Wheel-Rail Interaction Fundamentals

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Overview

• Part 1
  – The Wheel / Rail Interface Anatomy and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creepage and Traction Forces

• Part 2
  – Vehicle Steering and Curving Forces
  – Wear and Rolling Contact Fatigue

• Part 3
  – The Third Body Layer, Traction/Creepage and Friction Management
  – Frequency Domain Phenomena: Noise and Corrugations

This three-part session will provide an introduction to several fundamental aspects of vehicle-track interaction at the wheel/rail interface.
Part 1

- The Wheel / Rail Interface Anatomy and Key Terminology
- The Contact Patch and Contact Pressures
- Creepage and Traction Forces
(Very) Basic Vehicle Running Gear Anatomy

- Wheels
- Wheelsets
- Axleboxes
- Suspension
- Frame
(Very) Basic Track Anatomy

- Rail
- Crossties (Sleepers)
- Tie Plates
- Fasteners / Spikes & Anchors
- Ballast
- Subballast
- Subgrade
Recalling a few track geometry basics...

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

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

- Prep Question: What is the length of contact between a circle and a tangent line?
The Contact Patch and Contact Pressures

• Question #1: What is the area of contact between a (perfect) cylinder and a (perfect) plane?

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

• Question #3: If a cylindrical body (~wheel) is brought into contact with a planar 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

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

- 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
Why is **creepage** at the Wheel/Rail Interface important?

- Creepage at the wheel-rail interface is fundamentally related to all of the following (as examples):
  - Locomotive adhesion
  - Braking
  - Vehicle steering
  - Curving forces
  - Wheel and rail wear
  - Rolling contact fatigue
  - Thermal defects
  - Noise
  - Corrugations
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: \( \frac{R\omega - V}{V} \)
Free Rolling

In free rolling, a wheel would rotate 100 times to travel a distance of 100 circumferences.
Positive (Longitudinal) Creepage

At 1% positive creepage, a wheel would rotate 101 times to travel a distance of 100 circumferences.
At 1% negative creepage, a wheel would rotate 99 times to travel a distance of 100 circumferences.
Rolling vs. Sliding Friction

*They are not the same!*

\[ f = f(\text{creep}) \neq \text{simply } \mu N \]

\[ f \approx \text{simply } \mu N \]

- \( \mu \): coefficient of (sliding) friction

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

friction force shown as acting on block for positive sliding velocity

friction force shown as acting on wheel for positive creep
The Traction-Creepage Curve

Creep Force (Traction)

Longitudinal Creepage

$\mu N$

$-\mu N$
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)
Steering in “Steady State” Curving ("Sharp" Curves)

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

Angle of Attack (AoA)
An angle of attack (AoA) of 0.57 degrees (0.01 Radians) corresponds to a lateral creepage of 1% at the leading wheelset.
A quick (sample) calculation...

Wheelbase, 2L

Angle of Attack, $\alpha$

Curve Radius, $R$

**Example:**

- **6° curve** ($R = 955\,\text{'}$)
- **70” wheelbase** ($2L = 5.83\,\text{'}$)

Leading axle angle of attack:

$$\alpha \approx \sin^{-1}\left(\frac{2L}{R}\right)$$

$$\approx \frac{2L}{R} = 0.0061\,\text{rad} (0.1\,\text{mrad})$$
Spin Creepage
Think of spinning a coin on a tabletop...

OK, but when does this occur at the WRI?...
The net creepage vector at the wheel/rail interface is (in general) a combination of longitudinal, lateral and spin.

Spin Creepage

- Slower (Braking)
- Neutral (Free Rolling)
- Faster (Driving)
The Wheelset and Steering Forces

- Displacement ($y$)
- Conicity ($\gamma$)

Longitudinal traction/creepage

- $r_L (< r_0)$
- $r_R (> r_0)$

Longitudinal creep forces
Effective Conicity

Rolling Radius Difference
Effective Conicity (Worn Wheels)
Demonstration*: Steering forces in tangent track

* Wheel / rail demonstration rig, images and videos prepared by Josh Rychtarczyk
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.

Forward velocity

X

Y

Z

Displacement

Longitudinal friction forces
Questions & Discussion
Part 2

- Vehicle Steering and Curving Forces
- Wear and Rolling Contact Fatigue
Curving and Theoretical Equilibrium

Displacement ($y$)

$r_L (< r_0)$

$r_R (> r_0)$
Demonstration*: Steering forces in curved track

* Wheel / rail demonstration rig, images and videos prepared by Josh Rychtarczyk
Important Concept:

- Sometimes, forces give rise to creepage (e.g. traction, braking, steering)

- Other times, creepage gives rise to forces (e.g. curving)
Curving Forces (Two-Axle Vehicle, Sharp Curve)

**Trailing Axle, High Rail:**
- $R < R_{\text{equilibrium}}$
- Negative Longitudinal Creepage
- Longitudinal Creep Force

**Leading Axle, High Rail (Tread):**
- $R >> R_{\text{equilibrium}}$
- Positive Longitudinal Creepage
- Longitudinal Creep Force
*Plus:*
- Normal force (keeps vehicle on track)

**Trailing Axle, Low Rail:**
- $R > R_{\text{equilibrium}}$
- Positive Longitudinal Creepage
- Longitudinal Creep Force

**Leading Axle, High Rail (Flange):**
- $R >> R_{\text{equilibrium}}$
- Positive Longitudinal Creepage
- Longitudinal Creep Force

**Leading Axle, Low Rail:**
- Angle of Attack
- Primarily Lateral Creepage
- Lateral Creep Force

Reaction Forces (felt by track)
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
Quick Calculation: 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: L/V = _____ μ

At high creep L/V ~ μ
At low creep L/V ~ const * creep

~1(%) Creep

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, μ_{TOR}=0.5, μ_{GF}=0.15
Other Factors Affecting Curving Forces

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

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

- \( V_{\text{max}} \) = Maximum allowable operating speed (mph).
- \( E_s \) = Average elevation of the outside rail (inches).
- \( D \) = Degree of curvature (degrees).
Rail and Wheel Wear
Rail and Wheel Wear

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

- “Archard” Wear Law:
  - $V = \frac{cNl}{H}$
  - $c$ 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

\[ P_o = \frac{3}{2} P_{\text{avg}} \]
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></td>
<td>ksi</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 Material 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.
Question: 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:
  \[ \alpha \sim \arcsin\left(\frac{L}{R}\right) \sim \frac{L}{R} = 0.0030 \text{ Rad (3.0 mRad)} \]

- Lateral Creepage at low rail TOR contact:
  \[ \frac{V_{\text{lat}}}{V} \sim 2\frac{L}{R} \sim \alpha = 0.3\% \]
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) \sim 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
Part 3

• The Third Body Layer, Traction/Creepage and Friction Management

• Frequency Domain Phenomena: Noise and Corrugations
“Free Rolling”

\[ R\omega = V \]

- Third Body Layer is made up of iron oxides, sands, wet paste, leaves etc....

Wheel

Third Body Layer

Rail
“Small” Positive (Longitudinal) Creepage

Wheel

\[ R_\omega > V \]

Third Body Layer

Rail
“Large” Positive (Longitudinal) Creepage

Rω>V
The Traction-Creepage Curve

μN

Longitudinal Creepage

Rolling Direction

Microslip

Adhesion
Traction/Creepage Curves

“Heuristic” expressions used for the saturation and physical meaning of the different parts.
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)
Ideal Targets

**Low rail**

\[ \mu = 0.3 - 0.35 \]

**High Rail**

\[ \mu < 0.2 \]

\[ \mu = 0.3 - 0.35 \]
Friction Management Approaches

Applications

Trackside
- GF Lubrication
- TOR Friction Modifiers

Mobile
- Gauge/Flange
- TOR/Tread
- Liquid/Solid Lubrication
- Liquid/Solid Friction Modifiers
Trackside Top of Rail Friction Control
Solid stick application system

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

High speed train

Metro system
Mobile (Car Mounted) Top of Rail Friction Management
Mobile Gage Face Lubrication
(or Top of Rail Friction Control)
Hi-Rail Mounted Delivery Systems
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
Example: Friction Management impacts on Curving Forces

**TOR Friction Control:**
Reduction in COF at TOR/Tread → Reductions in TOR/Tread Creep Forces and *Negative* Steering Moments → Reductions in Lateral Forces, Wear, Energy, etc.

**GF Lubrication:**
Reduction in COF at GF/Flange → Reductions in wear and energy reduction in Longitudinal Creep Force and *Positive* Steering Moment → Small increase in AoA and Lateral Forces
Example: Friction Management, Wear and RCF wheel/rail rig test results

- **R260**
  - New
  - Dry
  - FM 100k
  - FM 400k

- **R350HT**
  - New
  - Dry
  - FM 100k
  - FM 400k

**Dry tests crack results**

- Crack depth [mm]:
  - R260: 2.00
  - R350HT: 1.00

- Crack distance [mm]:
  - R260: 2.04
  - R350HT: 1.77
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
The Traction-Creepage Curve:
Positive (Rising) and Negative (Falling) Friction
Absolute Friction Levels and Positive/Negative Friction

"Negative" or "Falling" friction

"Positive" or "Rising" friction

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

\[ \lambda = v/f \]
<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>Treatments 1</th>
<th>Should be successful</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Pinned-pinned resonance (‘roaring rails’)</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>
</tr>
<tr>
<td>2</td>
<td>Rutting</td>
<td>Second torsional resonance of driven axles</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>
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<tr>
<td>3</td>
<td>Other P2 resonance</td>
<td>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>
</tr>
<tr>
<td>4</td>
<td>Heavy haul</td>
<td>P2 resonance</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>
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<tr>
<td>5</td>
<td>Light rail</td>
<td>P2 resonance</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 EI</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
Question: 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