Wheel-Rail Interaction Fundamentals

Kevin Oldknow, Ph.D., P.Eng.
Principal Engineer, Wheel/Rail Interface
L.B. Foster Rail Technologies
Overview

• Part 1
  – The Wheel / Rail Interface and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creep, Traction Forces and Friction
  – Wheelset Geometry and Effective Conicity

• Part 2
  – Vehicle Steering and Curving Forces
  – Wheel and Rail Wear Mechanisms
  – Shakedown and Rolling Contact Fatigue

• Part 3
  – The Third Body Layer, Traction/Creepage and Friction Management
  – Curving Noise
  – Corrugation

This three-part session will provide an introduction to several fundamental aspects of vehicle-track interaction at the wheel/rail interface.
Three questions that we will aim to answer....
Question #1: How can we estimate the lateral forces (and L/V ratios) that a vehicle is exerting on the track?
Question #2: How can we determine if there is a risk of rolling contact fatigue (RCF) developing under a given set of vehicle/track conditions?
Question #3: How is the noise captured in these two sound files generated at the wheel/rail interface?

- File #1: 
- File #2:
Overview

• Part 1
  – The Wheel / Rail Interface and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creep, Traction Forces and Friction
  – Wheelset Geometry and Effective Conicity
Back to basics...

- Tangent
- Curve
- Spiral
- High Rail
- Low Rail
- Superelevation (aka Cant)
- Rail Cant
The Wheel / Rail Interface and Key Terminology

- Field Side
- Gage Side
- Ancillary
- Tread
- Flange Root
- Flange Face
- Ball / Crown / Top of Rail (TOR)
- Mid-Gage
- Gage Corner
- Gage Face
- Gage Side
- Back to Back Wheel Spacing
- Back of Flange (BoF)
- Track Gage

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WRI 2016
The Wheel / Rail Interface and Key Terminology
(e.g. Low Rail Contact)

“Lightly” Worn

“Heavily” Worn
The Wheel / Rail Interface and Key Terminology (e.g. High Rail Contact)

"Lightly" Worn

"Heavily" Worn
The Contact Patch and Contact Pressures

• Question #1: What is the length (area) of contact between a circle (cylinder) and a tangent line (plane)?

• Question #2: Given Force and Area, how do we calculate pressure?

• Question #3: If a circular body (~wheel) is brought into contact with a linear body (~rail) with a vertical force $F$ and zero contact area, what is the resulting calculated pressure?
Hertzian Contact

- Hertzian Contact (1882) describes the pressures, stresses and deformations that occur when curved elastic bodies are brought into contact.

- “Contact Patches” tend to be elliptical

- This yields parabolic contact pressures

\[ P_0 = \frac{3}{2} P_{\text{avg}} \]

- Contact theory was subsequently broadened to apply to rolling contact (Carter and Fromm) with non-elliptical contact and arbitrary creepage (Kalker; *more on this later...*)
Creepage, Friction and Traction Forces

- Longitudinal Creepage
- The Traction-Creepage Curve
- Lateral Creepage
- Spin Creepage
- Friction at the Wheel-Rail Interface
What does Longitudinal Creepage *mean*?...
What does Longitudinal Creepage *mean*?...

- The frictional contact problem (Carter and Fromm, 1926) relates frictional forces to velocity differences between bodies in rolling contact.

- Longitudinal Creepage can be calculated as: \[ \frac{R\omega-V}{V} \]

- In *adhesion*, 1% longitudinal creepage means that a wheel would **turn 101 times** while traveling a **distance of 100 circumferences**.

- In *braking*, -1% longitudinal creepage means that a wheel would **turn 99 times** while traveling a **distance of 100 circumferences**.
"Free Rolling"

Wheel

$R\omega = V$

Third Body Layer

Rail
“Small” Positive (Longitudinal) Creepage

Wheel

Third Body Layer

Rail

\[ R \omega > V \]
“Large” Positive (Longitudinal) Creepage

Wheel

$R\omega > V$

Third Body Layer

Rail
The Traction-Creepage Curve

- Microslip
- Adhesion

μN vs. Longitudinal Creepage

Rolling Direction
Lateral creepage
Imagine pushing a lawnmower across a steep slope...

OK, but when does this occur at the WRI?...
Steering in “Steady State” Curving (“Mild” Curves)

Angle of Attack (AoA)
Steering in “Steady State” Curving (“Sharp” Curves)

Angle of Attack (AoA)
Steering in “Steady State” Curving (“Very Sharp” Curves)

Angle of Attack (AoA)
Spin Creepage
Think of spinning a coin on a tabletop....

OK, but when does this occur at the WRI?...
Rolling vs. Sliding Friction

They are **not** the same!

\[ f = \mu N \]

\[ f(creep) \neq \mu N \]

\[ \text{creep: } R\omega - V \]

\[ V \]

\[ \omega \text{ (rotational speed)} \]

\[ R \text{ (radius)} \]

\[ N \text{ (normal load)} \]

\[ V \text{ (forward velocity)} \]

\[ V \text{ (sliding velocity)} \]

\[ f \text{ (friction force)} \]

\[ f \text{ (friction force)} \approx \text{simply } \mu N \]

\[ f \text{ (friction force)} \approx \text{simply } \mu N \]

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\[ f \text{ (friction force)} \approx \text{simply } \mu N \]
Traction/Creepage Curves

“Heuristic” expressions used for the saturation and physical meaning of the different parts.
Vehicle Steering and Curving Forces

- The wheelset
Displaced wheel set

\[
\frac{r_0 - \lambda y}{r_0 + \lambda y} = \frac{R - L_0}{R + L_0},
\]

\[
y = \frac{r_0 L_0}{R \lambda}.
\]

\(\lambda\) = effective conicity

\(r_0\) = wheel radius of undisplaced wheelset

\(R\) = curve radius

\(L_0\) = half gauge
Theoretical Equilibrium
Effective Conicity

![Graph showing Rolling Radius Difference](Image)

- Pregrind - Rolling Radius Difference
- Trial End - Rolling Radius Difference
- Postgrind - Rolling Radius Difference

mm

-15 -10 -5 5 10 15

-10 -5 0 5 10

mm
Effective Conicity (Worn Wheels)
Important Concept:

- Sometimes, forces give rise to creepage (e.g. traction, braking, steering)
- Other times, creepage gives rise to forces (e.g. curving)
Effect of rolling radius difference on steering moment

Figure 2: effect of rolling radius difference on longitudinal component of creepage force
Tangent Running and Stability

- Lateral displacement → ΔR mismatch → friction forces → steering moment

- Wheelset passes through central position with lateral velocity.

- At low speeds, oscillations decay.

- Above critical hunting speed, oscillations persist.
And now for something completely different...
Questions & Discussion
Overview

• Part 2
  – Vehicle Steering and Curving Forces
  – Wheel and Rail Wear Mechanisms
  – Shakedown and Rolling Contact Fatigue
Curving Forces (101)

- AoA / Flange Force
- Track Spreading Forces
- Friction Forces (Lateral Creepage from AoA)
- Anti-Steering Moment (Longitudinal Creepage from mismatched rolling radii)
- Direction of Travel
Impacts of High Lateral Loads:
Rail Rollover / Track Spread Derailments
Impacts of High Lateral Loads:
Plate Cutting, Gauge Widening
Impacts of High Lateral Loads: Wheel Climb Derailments
Impacts of High Lateral Loads: Fastener Fatigue / Clip Breakage
Returning to Question #1: How can we estimate the lateral forces (and L/V ratios) that a vehicle is exerting on the track?
Estimating AoA and Lateral Creepage in a “Sharp” Curve

- **Example:**
  - 6° curve (R = 955’)
  - 70” wheelbase (2L = 5.83’)
  - $\mu_{TOR} = 0.5$ (dry)

- **Leading Axle angle of attack:**
  - $\alpha \sim \arcsin(2L/R) \sim 2L/R = 0.0061$ Rad (6.1 mRad)

- **Lateral Creepage at TOR contact:**
  - $V_{lat}/V \sim 2L/R \sim \alpha = 0.61\%$
Estimating Low Rail L/V and Lateral Force

- At 0.61% creep: 
  \[ \frac{L}{V} = \mu \]

\[\text{At high creep } \frac{L}{V} \sim \mu\]
\[\text{At low creep } \frac{L}{V} \sim \text{const} \times \text{creep}\]

\[\text{Angle of Attack (AoA)}\]
How does this compare with simulation results?

VAMPIRE® Simulation: Low Rail L/V
6° curve (R=955'), SE = 3.9", Speed = 30mph, $\mu_{TOR} = 0.5$, $\mu_{GF} = 0.15$
Curving Forces (201)

• Remember this?

How often do we see a single (isolated) wheel set in operation?

Hopefully not very often!
Factors Affecting Curving Forces

- Creepage and friction at the gage face / wheel flange interface (e.g. GF Lubrication -> increased L/V)
- Speed (relative to superelevation) and centrifugal forces
- Coupler Forces
- Buff & Drag Forces
- Vehicle / Track Dynamics:
  - Hunting
  - Bounce
  - Pitch
  - Roll

\[
V_{\text{max}} = \sqrt{\frac{E_s + 3}{0.0007D}}
\]

Where:
- \(V_{\text{max}}\) = Maximum allowable operating speed (mph).
- \(E_s\) = Average elevation of the outside rail (inches).
- \(D\) = Degree of curvature (degrees).
An example...

• Why are the lateral forces measured a few cribs apart so different?
Mystery solved...

Crib 5 “on-flange”

Crib 6 “off-flange”
Rail and Wheel Wear
Rail and Wheel Wear

- Wear Types:
  - Adhesion
  - Surface Fatigue
  - Abrasion
  - Corrosion
  - Rolling Contact Fatigue
  - Plastic Flow

- “Archard” Wear Law:
  - $V = c \frac{Nl}{H}$
  - $c$ proportional to COF
  - $V$ = volume of wear
  - $N$ = normal load
  - $l$ = sliding distance (i.e. creepage)
  - $H$ = hardness
  - $c$ = wear coefficient
Wear regimes

\[ T = \text{Tractive force} \]
\[ \gamma = \text{Slip} \]
Shakedown and Rolling Contact Fatigue (RCF)
Recall: Hertzian Contact

- “Contact Patches” tend to be elliptical
- This yields parabolic contact pressures

\[ P_0 = \frac{3}{2} P_{\text{avg}} \]
The Contact Patch and Contact Pressures
The Contact Patch and Contact Pressures

Low Rail Contact Area, mm²
Example calculation: Average and Peak Pressure

- Let’s assume a circular contact patch, with a radius of 0.28” (7 mm)
- The contact area is then: 0.24 in² (154 mm²)
- Assuming a HAL vehicle weight (gross) of 286,000 lbs, we have a nominal wheel load of 35,750 lbs, i.e. 35.75 kips (159 kN)
- The resulting average contact pressure (Pavg) is then: 150 ksi (1,033 MPa)
- This gives us a peak contact pressure (Po) of: 225 ksi (1,550 MPa)

- What is the shear yield strength of rail steel?*
- What’s going on?


<table>
<thead>
<tr>
<th>Steel</th>
<th>Hardness (Brinnell)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ksi</td>
<td>MPa</td>
</tr>
<tr>
<td>“Standard”</td>
<td>260-280</td>
<td>65-70</td>
</tr>
<tr>
<td>“Intermediate”</td>
<td>320-340</td>
<td>80-85</td>
</tr>
<tr>
<td>“Premium”</td>
<td>340-380</td>
<td>85-95</td>
</tr>
<tr>
<td>“HE Premium”</td>
<td>380-400</td>
<td>95-100</td>
</tr>
</tbody>
</table>
Tensile Testing (1-D loading)

Cylindrical Contact with Elastic Half-Space (2-D loading)

Spherical Contact with Elastic Half-Space (3-D loading)
RCF Development: Contact Pressures, Tractions and Stresses

- Cylindrical contact pressure / stress distribution with no tangential traction

- Cylindrical pressure / stress distribution with tangential traction

Traction coefficient, \( f = 0 \)

Traction coefficient, \( f = 0.2 \)
RCF Development: Shakedown

Increased Mat’l Strength
Reduced Stress (e.g. wheel/rail profiles)

Reduced Traction Coefficient (e.g. reduced friction)
Hydropressurization: effect of liquids on crack growth

Figure 8: Influence of grease and water on crack propagation through a) control of crack-face friction, and b) hydraulic pressurization of the crack tip.
Wear and RCF wheel/rail rig test results

Dry tests crack results
Recalling Question #2: How can we determine if there is a risk of rolling contact fatigue (RCF) developing under a given set of vehicle/track conditions?
• Consider a heavy haul railway site, where heavy axle load vehicles (286,000 lb gross weight) with a typical wheelbase of 70” traverse a 3 degree curve at balance speed.

• Wheel / rail profiles and vehicle steering behavior are such that the curve can be considered “mild”

• The contact area at each wheel tread / low rail interface is approximately circular, with a typical radius of 7mm.

• The rail steel can be assumed to have a shear yield strength of $k=70$ ksi.

• The rail surface is dry, with a nominal COF of $\mu = 0.6$

• How would you assess the risk of low rail RCF formation and growth under these conditions?
Estimating lateral creepage, traction ratio & contact pressure:

- In “mild” curving, leading axle angle of attack:
  \[ \alpha \sim \arcsin(L/R) \sim L/R = 0.0030 \text{ Rad (3.0 mRad)} \]

- Lateral Creepage at low rail TOR contact:
  \[ \frac{V_{\text{lat}}}{V} \sim 2L/R \sim \alpha = 0.3\% \]
Estimating the traction ratio (L/V)

- At 0.3% creep: 
  \( \frac{T}{N} \sim 0.6 \mu \)
- With \( \mu = 0.6 \)
  Traction Ratio (T/N) ~ 0.36

*Note, we have neglected longitudinal and spin creep...
Where are we on the shakedown map?

- From the previous slide, \( T/N \sim 0.36 \)
- We previously calculated, \( P_0 = 225 \text{ ksi} \)
- With \( K = 70\text{ksi} \), \( P_0/K = 3.21 \)
Questions & Discussion
Overview

• Part 3
  – Traction/Creepage, The Third Body Layer and Friction Management
  – Curving Noise
  – Corrugation
The Traction-Creepage Curve

μN

Longitudinal Creepage

Rolling Direction

Microslip
Adhesion
"Large" Positive (Longitudinal) Creepage

Wheel

$R \omega > V$

Third Body Layer

Rail
Third Body at Wheel/Rail Contact

- Third Body is made up of iron oxides, sands, wet paste, leaves etc....
- Third Body separates wheel and rail surface, accommodates velocity differences and determines wheel/rail friction.
- Wheel/Rail friction depends on the shear properties / composition of the third body layer.
Third Body Layer – Micron Scale

Friction Management
Key Points

• The third body layer accommodates velocity differences between the wheel and rail (i.e. creepage)

• Friction forces are determined by the shear properties of the third body layer and its response to shear displacement (creepage)

• Friction management is the intentional manipulation of the shear properties of the third body layer.
Managing friction: two distinct interfaces

1. Gauge Face / Wheel Flange Lubrication
2. Top of Rail / Wheel Tread Friction Control
Controlling Friction at the Wheel/Rail Interface

Top of Rail (TOR) Friction Impacts:
- Lateral Forces
- Rail / Wheel Wear (TOR, Tread)
- RCF Development
- Fuel Efficiency
- Squeal Noise
- Flange Noise (indirect)
- Corrugations
- Hunting
- Derailment Potential (L/V, rail rollover)

Gage Face (GF) Friction Impacts:
- Rail / Wheel Wear (Gage Face, Flange)
- RCF Development
- Fuel Efficiency
- Flange Noise
- Derailment Potential (Wheel Climb)
- Lateral Forces (indirect)
Not Enough
Too Much
Ideal Targets

TOR: $\mu = 0.3 - 0.35$

Low rail

TOR: $\mu < 0.2$

High Rail
Friction Management Approaches

Applications

Trackside
- GF Lubrication
- TOR Friction Modifiers

Mobile
- Gauge/Flange
  - Liquid/Solid Lubrication
- TOR/Tread
  - Liquid/Solid Friction Modifiers
Trackside Gage Face Lubrication
Trackside Top of Rail Friction Control
Mobile Gage Face / Wheel Flange Lubrication
Solid Stick (LCF) Lubrication
Solid stick application system

- Mechanical bracket / applicator
- Solid stick applied by constant force spring.

High speed train  Metro system
Mobile Top of Rail Friction Management
Car & Locomotive Mounted
Mobile Gage Face Lubrication
(or Top of Rail Friction Control)
Hi-Rail Mounted Delivery Systems
Top of rail friction control with train mounted solid stick tread friction modifier
Maximizing system performance

• Critical areas to address include:
  
  – Assessment and Implementation of Solutions
  
  – Keeping units filled with lubricants / friction modifiers
  
  – Ensuring adequate year-round power supply & charging
  
  – Efficient removal / reinstallation to accommodate track programs
  
  – Proactive Maintenance / Efficient response to equipment damage
Assessment & Implementation

Inputs
- Territory Data (e.g., Curvature, Grade, Traffic, Train Handling)
- Detailed Track Maps (Mah, Sidings, Switches, Crossings, CF Units, Signals, Yards, ...)
- Site Visit Data (e.g., Sunlight availability, Tangent lengths, Rail surface condition)
- Verification Data (e.g., Locomotive forces, rail deflection)

Activity
- Top-level Design
- Detailed Design
- Final Design
- Optimization

Outputs
- "Coarse" Spacing & Application Rates
- "Refined" Unit Placement & Application Rates
- "Finalized" Unit Placement & Application Rates
- "Optimized" Unit Placement & Application Rates
Curving Noise
### Spectral range for different noise types

<table>
<thead>
<tr>
<th>Noise type</th>
<th>Frequency range, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling</td>
<td>30 - 2500</td>
</tr>
<tr>
<td>Rumble (including corrugations)</td>
<td>200 - 1000</td>
</tr>
<tr>
<td>Flat spots</td>
<td>50 - 250 (speed dependant)</td>
</tr>
<tr>
<td>Ground Borne Vibrations</td>
<td>30 - 200</td>
</tr>
<tr>
<td>Top of rail squeal</td>
<td>1000 - 5000</td>
</tr>
<tr>
<td>Flanging noise</td>
<td>5000 – 10000</td>
</tr>
</tbody>
</table>
**Top of rail wheel squeal noise**

- High pitched, tonal squeal (predominantly 1000 – 5000 Hz)
- Prevalent noise mechanism in “problem” curves, usually < 300m radius
- Related to both negative friction characteristics of Third Body at tread / top of rail interface and absolute friction level
  - Stick-slip oscillations

**Flanging noise**

- Typically a “buzzing” OR “hissing” sound, characterized by broadband high frequency components (>5000 Hz)
- Affected by:
  - Lateral forces: related to friction on the top of the low rail
  - Flanging forces: related to friction on top of low and high rails
  - Friction at the flange / gauge face interface
Absolute Friction Levels and Positive/Negative Friction

“Negative” or “Falling” friction

“Positive” or “Rising” friction


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Sound spectral distribution for different wheel / rail systems
Effect of friction characteristics on spectral sound distribution: Trams
Effect of friction characteristics on spectral sound distribution: Trams
“Low Frequency” Stick-Slip / Noise

* Video used with permission, Brad Kerchof, Norfolk Southern
Corrugations (Short Pitch)
Corrugation formation: common threads

\[ \lambda = \nu f \]
<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength-fixing mechanism</th>
<th>Where?</th>
<th>Typical frequency (Hz)</th>
<th>Damage mechanism</th>
<th>Relevant figures</th>
<th>References</th>
<th>Demonstrably successful</th>
<th>Should be successful</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pinned-pinned resonance</td>
<td>Straight track, high rail of curves</td>
<td>400–1200</td>
<td>Wear</td>
<td>2–6</td>
<td>[5–23]</td>
<td>Hard rails, control friction</td>
<td>Increase pinned-pinned frequency so that corrugation would be &lt;20 mm wavelength</td>
</tr>
<tr>
<td>2</td>
<td>Rutting</td>
<td>Low rail of curves</td>
<td>250–400</td>
<td>Wear</td>
<td>2, 7–11</td>
<td>[5, 6, 24–36]</td>
<td>Friction modifier, hard rails, reduce cant excess, asymmetric profiling in curves</td>
<td>Reduce applied traction in curving, improve curving behaviour of vehicles, dynamic vibration absorber</td>
</tr>
<tr>
<td>3</td>
<td>Other P2 resonance</td>
<td>Straight track or high rail in curves</td>
<td>50–100</td>
<td>Wear</td>
<td>3, 6, 17, 18</td>
<td>[4, 24, 37]</td>
<td>Hard rails, highly resilient trackforms</td>
<td>Reduce unsprung mass</td>
</tr>
<tr>
<td>4</td>
<td>Heavy haul</td>
<td>Straight track or curves</td>
<td>50–100</td>
<td>Plastic flow in troughs</td>
<td>10, 12–14</td>
<td>[38–40]</td>
<td>Hard rails</td>
<td>Reduce cant excess when corrugation is on low rail</td>
</tr>
<tr>
<td>5</td>
<td>Light rail</td>
<td>Straight track or curves</td>
<td>50–100</td>
<td>Plastic bending</td>
<td>15, 16</td>
<td>[41]</td>
<td>Increase rail strength and E'</td>
<td>Reduce unsprung mass</td>
</tr>
</tbody>
</table>
Pinned-Pinned corrugation ("roaring rail")

- At the pinned-pinned resonance, rail vibrates as it were a beam almost pinned at the ties / sleepers
- Highest frequency corrugation type: 400 – 1200 Hz
- Modulation at tie / sleeper spacing – support appears dynamically stiff so vertical dynamic loads appear greater
Rutting

- Typically appears on low rail
- Frequency corresponds to second torsional resonance of driven wheelsets
- Very common on metros
- Roll-slip oscillations are central to mechanism
Recalling Question #3: How is the noise captured in these two sound files generated at the wheel/rail interface?

- File #1: 🎧
- File #2: 🎧
Summary

• Returning to our objectives, we have reviewed:
  – The Wheel / Rail Interface and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creep, Traction Forces and Friction
  – Wheelset Geometry and Effective Conicity
  – Vehicle Steering and Curving Forces
  – Wheel and Rail Wear Mechanisms
  – Shakedown and Rolling Contact Fatigue
  – The Third Body Layer, Traction/Creepage and Friction Management
  – Curving Noise
  – Corrugation

• The intent has been to establish a framework to understand, articulate, quantify and identify key phenomena that affect the practical operation, economics and safety of heavy haul and passenger rail systems.
Questions & Discussion