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Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction

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ABSTRACT

'*Big data*' obtained from wayside detection systems and sensors installed on board a train show that actual loading history for a railway track is rather dynamic and transient. The dynamic loadings due to train and track interactions redistribute from the rails to the rail pad, from the rail pad to the railway sleeper, and from the railway sleeper to the underlying ground. Dynamic content redistributed onto each layer of track is also filtered by energy dissipation characteristic of materials and structures. As a critical infrastructure, railway turnout is a structural grillage system used to divert a train to other directions or other tracks. The wheel–rail contact over the crossing transfer zone often causes detrimental impact loads that rapidly deteriorate the turnout and its components. The dynamic responses of wheel–rail interaction depend largely on the non-smooth trajectory or wearing condition of crossing geometry. In reality, a railway line spreads over a large distance and monitoring such rail infrastructure is one of the challenges in rail industry. This paper presents a methodology and application to evaluate and monitor the structural deterioration of railway turnout systems in an Australian urban rail network. The method has integrated numerical train/track simulations, axle box acceleration and ride quality data obtained from the calibrated track inspection vehicle "AK Car".

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1. Introduction

Railway turnout is a special track system used to divert a train from a particular direction or a particular track onto other directions or other tracks. As a critical infrastructure, it is a structural grillage system that consists of steel rails, points (or called 'switches'), crossings, steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation, as shown in Fig. 1 [1]. Traditional turnout structures are generally constructed using timber bearers. The timber bearers allow the steelwork to be mounted directly on steel plates that are spiked or screwed into the bearers. Modern turnouts have adopted tangential geometry to smooth the ride quality and have installed concrete bearers to stabilize the track structure. The turnout structure generally imparts high impact forces on to its structural members because of its blunt geometry and mechanical connections between closure rails and switch rails (i.e. heel-block joints) [2]. In general, the turnout area contains no superelevation or has a flat surface installed on a canted formation. Although a new geometric design method provides a smooth transition from a tangent track, a wheel still has to transfer from the wing rail to the crossing nose, or vice versa.

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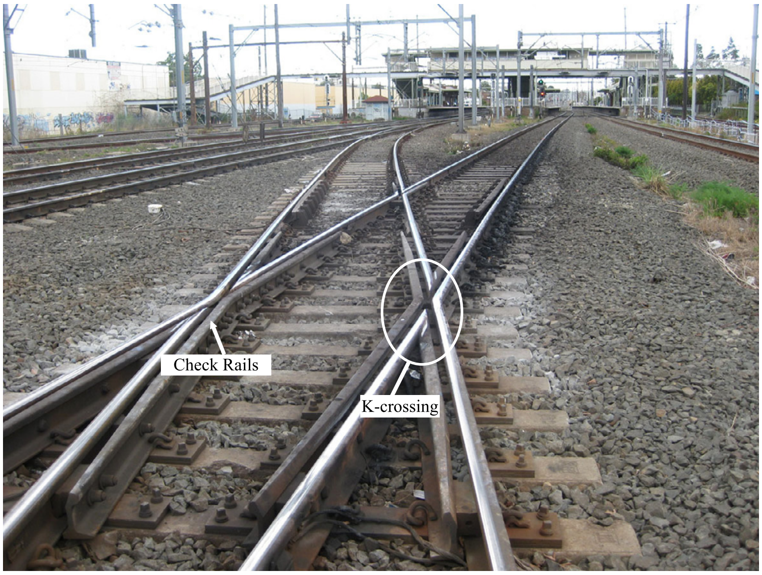


Fig. 1. A typical turnout structure.

In rail transport infrastructure, a turnout is an inevitable and critical system whose crossing imparts a considerable discontinuity in the wheel/rail running surface, so-called the contact patch. The wheel/rail interaction on such imperfect contact transfer can cause high-frequency impact loads on the turnout system and its components [1–4]. The dynamic loads apply vertically and laterally to steel crossing part, resulting in high wear rate and rapid deterioration. Then, the wheel/rail discontinuity becomes more significant causing larger impact loads over time as a cycle. The transient vibration could also affect surrounding building structures via ground-borne and/or structural-borne vibration. In addition, a significant impact can radiate nuisance noises to communities along the railway corridor [5]. It is important to note that such impact and ground-borne noises are additional to rolling noise, commonly generated by wheel/rail roughness interaction.

Many previous studies have predicted impact forces and noise using numerical models [5]. However, only a few have monitored damage and deterioration of turnout crossings in the field and even fewer field trial reports are available in the literature [1,6]. This paper presents a case study using a basis of dynamic wheel/rail interaction to evaluate and monitor the structural deterioration of railway turnout systems in an Australian urban rail network. The methodology integrates numerical train/track simulations, axle box acceleration and ride quality data obtained from the calibrated track inspection vehicle "AK Car". Structural health monitoring of an urban turnout diamond will be emphasized with respect to wheel/rail transverse and longitudinal profilings of crossings, later referred to as '*equivalent dip angle*'.

2. Wheel/rail interaction over turnout crossing

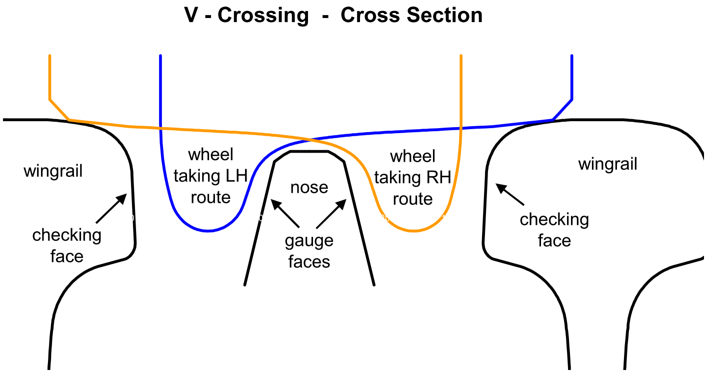
Wheel/rail interaction and its deviations depend considerably on various factors, including the wheel/rail contact, train speeds, train and track mechanical properties, as well as track geometry or alignment. The wheel/rail running contact over the crossing transfer zone has a dip-like shape where the wheel trajectory is not smooth. The accurate shape of the wheel trajectory (running top) and dip angle will depend on the wheel and running rail profiles. The associated dip angles, which are the acute angle between the tangents to the wheel trajectory at the point where it abruptly changes direction, can then be estimated from the wheel trajectories, as illustrated in Fig. 2.

Fig. 3 shows the typical impact load due to a rail dip irregularity [1]. It is generally assumed that the high frequency impact force (P_1) that occurs either at a nose or at a wing rail has little effect on the rail foot [7]. On the other hand, the dynamic P_2 force (the second peak in the impact force history) has significant influence on the crossing components. The distance from the point of impact to the point of the peak impact force depends on a number of factors including train speed. The common damage zones to be considered are the rail foot within 0.75 m of any joints to plain rail; and the base of the crossing in transfer zone (extending 0.75 m on both sides of the pick up point); and other components in vicinity of the crossings.

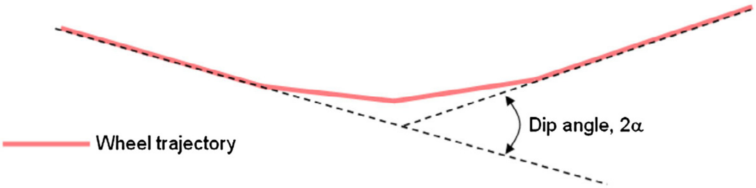
In a calculation of P_2 force, the track damping C_t is normally negligible. For plain tracks, it is commonly found that the track mass is relatively low in comparison with the wheel set mass and is then neglected. In contrast, for a turnout crossing, the track mass tends to be of significance and it cannot be neglected. Jenkins et al. [8] have proposed a formula for estimating a dynamic P_2 force as follows:

$$P_2 = P_0 + 2\alpha \cdot v \cdot \left[\frac{M_u}{M_u + M_t}\right]^{\frac{1}{2}} \cdot \left[1 - \frac{\pi \cdot C_t}{4\sqrt{K_t \cdot (M_u + M_t)}}\right] \cdot [K_t \cdot M_u]^{\frac{1}{2}} \qquad (1)$$

a) wheel traversing a v-crossing (white paint showing the contact band)



b) wheel/rail contact at crossing



c) wheel trajectory in transfer zone

Fig. 2. Transfer zone at crossing.

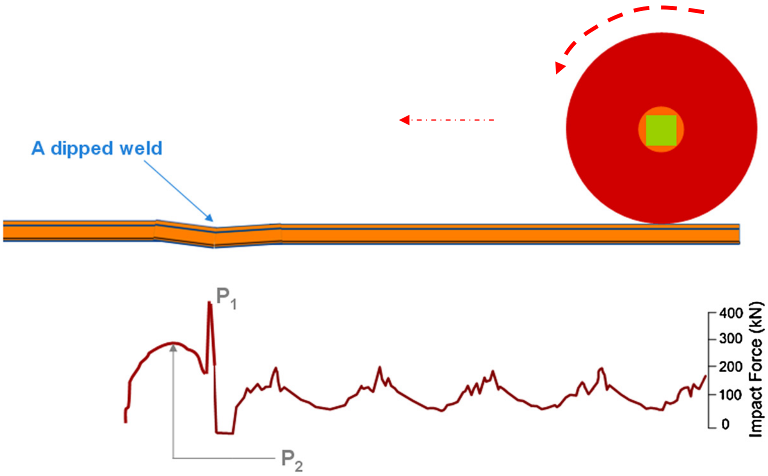


Fig. 3. Typical impact load at a dip joint.

Fig. 4. Ballast pulverisation at crossing.

where P_2 = Dynamic vertical force (kN); P_0 = Vehicle static wheel load (kN); M_u = Vehicle unstrung mass per wheel (kg); 2α = Total joint angle or equivalent dip angle (rad); v = Vehicle velocity (m/s); K_t = Equivalent track stiffness (MN/m); C_t = Equivalent track damping (kN s/m); and M_t = Equivalent track mass (kg).

Based on previous studies [9], a vehicle model was developed based on specifications of a widely used container wagon with 92 tonne gross mass and ride control bogies. The wagon model contains 11 masses (1 wagon car body, 2 bolsters, 4 sideframes, and 4 wheelsets). The connections among these 11 masses were modelled using 17 stiffness elements, 74 bumpstop elements, 13 viscous damper elements, 116 friction elements, and 4 shear spring elements, which fully consider the non-linear characteristics of the connections. All simulations were completed and calibrated using the Australian WPR2000 wheel profile and the rail profile of a new 60 kg rail. Model validations were benchmarked with field test data [9,10]. The vehicle–track model can predict body and axle accelerations of any vehicle as well as the impact force generated at wheel/rail interface. In addition, the algorithm to back estimate the dynamic equivalent dip angle from the axle box acceleration was developed [9,10]. Note that twisted geometry, worn parts, local deformation, ballast breakage and settlement, degraded elastomeric pads, and so on are contributing to the dynamic wheel–rail interaction, which is best represented by a normalized 'equivalent dip angle' that could be reliably and accumulatively obtained from a calibrated, instrumented track inspection vehicle. The equivalent dip angle can be used as a benchmark to monitor the structural deterioration of the turnout crossing or any short-pitch rail irregularity. It should be noted that the inertia concept (by using axle box's vibration-based recording) has an advantage in that it has a direct link to train passenger experience or '*ride quality*'.

3. Case study

There was a problem in relation to significant degradation of turnout components due to large impact force from the Clyde 700 diamond (RailCorp's western main rail network). White ballast (ballast pulverisation) could be observed near the crossings, as shown in Fig. 4. The ballast was pulverised due to the impact vibration of crossing structures and bearers, which is excited by the rail dip-like irregularity. Large turnout settlement could also be observed.

To evaluate and monitor the structural deterioration of the turnout system, the axle box acceleration data was collected from AK Car archive for the runs between April 2005 and November 2008. It is noted that the data sampling rate is 3500 Hz, resulting in a maximum limit of frequency analysis of 1600 Hz. The previous numerical simulations [11] have been used to predict the impact forces from the historical axle box acceleration data. Filtering bands have applied to the vibration data in order to distinguish between P_1 related vibration and P_2 related vibration. In relation to track dynamics, the frequency bands used in this study are 70–200 Hz for P_1 and 20–70 Hz for P_2.

Fig. 5 shows the average summary data of the track dynamic forces, which are associated with the recorded wheel vibrations. Using a least square best fitting, the estimated linear trend line of track condition has been appended into the curves to project the level of vibration and associated equivalent dip angle. This study focuses on the track deterioration before and after the track reconditioning (when the pads were replaced) in July 2006. It should be noted that the wheel vibration could vary because the AK car speeds were inconsistent (57 km/h – 11/04/2005; 38 km/h – 13/07/2005; 40 km/h – 19/12/2005; 56 km/h – 23/03/2006; 49 km/h – 12/07/2006; 40 km/h – 22/03/2007; 49 km/h – 8/09/2008; and 52 km/h – 20/11/2008). Accordingly, a train/track simulation that has already taken the vehicle speeds into account has been used in order to calculate the equivalent dynamic dip angle [11]. Note that the rate of deterioration was improved through added structural resiliency [12,13]. Ride quality is shown in Fig. 6, demonstrating the improvement of turnout structural condition. It is found that overall the combined ride comfort has been significantly improved as the train body's vertical vibration suppressed from 350 mG to 250 mG over the turnout length [11]. This case study demonstrates a possibility of using the equivalent dip angle as an indicator of when a turnout requires maintenance or predicting the remaining life before maintenance.

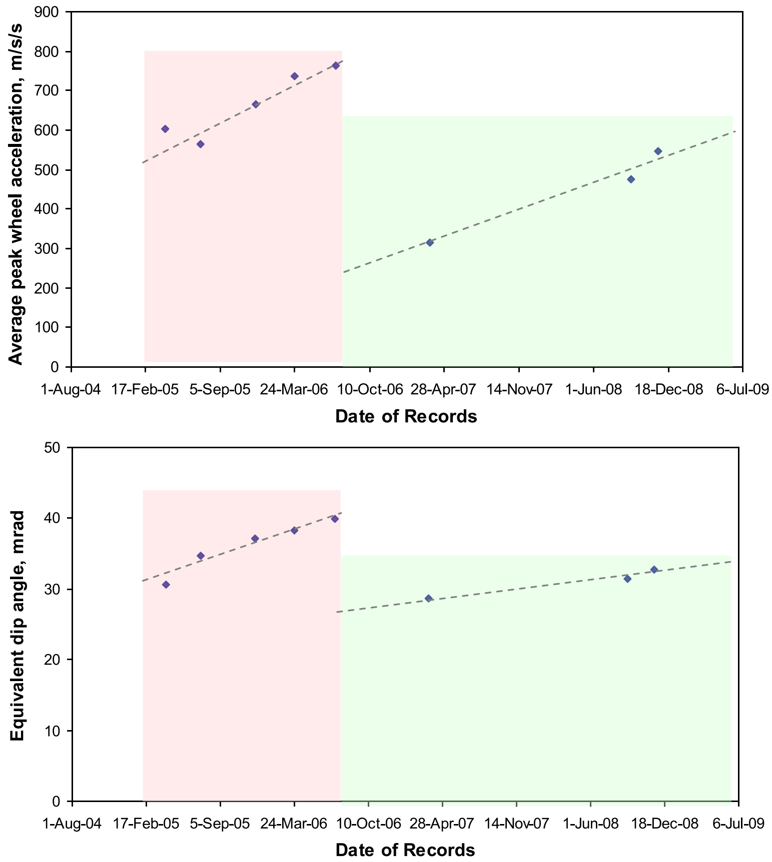


Fig. 5. Wheel peak impact forces (top – axle vibration; bottom – equivalent dip angle).

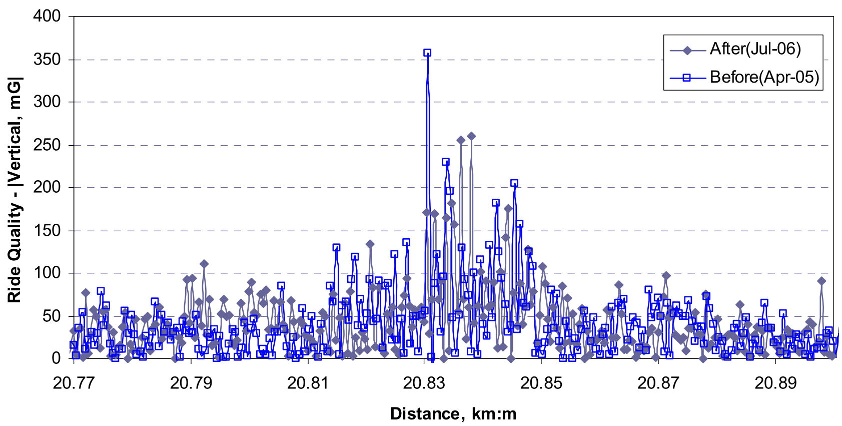


Fig. 6. Ride comfort.

4. Conclusion

Understanding in the vehicle–track interaction is vital for structural health monitoring and vibration control strategies for rail asset management. This paper demonstrates an application of dynamic wheel/rail interaction to assess and monitor the structural deterioration of railway turnout system, which has been adopted by railway maintainers in Australia [10–12].

This case study demonstrates the assessment and monitoring for the structural deterioration of an urban turnout, which directly relates to impact vibration and passenger ride comfort. The effectiveness of the track reconstruction can be assessed by considering the difference between the vibration after track upgrading and the vibration before track upgrading. Considering the condition before and after, the unfiltered wheel vibrations reduce significantly. Taking into account the train speeds, the train/track simulation shows that the associated equivalent dip angle leading to the dynamic P_2 force could be decreased as much as 27.5%. It is also found that the ride quality has been improved significantly.

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