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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

Shear stress

Normal Force

Normal stress
(Contact pressure)
The source of the ‘problem’...

An idealised conical wheelset displaced laterally on cylindrical rails:

\[ R \]

\[ r_i \]

\[ r_r \]

\[ l_0 \]

\[ l_0 \]

\[ y \]
The source of the ‘problem’...

For perfect curving (pure rolling):

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

So:

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

Where

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

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/m\(^2\) 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/m²
Wheel-Rail contact modelling for damage prediction

Hertz+FASTSIM

ANALYN+FaStrip

CONTACT code

Fast

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
**RCF Prediction**

**RCF Initiation Model:**
(R260 Grade Steel)

- 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 Prediction

Wear Model:

- Wear model based on BR Research twin-disc tests for a single rail steel grade
- $T\gamma \leq 100\text{N}$, mild wear regime
- $100\text{N} > T\gamma \leq 200$; Severe region
- $T\gamma > 200\text{N}$; 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

Above figures indicative
Curvature distribution

Route Comparisons – On-network v Tunneled

Maidenhead to Royal Oak

Royal Oak to Abbey Wood (Eastbound)

- Population of Route (Excl. Straights)

- Curve Radius (m)

- Population of Total Route (%)

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

\[
\begin{align*}
T_{\gamma}^{\text{Threshold}} &= 15 \times \frac{\text{HB}_{\text{New Material}}}{\text{HB}_{260 \text{ Material}}} \\
T_{\gamma}^{\text{Balance}} &= 175 \times \frac{\text{HB}_{\text{New Material}}}{\text{HB}_{260 \text{ Material}}} \\
\text{RCF}_{65} &= 10 \times \frac{\text{RCF Res}^{\text{260 Material}}}{\text{RCF Res}^{\text{New Material}}} \\
\text{RCF}_{\text{Peak}} &= 10 \times \frac{\text{Elongation}^{\text{260 Material}}}{\text{Elongation}^{\text{New Material}}}
\end{align*}
\]
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
A maintenance planning tool
RCF prediction example

Peak Accumulated Wear and RCF Damage
EB Westbourne Park to Abbey Wood

Left Rail

Right Rail

RCF (DI)

Track Curvature (1/km)

Chainage (km)
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)

Chainage (km)

Right Rail Lateral Position (mm)

Track Curvature (1/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
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

Network Rail:
- 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......
Track to the Future (T2F)

- £6.2M, 5 year EPSRC Programme Grant
  - TRack4Life (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