominant wavelength observed at measured standard deviation was no longer the most dominant for the doubled standard deviation.

Experimental equipment to modify the speed distribution at this site is currently being installed and will provide data for field validation of the effect of speed distribution on the growth of corrugation and the dominant corrugation wavelengths present.

## 6 Acknowledgements

The authors are grateful for the support of the Rail CRC, Queensland Rail, Rail Infrastructure Corporation and the Australian Rail Track Corporation.

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# Appendix

### Properties of the model

| **Wheelset properties** | | **Primary suspension and bogie** | | **Other parameters** | |
|---|---|---|---|---|---|
| Mass *(kg)* | *800* | Longitudinal stiffness $k_x$ *(MN/m)* | 31.39 | Guage of track *(m)* | *1.067* |
| I of wheel about axle *(kg m$^2$)* | *34.65* | Lateral stiffness $k_y$ *(MN/m)* | 3.884 | Rail mass per length *(kg/m)* | *50* |
| I of wheel about a centroidal diameter | *21* | Vertical stiffness $k_z$ *(MN/m)* | 1.2 | Sleeper spacing *(m)* | *0.685* |
| Axle parameters:<br>Diameter<br>Length btw wheels<br>Length from wheel to bearing *(mm)* | <br>*155*<br>*1000*<br>*225* | Longitudinal damping $c_x$ *(Ns/m)* | 10000 | Secondary suspension damping:<br>Yaw *(Ns/rad)*<br>Lateral *(Ns/m)* | <br><br>*40000*<br>*80000* |
| Wheel nominal rolling radius *(mm)* | *421* | Lateral damping $c_y$ *(Ns/m)* | 2000 | Wagon mass per bogie *(kg)* | *20000* |
| Wheel radius at flange contact *(mm)* | *428* | Vertical damping $c_z$ *(Ns/m)* | 4000 | Heigh of wagon centre of mass *(m)* | *1.6* |
| Flange contact angle from vertical *(rad)* | *1.12* | Wheelbase *(m)* | 2.5 | Cant – elevation of high rail *(mm)* | *56.2* |
| Equivalent inertia at gear on a driven axle *(kg m$^2$)* | *111.4* | Bogie mass *(kg)* | 4000 | Curve radius *(m)* | *242* |

| **Rail Modal Parameters** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Vertical modes | $m_{ri}$ (kg) | $k_{ri}$ (MN/m) | $c_{ri}$ (Ns/m) | Lateral modes | $m_{ri}$ (kg) | $k_{ri}$ (MN/m) | $c_{ri}$ (Ns/m) |
| 1 midspan | 5000 | 896.3 | 320000 | 1 midspan | 600 | 137.3 | 70000 |
| 2 midspan | 2800 | 1067 | 180000 | 2 midspan | 70 | 130.1 | 18000 |
| 3 midspan | 1600 | 1169 | 240000 | 3 midspan | 400 | 888.0 | 28000 |
| 4 midspan | 80 | 1347 | 260000 | 4 midspan | 90 | 450.0 | 180000 |
| 5 midspan | 40 | 1021 | 29000 | 5 midspan | 200 | 1328 | 14000 |
| 1 sleeper | 25000 | 3558 | 480000 | 1 sleeper | 400 | 146.7 | 180000 |
| 2 sleeper | 4800 | 1072 | 250000 | 2 sleeper | 70 | 149.1 | 20000 |
| 3 sleeper | 500 | 449.4 | 250000 | 3 sleeper | 650 | 4294 | 40000 |
| 4 sleeper | 130 | 2224 | 75000 | 4 sleeper | 300 | 3610 | 30000 |
| 5 sleeper | 900 | 28670 | 160000 | 5 sleeper | 200 | 4350 | 32000 |