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Wheels v Rails

A lecture presented to the IMechE Railway Division 7th November 2016

Dr Paul Allen and Dr Philip Shackleton
Overview

- The Institute of Railway Research
- A bit of wheel-rail interface history
- Some science and maths but not too much!
- Wheel-rail interface maintenance challenges
- Case Study: Crossrail
- A few other related research activities (time permitting!)
The IRR Team

Management Team
• 6 Senior staff

Research and Enterprise Team
• 25 Multidisciplinary specialists

Administration and Support
• 1 Group Administrator
• 1 Test Applications Engineer
Expertise

Wheel-Rail Interaction: Modelling and full-scale testing of wheel-rail contact and resulting damage (wear, rolling contact fatigue corrugation etc). Methods of optimising the interface for heavy rail, light rail and metro systems. Wheel-rail adhesion investigations.

Railway Vehicle Dynamics: Vehicle behaviour and track interaction, performance optimisation for heavy rail, light rail and metro vehicles. Train braking system modelling and full-scale bogie testing facility.

Track-system Dynamics: Modelling and full-scale testing of complete trackforms and vehicle interaction. Predictions of force distributions, track and fixing response and structural resistance. Trackform design and failure mode investigations.

Instrumentation and Condition Monitoring: Vehicle and track mounted measurement systems, condition monitoring systems and asset life optimisation to aid a migration to predictive maintenance.

Railway Safety and Data Analytics: safety/risk modelling, safety system development, societal risk (e.g. modal shift), prognostics and Big data analytics for safety and engineering problems.

Civils and Structures: Masonry arch bridge and tunnel analysis, structural transition zone optimisation, train-structure interaction, noise and vibration.
Wheels v Rails

1803, Plateway for cylindrical wheels

Trevithick’s ‘tram engine’ in 1804 running on a Plateway
Wheels v Rails

1789, Iron ore cart; William Jessop developed the cast iron Edge Rail and credited with the flanged wheelset.

William Jessop’s flanged Wheelset and Fish-belly Edge Rails circa 1806
200 years on – unrecognisable??!!!

- Creep Forces
- Normal Force
- Shear stress
- Normal stress (Contact pressure)
An idealised conical wheelset displaced laterally on cylindrical rails:

The source of the ‘problem’...
For perfect curving (pure rolling):

\[
\frac{r_0 - \lambda y}{r_0 + \lambda y} = \frac{R - l_o}{R + l_o}
\]

Where
- \( r_0 \) = the radius when the wheelset is central
- \( l \) = half the gauge
- \( R \) = the radius of the curve
- \( \lambda \) = the conicity

So:

\[
y = \frac{r_0 l}{R\lambda}
\]

In reality, for a constrained wheelset, pure curving does not exist. The wheel-rail relative slip (creepage) and tangential forces increase as curve radius decreases. This results in shear stresses over 2000 MN/m² within the interface and energy dissipated as heat and material wear.
In the UK a single wheel can see a vertical load (Q) of up to 12.5t

The resultant contact patch between wheel and a rail is typically the size of a thumbnail and the *Normal Stress* can exceed 5000 MN/m\(^2\)
Wheel-Rail contact modelling for damage prediction

Fast ← Hertz+FASTSIM ← ANALYN+FaStrip ← CONTACT code ← Accurate

~ 0.02 second ~ 0.12 second ~ 20 seconds
Great progress has been made over the last 15 years in managing the wheel-rail interface but Plain line and S&C renewals remain a huge proportion of the railway’s asset and maintenance costs.

Wheel-rail forces and contact stresses result in three key degradation mechanisms:
- Wheel-rail wear ($T \gamma$ and contact stress)
- Rolling contact fatigue (RCF)
- Loss of profile shape (Plastic flow)

Costly maintenance measures include:
- Rail re-profiling for loss of shape and RCF crack removal (milling and grinding)
- Wheelset re-profiling for wear/shape loss but also RCF
- Rail renewals
- Wheelset renewals
• The units of the RCF damage index are $10^{-5}$ per axle pass, a damage index of 1, would require 100,000 axle passes for RCF initiation.

• In addition to modelling and prediction work, RCF mitigation measures now include:
  • NDT as an inspection measure (Eddy-current and ultrasonic trains)
  • Optimisation of a train’s Primary Yaw Stiffness (PYS)
  • Enhanced visual inspection routines for heavy/severe RCF sites
Wear Predictions

Wear Model:

- Wear model based on BR Research twin-disc tests for a single rail steel grade
- $T\gamma \leq 100$N, mild wear regime
- $100N > T\gamma \leq 200$; Severe region
- $T\gamma > 200$N; Catastrophic wear regime – typical of non-lubricated flange contacts
- Limited data at high $T\gamma$ and under lubricated conditions or Friction Modification
Case study: Crossrail

- The Crossrail network consists of 118km of new and existing line
- 53km of tunnelled sections, low radius curves (≈500m) and challenging gradients
- Very high peak service pattern (average 383 trains per day/60MGTPA!)
- Ongoing maintenance overhead and maintaining service levels and reliability is a significant challenge
- Crossrail is adopting an early proactive approach to managing the interface and assisting in developing the science of wheel-rail damage prediction
Aims of the study:

- To identify and manage locations which may be prone to early initiation of rolling contact fatigue (RCF) and high levels of wear
- To investigate a range of influencing parameters such as cant deficiency, w/r profile, lubrication and friction modifiers
- To develop a rail life and maintenance visualisation tool to facilitate maintenance planning
- To help further the state-of-the-art in rail damage prediction modelling

- The work includes some developments over previous studies:
  - A revised implementation of the RCF model based on the direction of the creep forces
  - A wide ranging literature review and subsequent inclusion of RCF functions for alternative rail steels
  - A whole route, multi-scenario simulation approach
  - Development of a rail life and maintenance planning visualisation tool
Traffic levels calculated from initial Crossrail service timetable, using following assumptions:

- 9 vehicles per Full Length Unit (FLU)
- Tare FLU tonnage of 320t
- 1500 passengers @80kg (EN 15663)
- Design vehicle gross tonnage of 440t
Curvature distribution

Route Comparisons – On-network v Tunnneled

Maidenhead to Royal Oak

Royal Oak to Abbey Wood (Eastbound)

- Population of Route (%)
- Curve Radius (m)
- Line speed (mph)
- Cant Def/Excess (mm)
Creep force angle

For sites where the w-r conditions differed from the original RCF model validation, it became necessary to consider the varying direction of the creep forces.

$$T\gamma' = T\gamma \times \cos(\alpha) \sqrt{2}$$

- As a general rule, only creepages acting in the tractive direction (crack opening) contribute to the accumulation of RCF damage.
- The modified function ensures the correct resultant of these forces is used in mapping $T\gamma$ to RCF damage.
Alternative steels for RCF resistance

The original Crossrail work was extended and the following RCF functions were included in the study (RSSB T775, M. Burstow, NR):

- **RCF Peak**
- **RCF 65**
- **Threshold**
- **Peak**
- **Balance**

![Graph showing the comparison of different steels for RCF resistance](image-url)

\[
\begin{align*}
T_{\gamma_{\text{Threshold}}} &= 15 \times \frac{\text{HB}_{\text{New Material}}}{\text{HB}_{\text{260 Material}}} \\
T_{\gamma_{\text{Balance}}} &= 175 \times \frac{\text{HB}_{\text{New Material}}}{\text{HB}_{\text{260 Material}}} \\
\text{RCF}_{65} &= 10 \times \frac{\text{RCF Resistance}_{\text{260 Material}}}{\text{RCF Resistance}_{\text{New Material}}} \\
\text{RCF}_{\text{Peak}} &= 10 \times \frac{\text{Elongation}_{\text{260 Material}}}{\text{Elongation}_{\text{New Material}}} 
\end{align*}
\]
Crossrail’s rail maintenance strategy is based on milling operations to manage RCF/Wear and restore profile shape:

- Three maintenance triggers identified
  - Periodic preventive milling
  - Reactive milling to manage RCF
  - Reactive milling to restore loss of profile (due to wear or material flow)

- A maintenance planning and visualisation tool is being developed which will:
  - Help facilitate a scenario based approach to optimising rail asset management
  - Aid the review of predicted damage against in-track observations
  - Continuously monitor and update milling and renewals planning activities
  - The tool is based around just under 20,000 pre-calculated and tabulated whole-route based vehicle dynamics simulations
A maintenance planning tool

[Image of software interface for Crossrail Visualisation Tool]

- Select the parameter combinations of interest
- Specify track options
- Specify plotting options

[Options for Crossrail Visualisation Tool for RCF and Wear Management]
A maintenance planning tool
RCF prediction example
Wear and RCF prediction (R260)

Accumulated Wear (blue shading) and RCF Damage (red shading) - V=FLU X=3 S=1 W=3 R=1 F=4 D=1
EB Westbourne Park to Abbey Wood for one FLU passage

Left Rail Lateral Position (mm)

Track Curvature (1/km)

Wear: 1.00e-07 (mm³)
Wear: 5.00e-06 (mm³)

Right Rail Lateral Position (mm)

RCF: 5.00e-04 DI
RCF: 2.50e-04 DI

Chainage (km)
Guidance on maintenance actions

- Rail life calculation must terminate at some point
  - Rail ‘failures’
    - RCF damage
    - Wear (loss of profile)
    - Head loss (from milling)
  - Duration of interest is exceeded
    - E.g. 10 years

- Rail life with respect to milling (head loss)
  - Sum of material removed for the three maintenance triggers
  - Rail life determined in relation to
    - Number of vehicle or unit passages
    - MGT
    - Time
Guidance on maintenance actions
Summary

The final tool will be delivered at the end of 2016

• Will be used to inform planning and aid optimisation of maintenance activities
  – Lubrication and friction modifiers
  – Resource allocation (Milling activities)
  – Expected asset life (Renewals schedules)

• Data from the live network will feed back to support further development of the modelling tools
  – Improve damage prediction accuracy
  – Particularly premium rail grades
  – A significant opportunity to further the state-of-the-art
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  – Mike Allen
  – Susan Simmonds

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  – Dr Mark Burstow; collaborating author of the original and on-going developments in rail degradation modelling and RCF predictions
Before we finish....

Wheels v Rails
A few other related research activities......
• £6.2M, 5 year EPSRC Programme Grant
  – TTrack4Life (RC1)
    • to develop low-maintenance, long-life track systems with optimised material use
  – Designer crossings and transitions (RC2)
    • Design crossings and transitions so as to optimise vehicle behaviour through them, hence maximising resistance to damage
  – Noise-Less track (RC3)
    • develop and demonstrate an integrated approach to designing a low-noise, low-vibration track consistent with reduced whole life costs and maintenance needs
Rail Steel Composition

• 2-year EPSRC/RSSB/DfT research programme

Objectives:

– Improve the understanding of steel microstructures to imposed loading conditions
– Establish features of microstructures that provide maximum resistance to key degradation mechanisms
– Development of standardised material tests and guidance for rail steel grade selection
Research Project: H2020 In2Rail

- Novel S&C concept generation and validation
- New rail repair techniques development
- Enhanced ballast and hybrid track systems
Siemens “Tracksure” Void Detection System

- Detailed vehicle-track modelling to investigate feasibility of using in-vehicle acceleration data for the detection of track defects
- Assisted in sensor selection and development of a highly efficiently algorithm to process large quantities of acceleration data to detect and categorise severity of under-track voids using in-vehicle sensors
Wheelset Maintenance

- Wheelset account for a large proportion of a fleet's whole-life costs (40%)
  - Strong demand to reduce costs through extended reprofiling intervals and better wheelset life
- Research areas include:
  - Improved understanding of damage mechanisms
    - Wheel Tread Damage Guide (RSSB T963)
  - Quantifying surface damage
    - MRX Surface Crack Measurement (Future Railway)
  - Optimisation of maintenance routines to prolong life
    - Siemens TPE Class 185
    - Economic tyre turning (RSSB)
Full-scale bogie test rig
Potential research applications

Example applications:
- **Bogie/wheelset dynamics**
  - Wheelset longitudinal suspension (yaw) optimisation for minimisation of steering forces
  - Vertical bogie dynamics; optimisation of primary and secondary suspension
  - Analysis of novel wheelset and bogie technologies
  - Noise and vibration analysis (wheel squeal)

- **Adhesion and braking research**
  - Effect of wheel-rail contaminants on interface performance
  - Wheel-rail friction modifier evaluation
  - Traction and braking/WSP performance optimisation
  - Brake pad material development and change-out studies (duty cycles)

- **Wheel and rail profile design evaluation**
  - Assessment of existing (measured) wheel and rail profiles
  - Identification of profile development areas (e.g. flange root/tread geometry) and trial of new profile shapes
  - Assessment of ground/milled rail profile proposals
  - Wheelset life estimation and extension
  - Minimisation of contact forces – reductions in wear and RCF

- **Materials research**
  - Novel wheel and rail material evaluation
  - Composite and conventional wheelset testing
  - Accelerated fatigue testing