Fundamentals of Wheel-Rail Interaction

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Introduction and Objectives

• This session will provide an introduction to several fundamental aspects of vehicle-track interaction at the wheel/rail interface, including:

  – The Wheel / Rail Interface and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creepage, Friction and Traction Forces
  – Wheelset Geometry and Effective Conicity
  – Vehicle Steering and Curving Forces
  – Rail and Wheel Wear
  – Shakedown and Rolling Contact Fatigue (RCF)
  – Corrugations

• The objective is to develop a framework to understand, articulate, quantify and identify key phenomena that affect the practical operation, economics and safety of heavy haul rail systems.
Two 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?
Overview: Part I

- The Wheel / Rail Interface and Key Terminology
- The Contact Patch and Contact Pressures
- Creepage, Friction and Traction Forces
- Wheelset Geometry and Effective Conicity
- Vehicle Steering and Curving Forces
The Wheel / Rail Interface and Key Terminology

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

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

- Under the rail surface, this yields a tri-axial stress state, less so as contact patch nears the edge of rail and wheel.
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*?...

- 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.
Creep Forces

Concept of creep

- "Marries" rigid body mechanics & theory of elasticity
- Traction under conditions of rolling produces differential strain between wheel & rail in contact
- Slip occurs across portion of the contact patch

Wheel

- Direction of rolling and applied torque

Rail

Comment:
- There is no such thing as "static" vs. "rolling" friction!
"Free Rolling"

$$R\omega = V$$

Wheel

Third Body Layer

Rail
"Large" Positive (Longitudinal) Creepage

Wheel

\[ R\omega > V \]

Third Body Layer

Rail
The Traction-Creepage Curve
Lateral creepage
Imagine pushing a lawnmower across a steep slope…

OK, but when does this occur at the WRI?...
Other Forces on the Wheelset

Flange force

- Synonymous with the lateral creep force & with a root cause associated with the angle of attack of the wheelset

Lateral Creep

Flange & Rail Wear

Flange Force

Lateral Creep

High Contact Stresses

Comment:

- Flange contact under an angle of attack might be ranked as the most damaging contact mode under heavy haul conditions

Longitudinal Traction Force

Lateral Creep Force

Angle of Attack

Direction of Travel
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!

\[ f = \mu N \]

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

- \( \mu \): coefficient of (sliding) friction
- \( N \): normal load
- \( V \): forward velocity
- \( R \): radius
- \( \omega \): rotational speed
- \( \text{creep: } \frac{R \omega - V}{V} \)

Friction force shown as acting on block for positive sliding velocity.

Friction force shown as acting on wheel for positive creep.
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.
- No third body layer = asperity welding, gouging and high wear rates.
Displaced wheel set

\[ \lambda = \text{effective conicity} \]
\[ r_0 = \text{wheel radius of undisplaced wheelset} \]
\[ R = \text{curve radius} \]
\[ L_0 = \text{half gauge} \]

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

\[ y = \frac{r_0 L_0}{R \lambda} \]
Curving Forces (201)

• Remember this?

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

Hopefully not very often!
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)
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.
Curving Forces (101)

- Flange Force
- Curving Forces
- Friction Forces (Lateral Creepage from AoA)
- Anti-Steering Moment (Longitudinal Creepage from mismatched rolling radii)
- Track Spreading Forces
- Direction of Travel
- AoA
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

- Leading Axle angle of attack:
  \[ \alpha \sim \arcsin\left(\frac{2L}{R}\right) \sim \frac{2L}{R} = 0.0061 \text{ Rad (6.1 mRad)} \]
- Lateral Creepage at TOR contact:
  \[ \frac{V_{\text{lat}}}{V} \sim \frac{2L}{R} \sim \alpha = 0.61\% \]

Example:
- 6° curve (R = 955’)
- 70” wheelbase (2L = 5.83’)
- \( \mu_{\text{TOR}} = 0.5 \) (dry)
Estimating Low Rail L/V and Lateral Force

- At 0.61% creep: 
  \[ L/V = \mu \]

At low creep: \( L/V \sim \text{const} \times \text{creep} \)

At high creep: \( L/V \sim \mu \)

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, $\mu_{TOR}=0.5$, $\mu_{GF}=0.15$
Overview: Part II

• Curving Forces (Continued)
• Damage Mechanisms
  – Wheel and Rail Wear
  – Shakedown and Rolling Contact Fatigue (RCF)
• Curving Noise
• Corrugations
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

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

- \( V_{\text{max}} \) = Maximum allowable operating speed (mph).
- \( E_a \) = 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:
  \[ V = c \frac{Nl}{H} \]
  - \( V \) = volume of wear
  - \( N \) = normal load
  - \( l \) = sliding distance (i.e. creepage)
  - \( H \) = hardness
  - \( c \) = wear coefficient

\( c \) proportional to COF
Wear regimes

\( T = \text{Tractive force} \)

\( \gamma = \text{Slip} \)
Shakedown and Rolling Contact Fatigue (RCF)
Manifestations of Rail RCF

- Wear
- Scuffing (& head checks)
- Spalls (Wheel terminology: Shells)
- Engine Burns
- Corrugations
- Squats ... etc.
Manifestations of Wheel RCF

- **Wear**

- **Tread Scuffing**
  Result:
  - Surface damage
  - High impact wheels (HIW)

- **Tread Shelling**
  Result:
  - Subsurface fatigue
  - HIW
  - Possible vertical split rims (VSR)

- **Spalling & Continuous Spalling**
  (Related to skidded wheels)
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

CONTACT DATA PLOT

Low Rail Contact Area, mm²

- Lightly Worn Wheel, Loaded Gauge: +0.75", LCant = RCant = 1 deg
- Heavily Worn Wheel, Loaded Gauge: +0.75", LCant = RCant = 1 deg
Example calculation: Average and Peak Pressure

- Let’s assume a circular contact patch, with a radius of \(0.28\)” \((7 \text{ mm})\)
- The contact area is then: \(0.24 \text{ in}^2 (154 \text{ mm}^2)\)
- Assuming a HAL vehicle weight (gross) of 286,000 lbs, we have a nominal wheel load of 35,750 lbs, i.e. \(35.75 \text{ kips} (159 \text{ kN})\)
- The resulting average contact pressure \((P_{avg})\) is then: \(150 \text{ ksi} (1,033 \text{ MPa})\)
- This gives us a peak contact pressure \((P_o)\) of: \(225 \text{ ksi} (1,550 \text{ MPa})\)

- 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>
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<tbody>
<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>
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</tbody>
</table>

Corrugations

- Heavy Haul corrugation
  - High dynamic forces
    - degrades ballast
    - noise
  - Heavy unit trains
  - Consistent speed
  - Discrete irregularities
    - welds, joints, crossings
  - P2 resonance
  - Plastic flow

- RCF Corrugation
  - Same as above but damage mechanism is fatigue
Corrugation formation: common threads

\[ \lambda = \frac{v}{f} \]
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
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

New dry FM 100k FM 400k

Dry tests crack results

<table>
<thead>
<tr>
<th>distance [mm]</th>
<th>R260</th>
<th>R350HT</th>
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<tr>
<td>2,00</td>
<td></td>
<td></td>
</tr>
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<td>1,00</td>
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<td>2,04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,77</td>
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</table>

R260
R350HT
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: 
  \( T/N \sim 0.6 \mu \)

- 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 $P_o = 225$ ksi
- With $K = 70$ ksi, $P_o/K = 3.21$
Control of Variables – Surface Stresses for a given track alignment and axle load

• Reduce lateral and longitudinal creep forces across the contact patch by:
  – Utilizing steering bogies
  – Ensuring accurate tracking accuracy (axle alignment, bogie/body interface, wheelset geometry and wheel profiles)
  – Reducing dynamic action (stable vehicles, track discontinuities, including rail joints)
  – TOR friction control (RCF & flange wear)
  – Gauge face and flange lubrication
Control of Variables – Surface Stresses for a given track alignment and axle load

• Profile Control
  – “Spread” the contact
  – Maximise contact area
  – Minimal 2-point contact

• Operations
  – Do not “cook” the wheels
  – Release handbrakes

• Optimized maintenance (wheel & rail re-profiling) to remove fatigued material

• In service monitoring (on-board & wayside monitoring)
Control of Variables – Sub-Surface Stresses for a given track alignment and axle load

• Maximize contact area
• Choose “good” materials
  – Cleanliness is close to Godliness
  – Controlled wheel temperatures
  – Increased YS, UTS, & fracture toughness
• Optimized maintenance (wheel & rail re-profiling) to remove fatigued material
• In service monitoring (on-board & wayside monitoring)
Summary

• Returning to our objectives, we have reviewed:

  – The Wheel / Rail Interface and Key Terminology
  – The Contact Patch and Contact Pressures
  – Creepage, Friction and Traction Forces
  – Wheelset Geometry and Effective Conicity
  – Vehicle Steering and Curving Forces
  – Rail and Wheel Wear
  – Shakedown and Rolling Contact Fatigue (RCF)
  – Corrugations

• 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 rail systems.
Questions & Discussion