

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



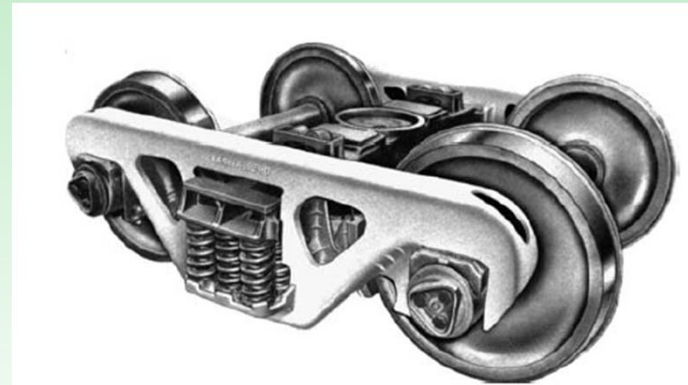
Part 1

- The Wheel / Rail Interface Anatomy and Key Terminology
- The Contact Patch and Contact Pressures
- Creepage and Traction Forces



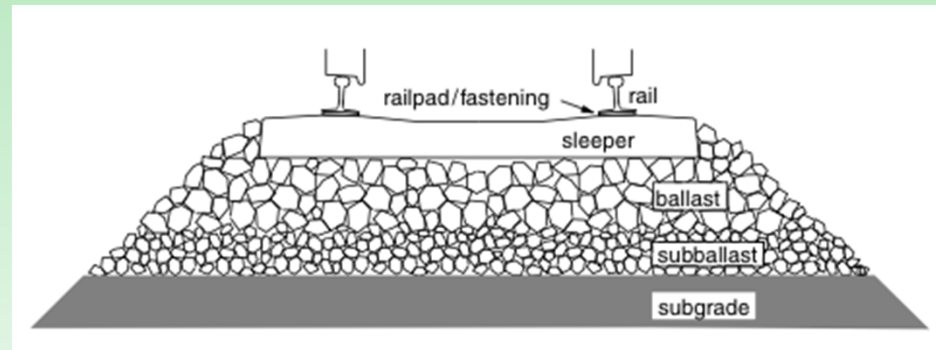
(Very) Basic Vehicle Running Gear Anatomy

- Wheels
- Wheelsets
- Axleboxes
- Suspension
- Frame



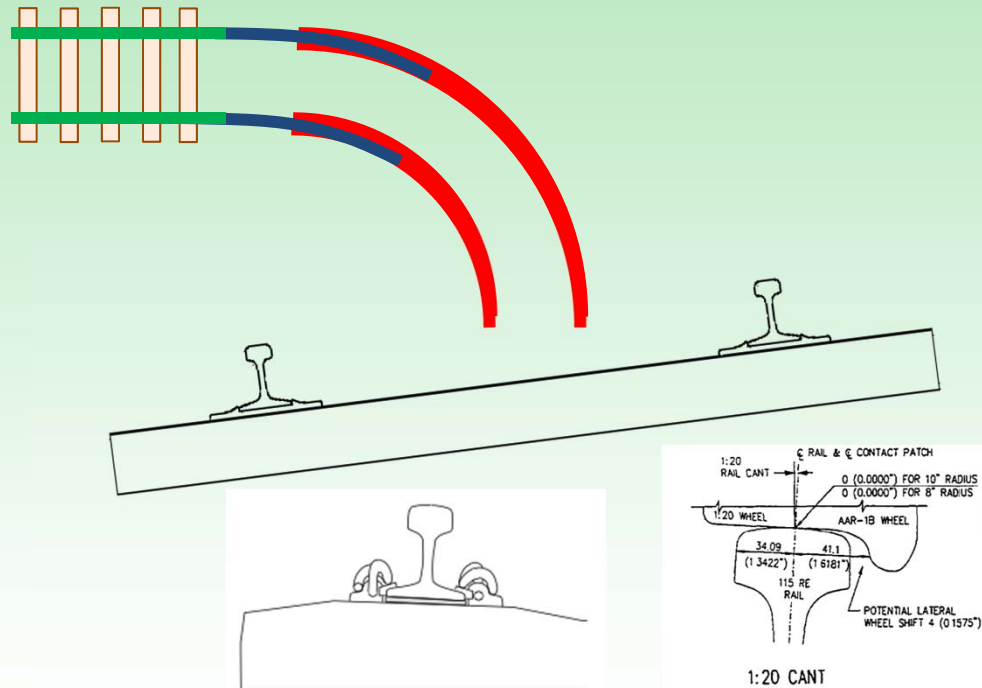
(Very) Basic Track Anatomy

- Rail
- Crossties (Sleepers)
- Tie Plates
- Fasteners / Spikes & Anchors
- Ballast
- Subballast
- Subgrade

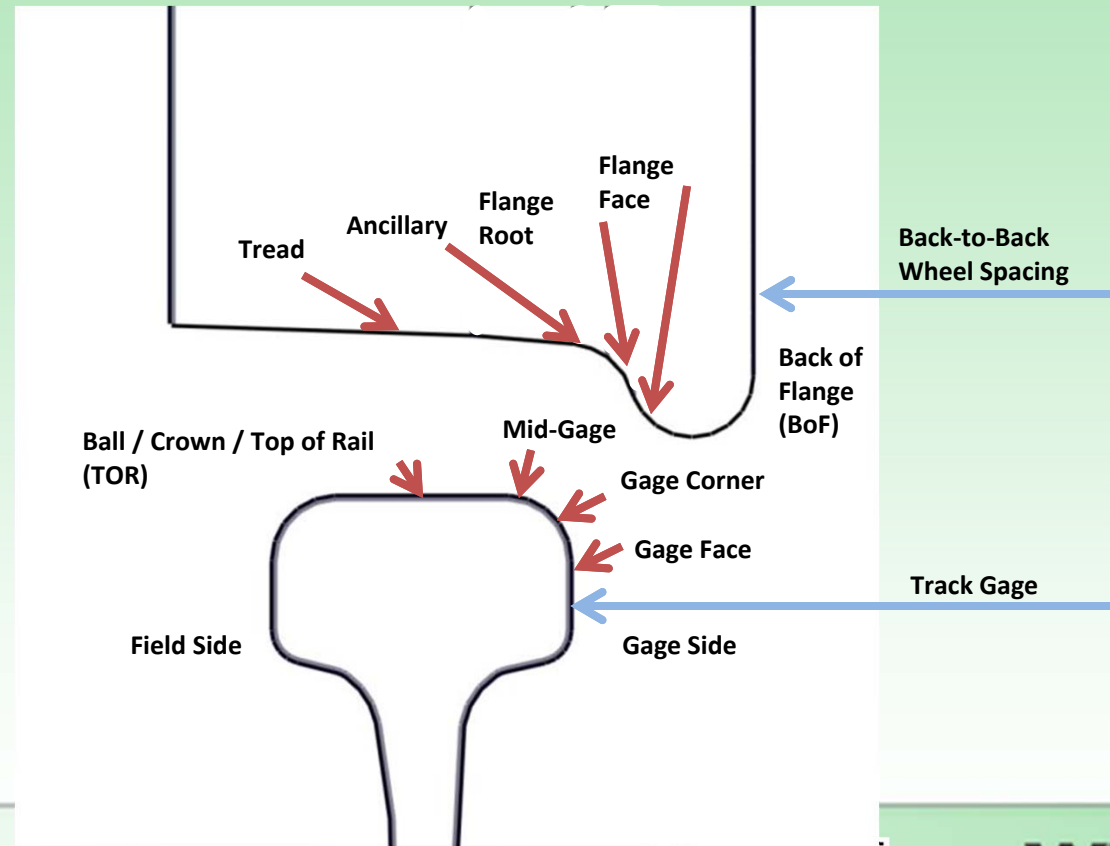


Recalling a few track geometry basics...

- Tangent
- Curve
- Spiral
- High Rail
- Low Rail
- Superelevation (aka Cant)
- Rail Cant



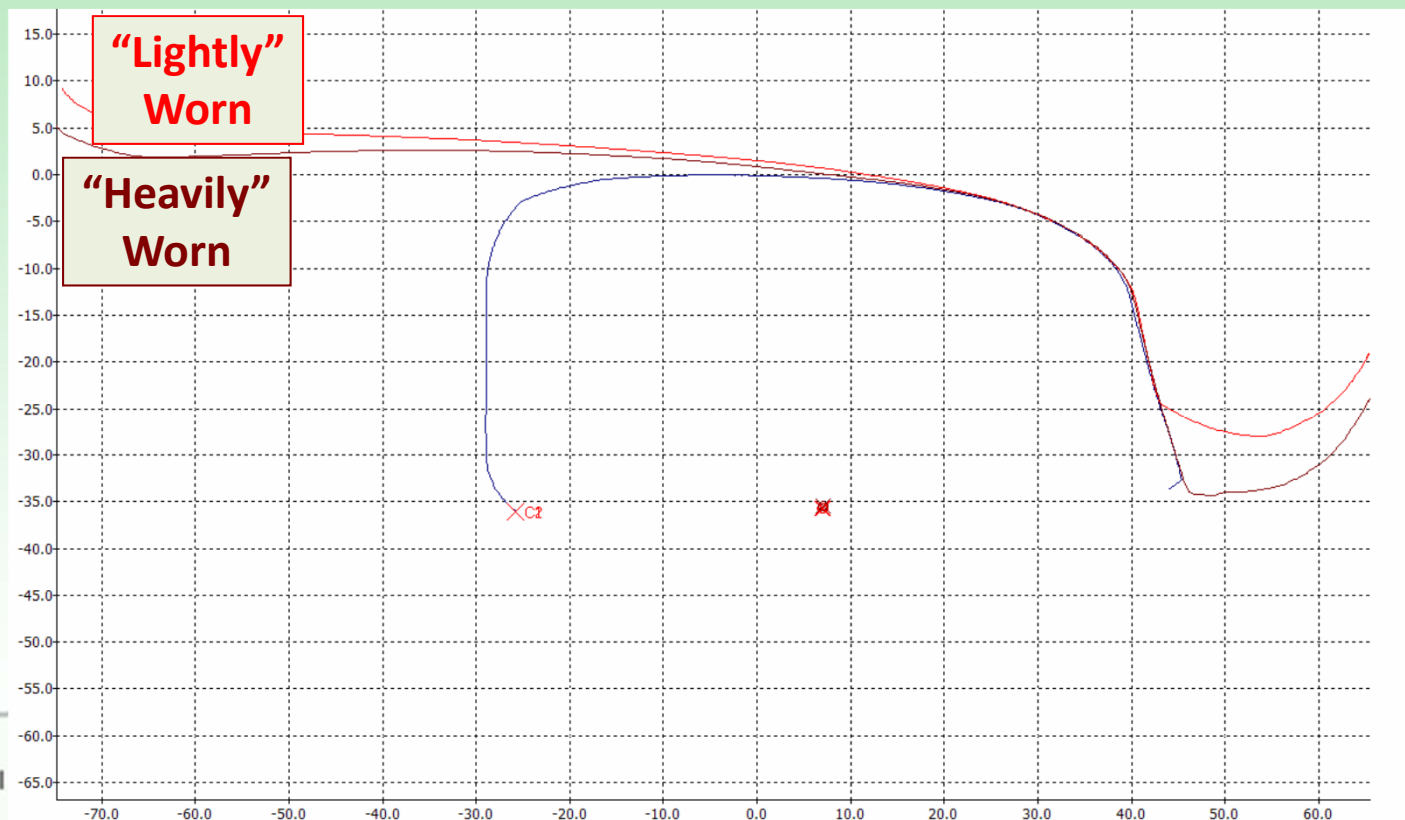
The Wheel / Rail Interface and Key Terminology



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

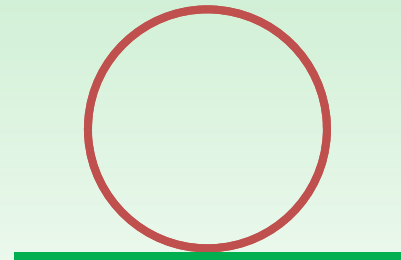


The Wheel / Rail Interface and Key Terminology (e.g. High Rail Contact)



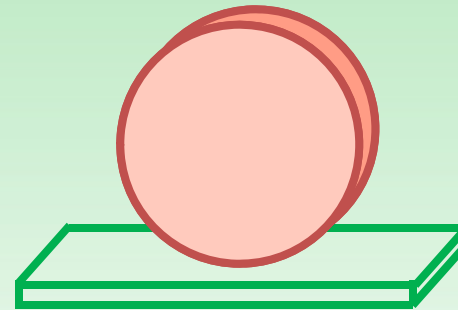
The Contact Patch and Contact Pressures

- 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?

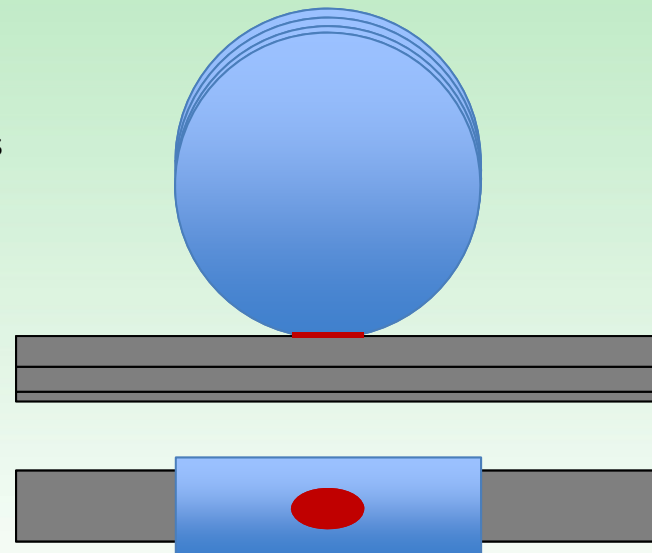
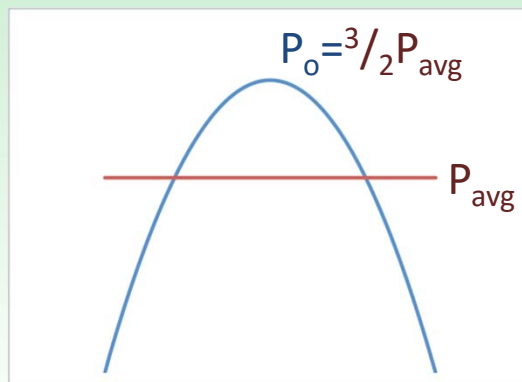


- Question #2: Given Force and Area, how do we calculate pressure?
- Question #3: If a cylindrical body (~wheel) is brought into contact with a planar body (~rail) with a vertical force F and zero contact area, what is the resulting calculated pressure?



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



- 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*?...



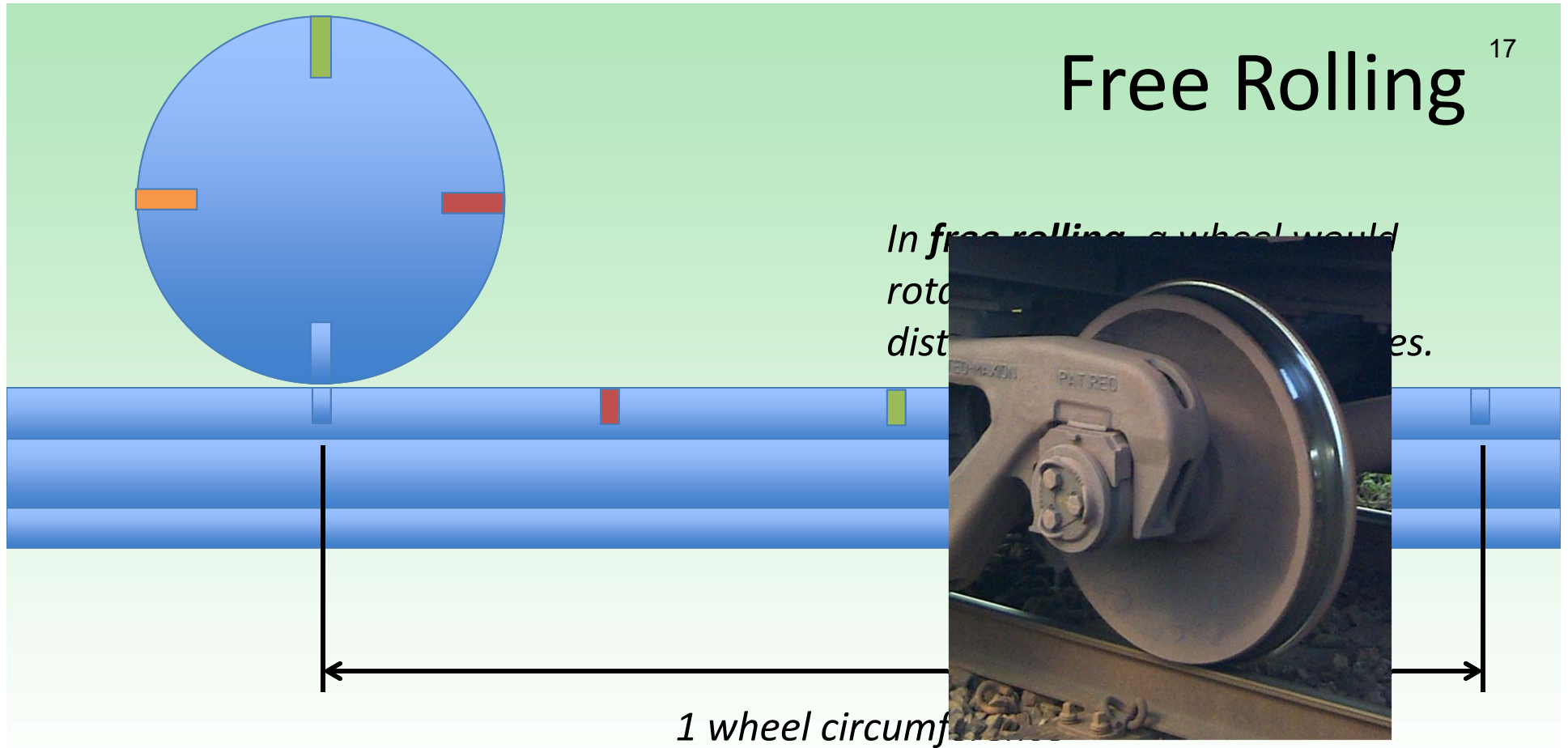
What does Longitudinal Creepage *mean*?...

- 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: $\frac{R\omega - V}{V}$

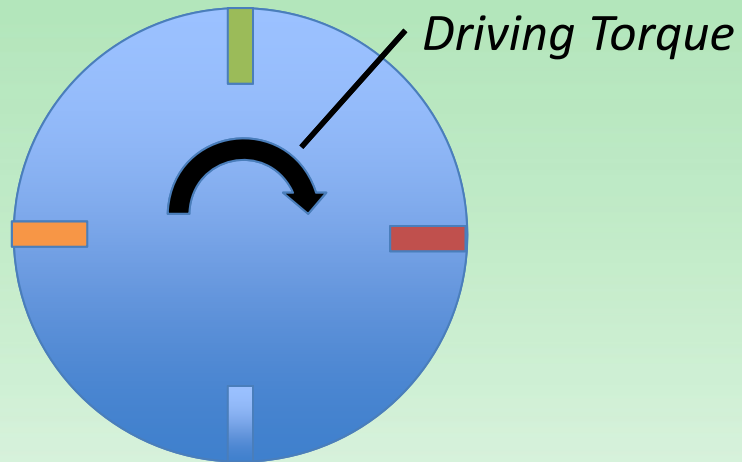


Free Rolling¹⁷

In free rolling, a wheel would rotate such that the distance traveled equals the arc length of the rotation.



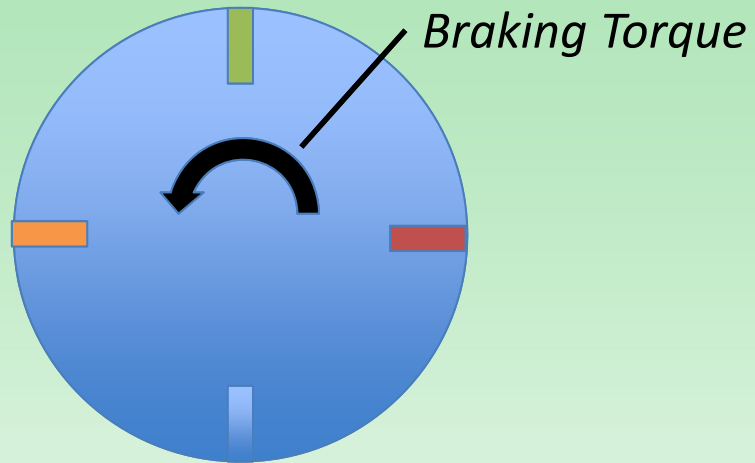
Positive (Longitudinal) Creepage¹⁸



*At 1% **positive** creepage, a wheel would rotate **101** times to travel a distance of **100** circumferences.*

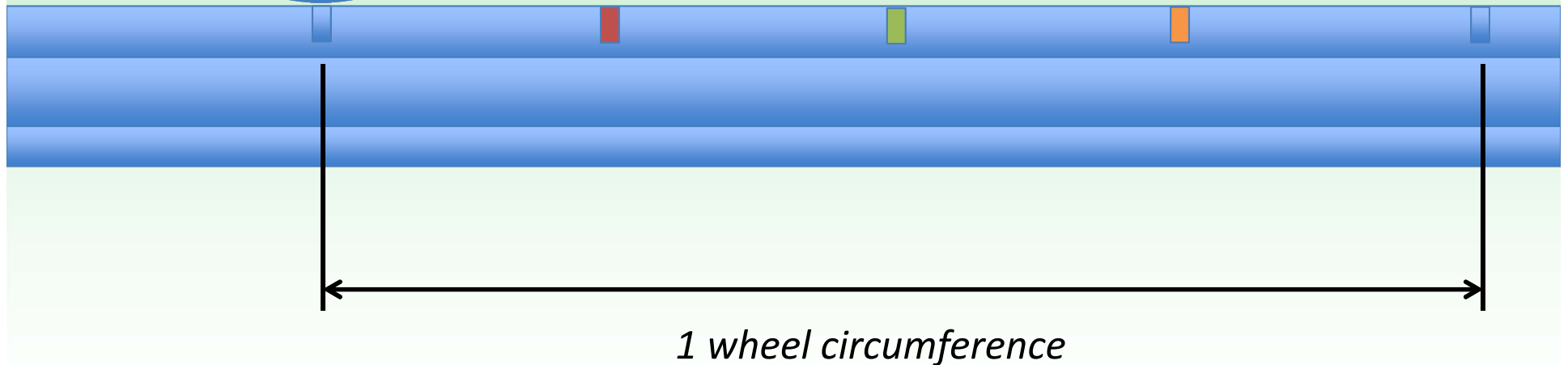
1 wheel circumference





Negative (Longitudinal) Creepage¹⁹

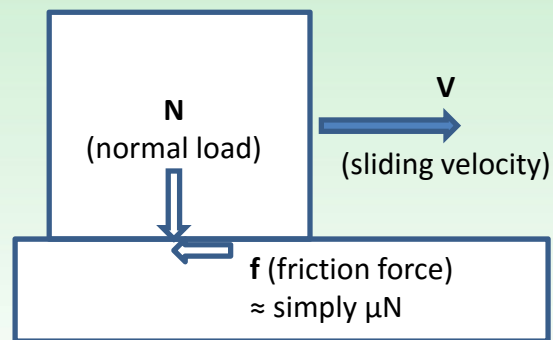
At 1% **negative** creepage, a wheel would rotate **99** times to travel a distance of **100** circumferences.



Rolling vs. Sliding Friction

They are not the same!

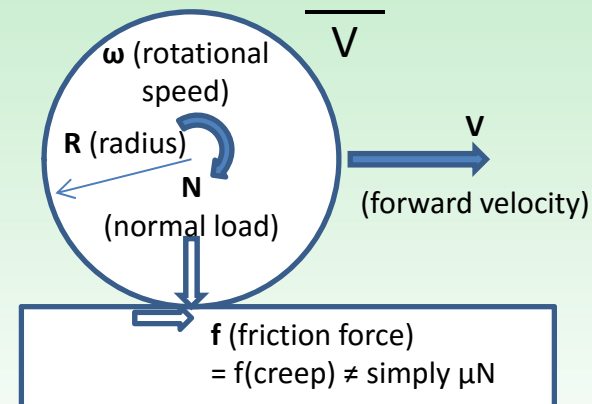
μ : coefficient of (sliding) friction



*friction force shown as
acting on block for
positive sliding velocity*

creep:

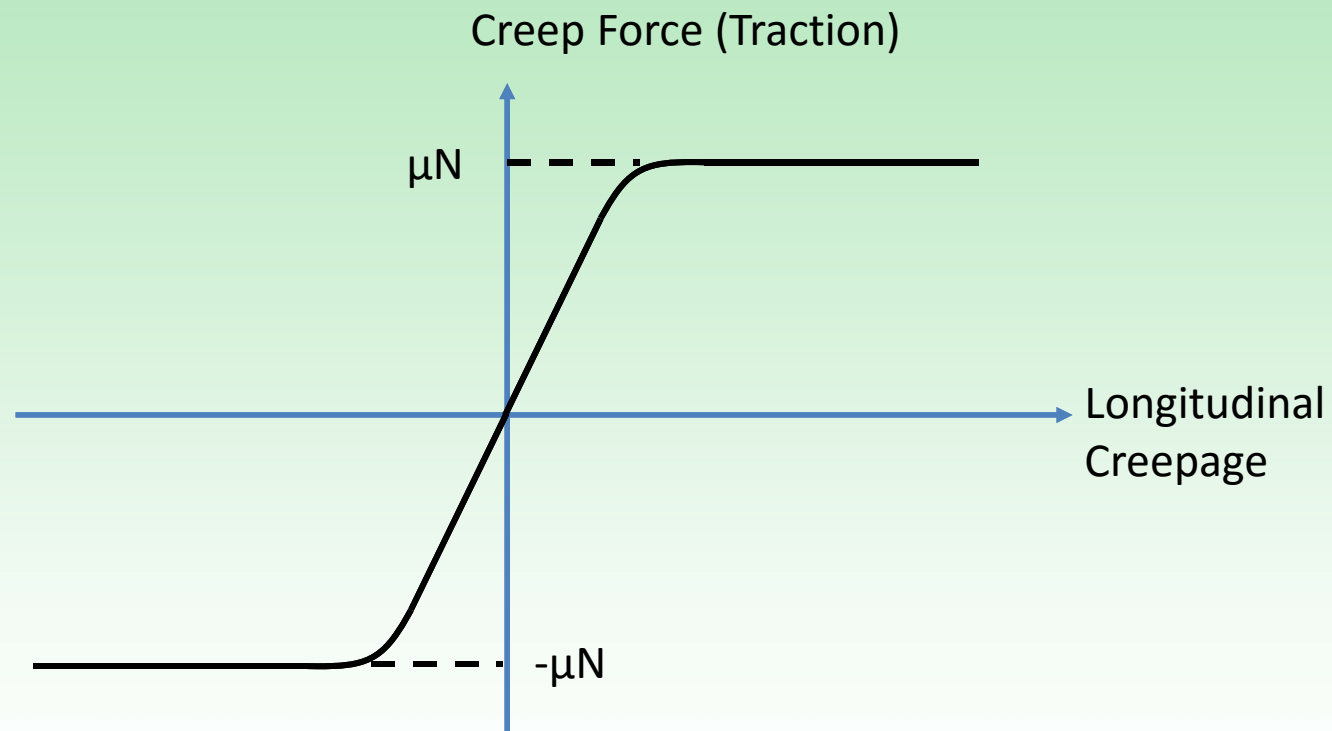
$$\frac{R\omega - V}{V}$$



*friction force shown as
acting on wheel for
positive creep*

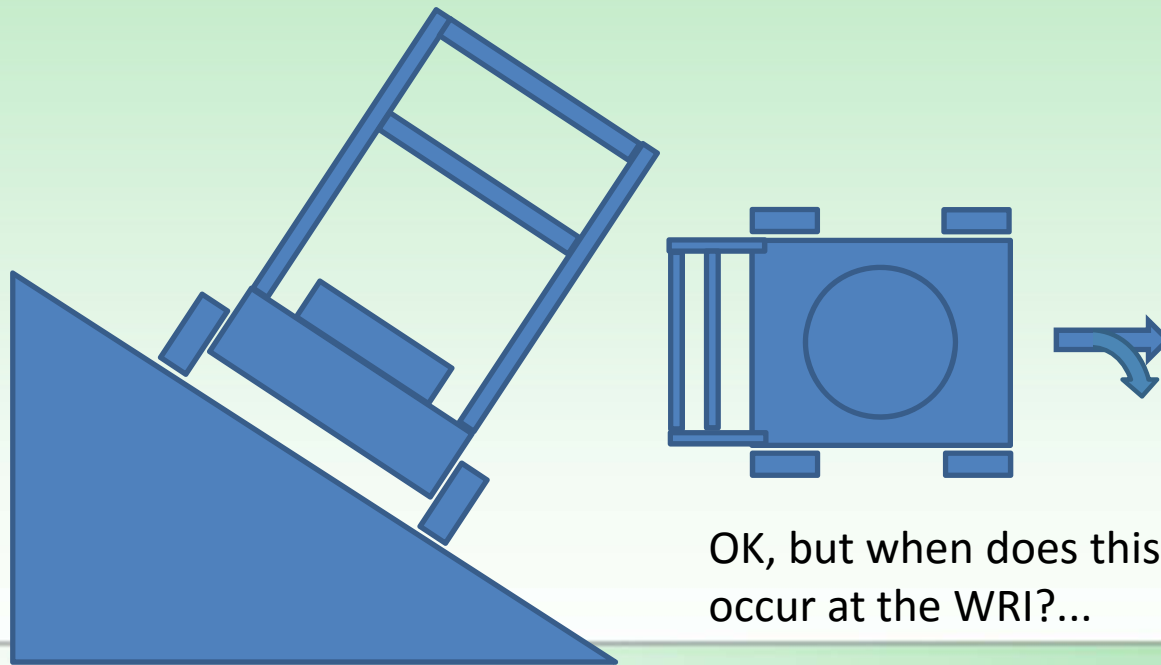


The Traction-Creepage Curve



Lateral creepage

Imagine pushing a lawnmower across a steep slope...

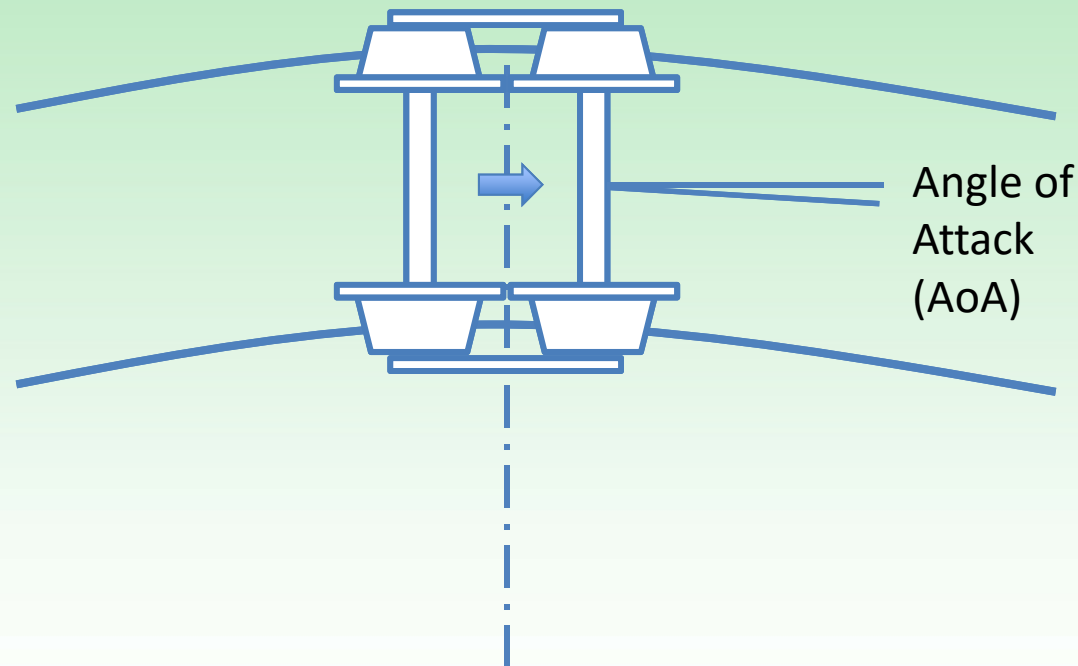


OK, but when does this occur at the WRI?...



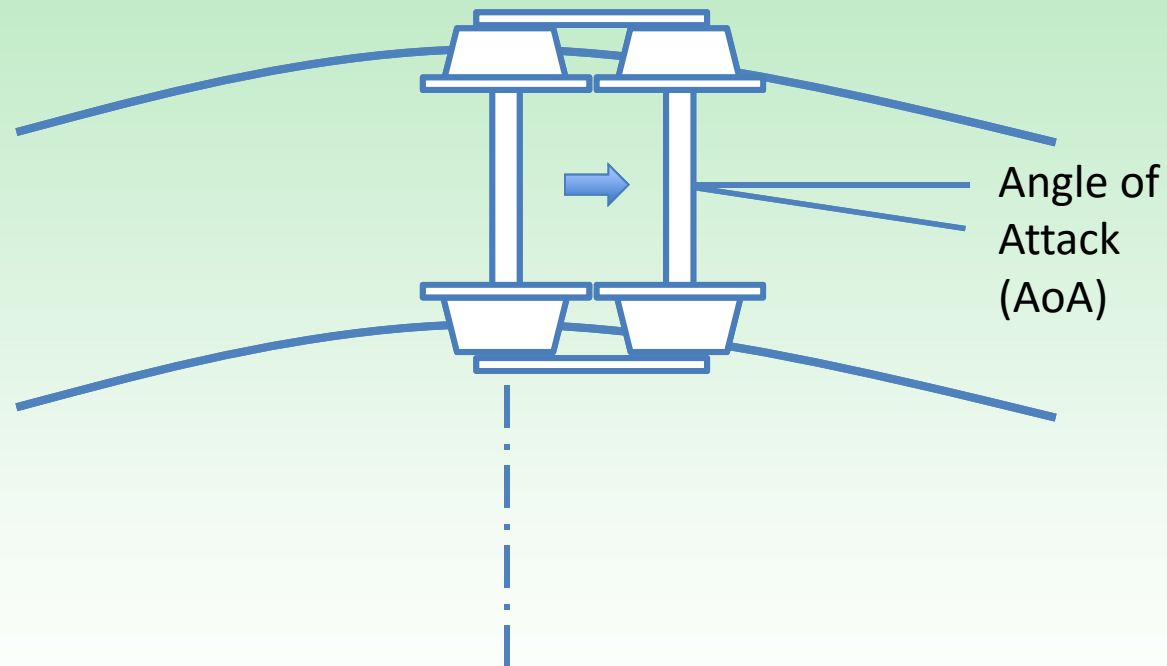
Steering in “Steady State” Curving (“Mild” Curves)

23



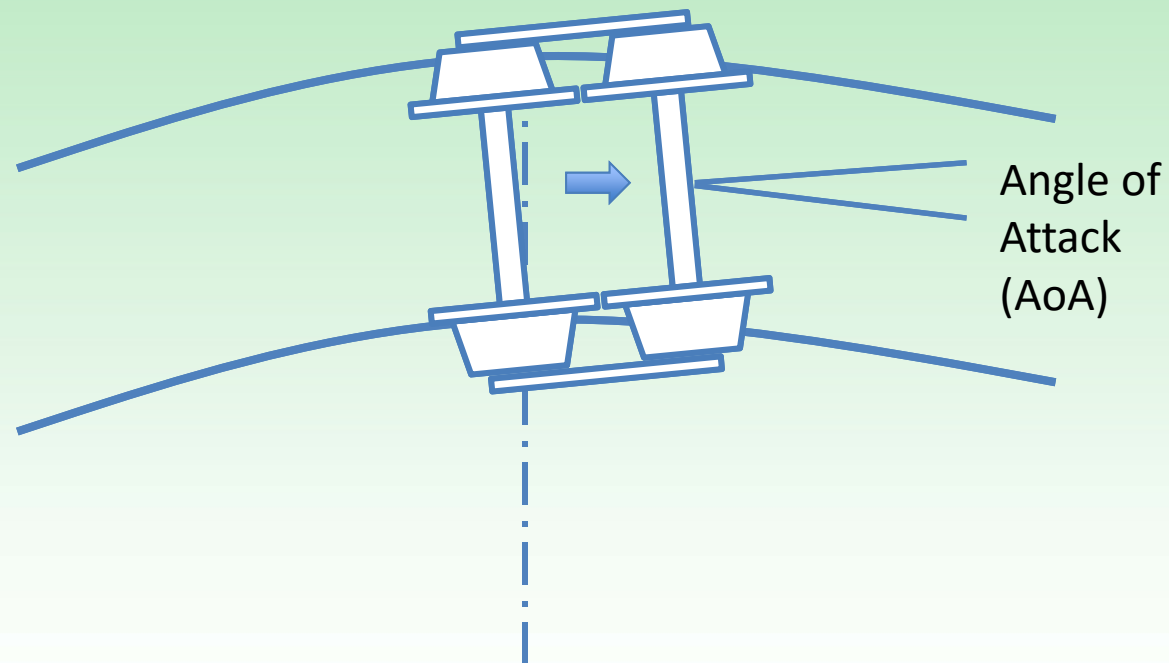
Steering in “Steady State” Curving (“Sharp” Curves)

24

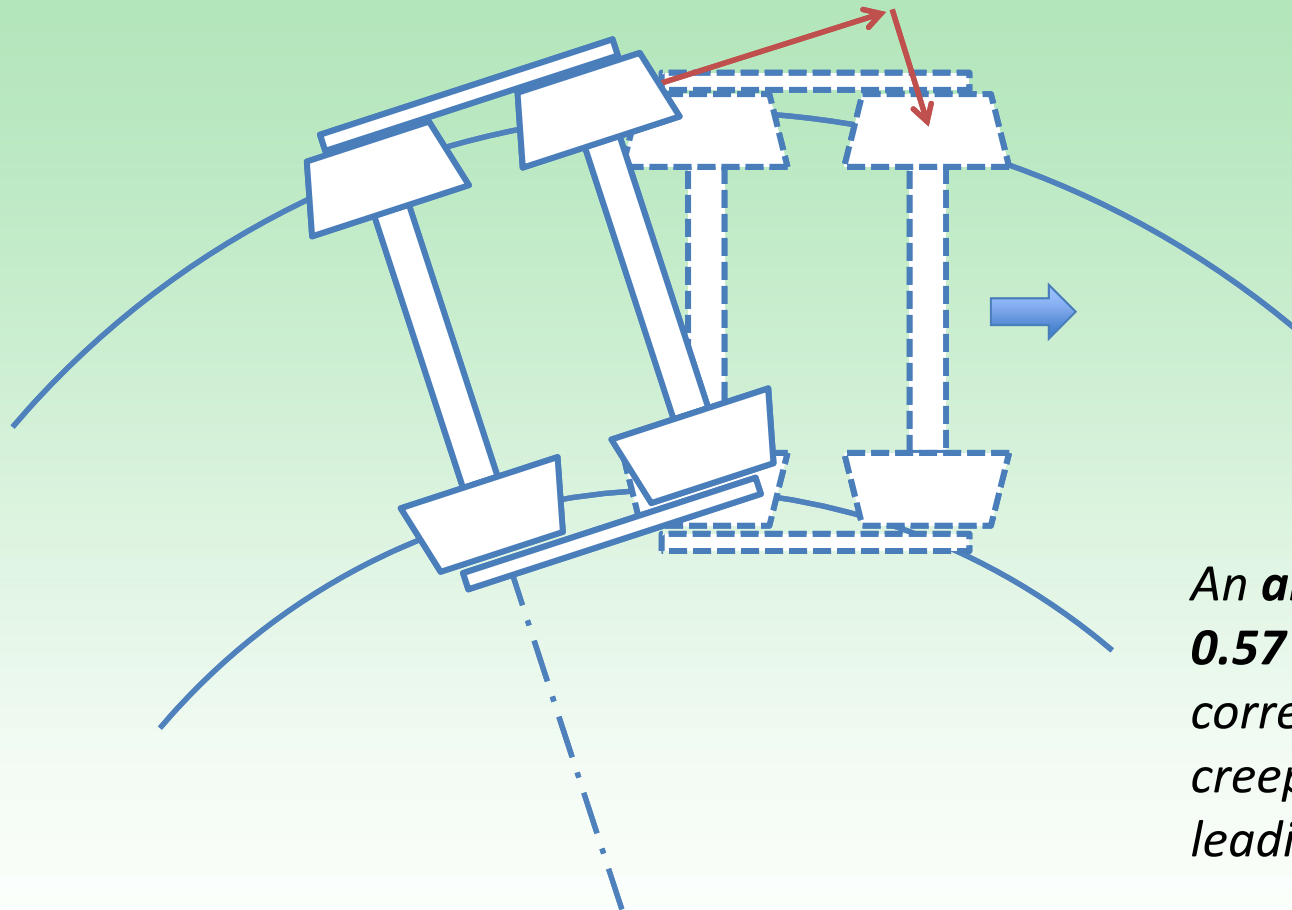


Steering in “Steady State” Curving (“Very Sharp” Curves)

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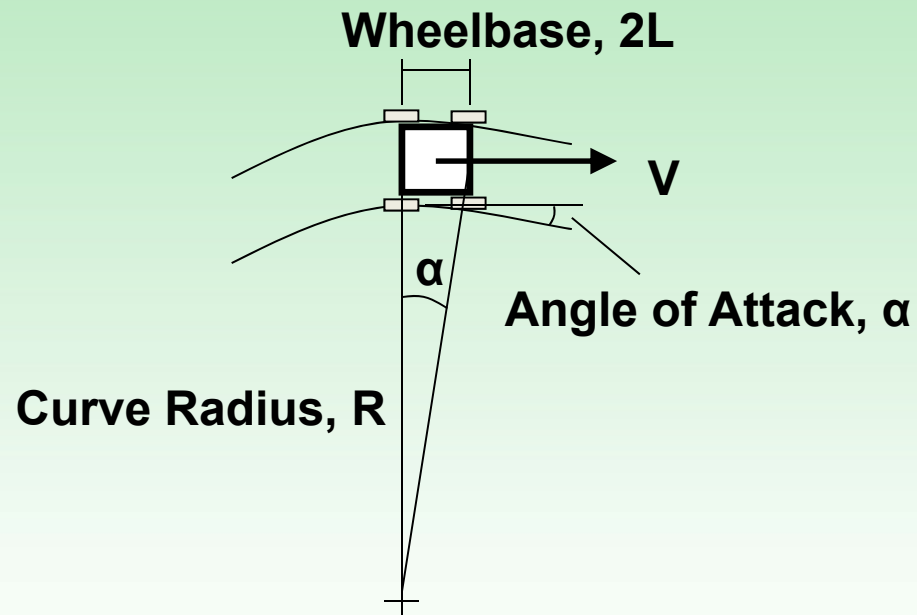
Lateral Creepage²⁶



*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...



EXAMPLE:

6° CURVE ($R = 955'$)

70" WHEELBASE ($2L = 5.83'$)

LEADING AXLE ANGLE OF ATTACK:

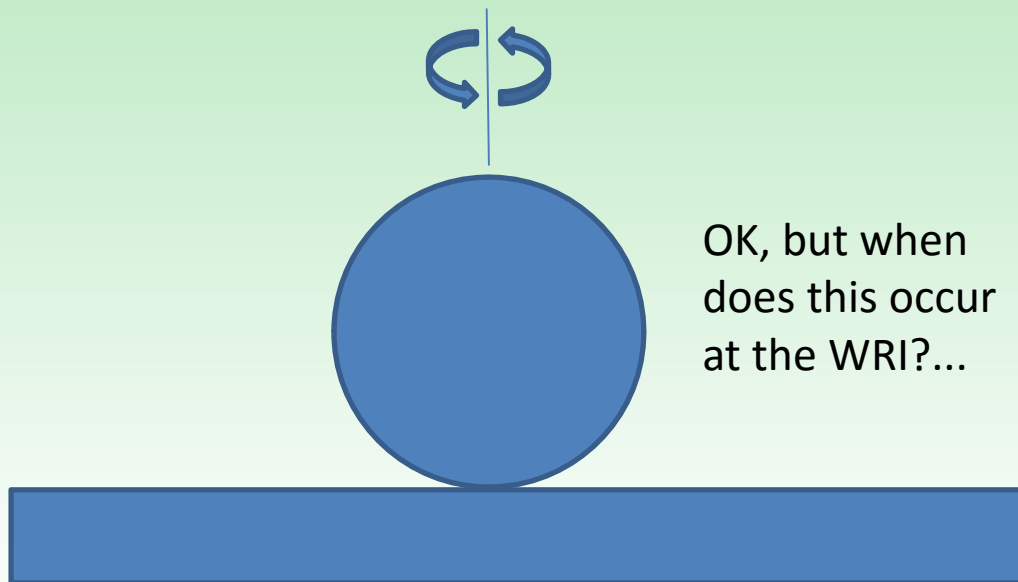
$$\alpha \approx \sin^{-1}\left(\frac{2L}{R}\right)$$

$$\approx \frac{2L}{R} = 0.0061 \text{ RAD (6.1 mRAD)}$$



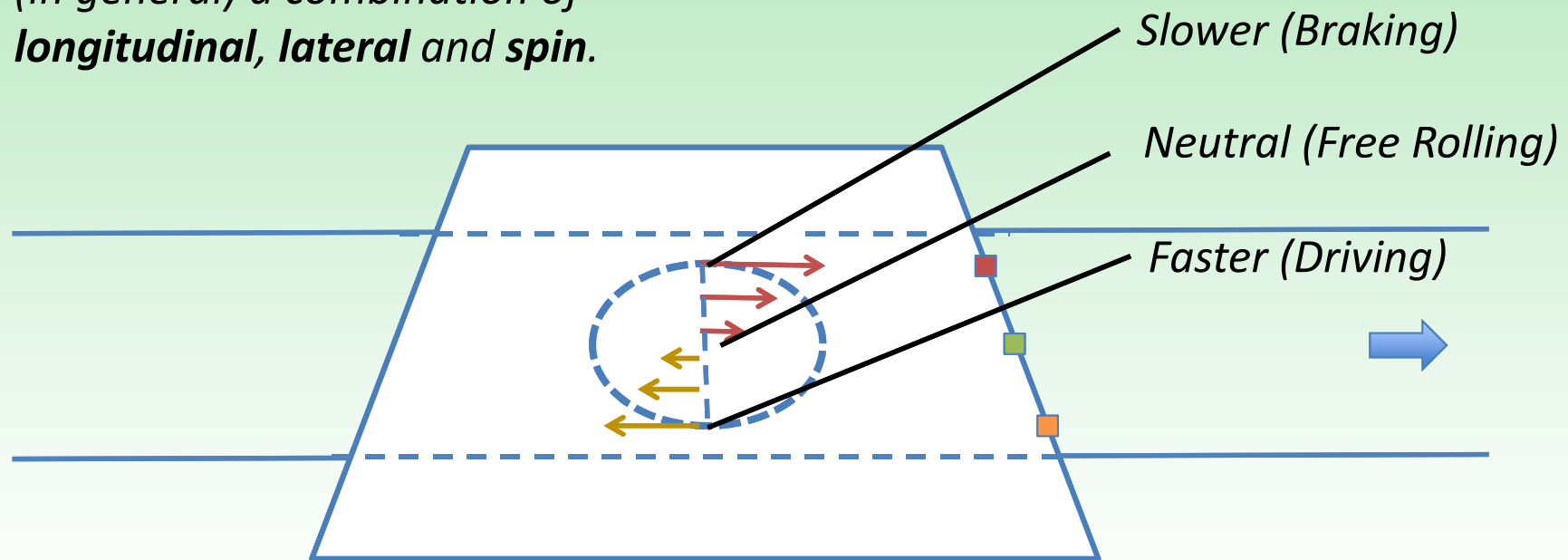
Spin Creepage

Think of spinning a coin on a tabletop....



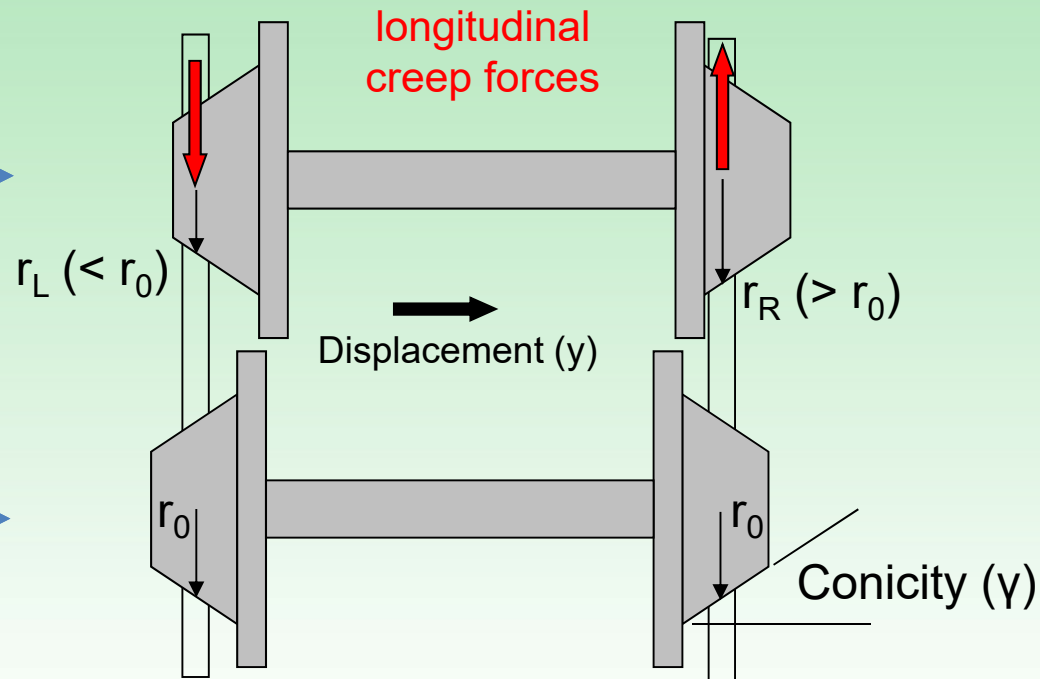
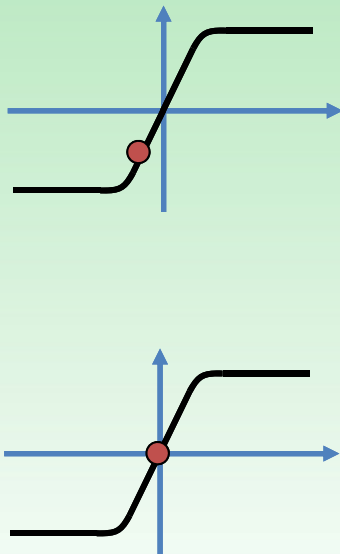
The **net creepage** vector at the wheel/rail interface is
(in general) a combination of
longitudinal, lateral and spin.

Spin Creepage

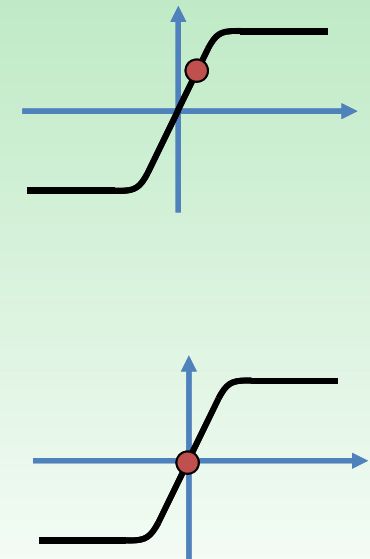


The Wheelset and Steering Forces

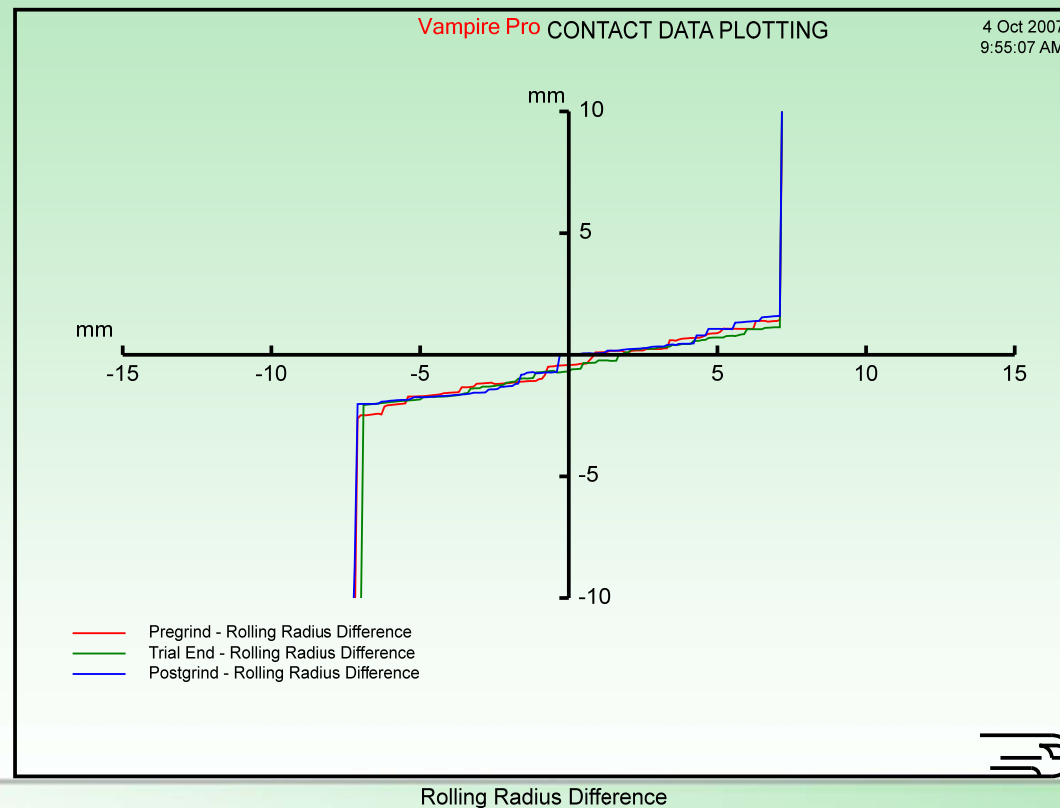
longitudinal
traction/creepage



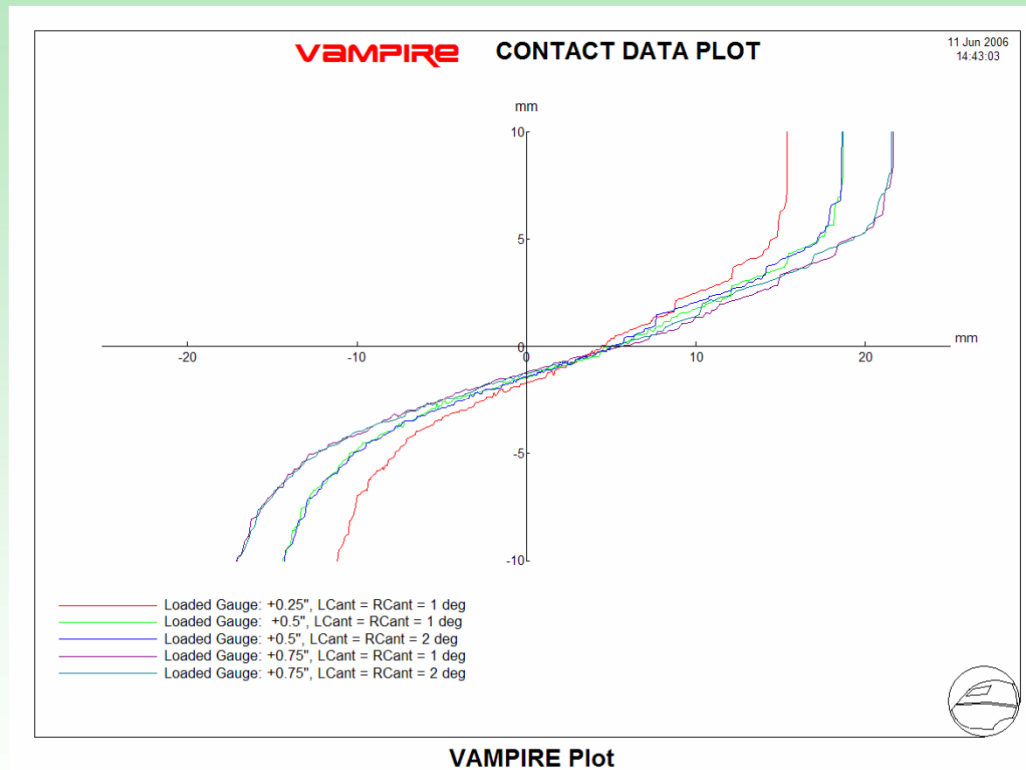
longitudinal
traction/creepage



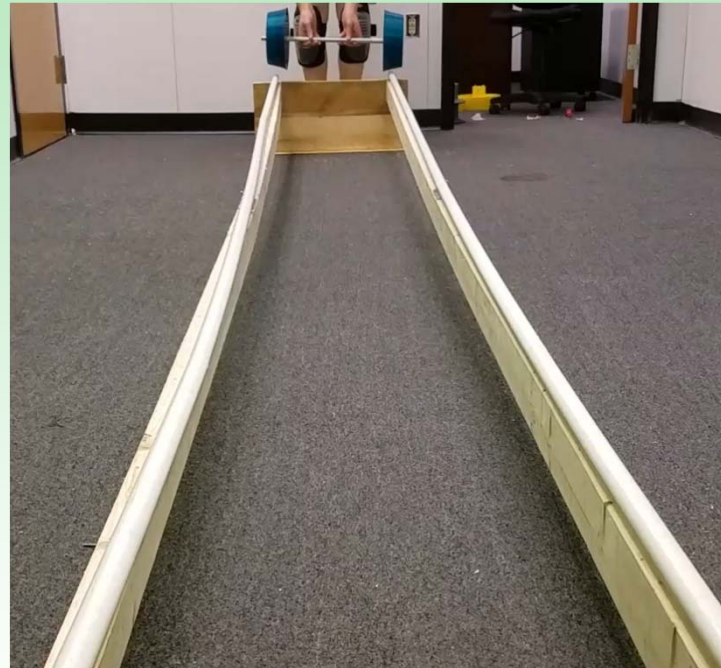
Effective Conicity



Effective Conicity (Worn Wheels)



Demonstration*: Steering forces in tangent track

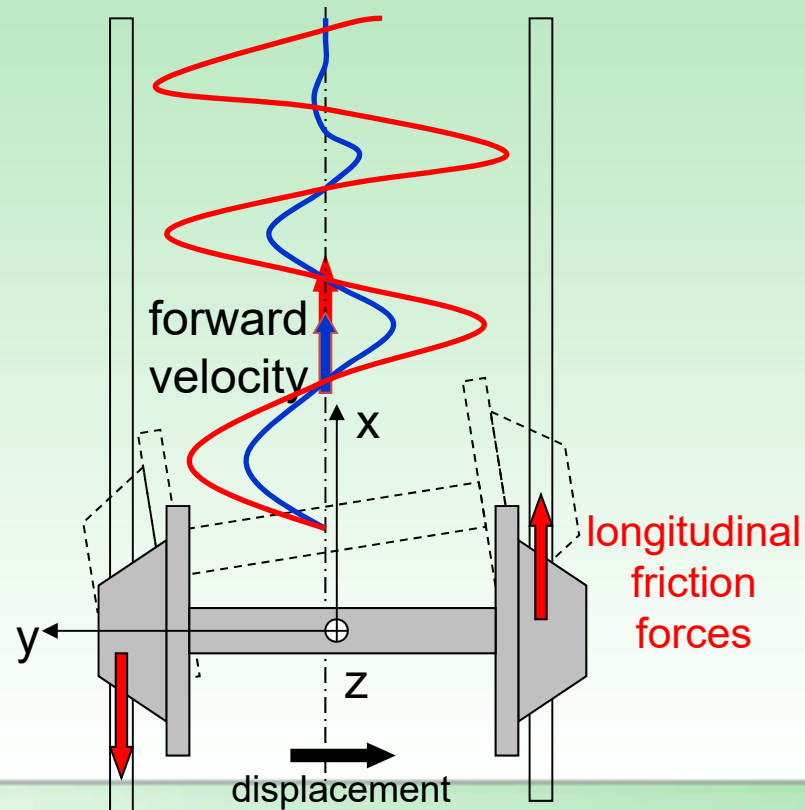


* Wheel / rail demonstration rig, images and videos prepared by **Josh Rychtarczyk**



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.



Questions & Discussion

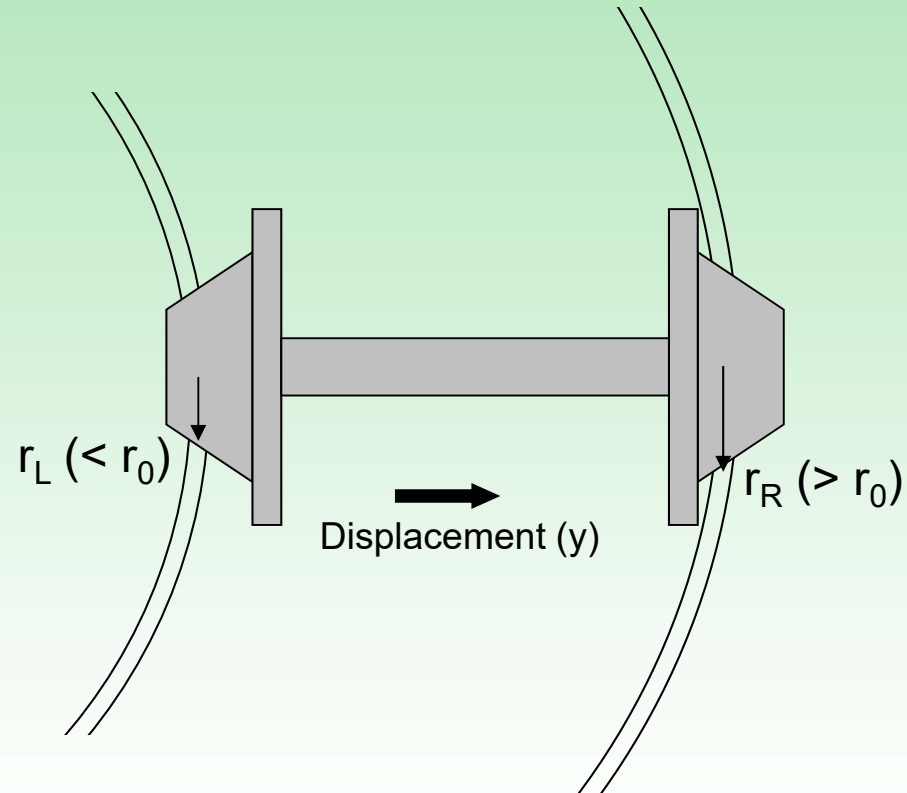


Part 2

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

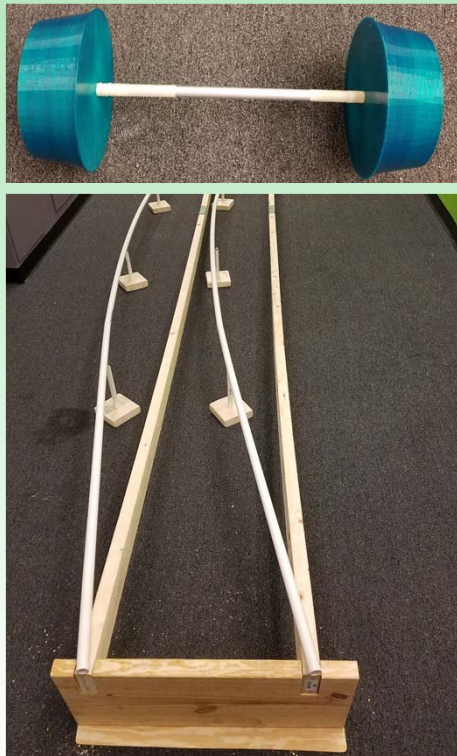


Curving and Theoretical Equilibrium



Demonstration*: Steering forces in curved track

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



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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

Reaction Forces (felt by track)

Trailing Axle, Low Rail:

- $R > R_{\text{equilibrium}}$
- Positive Longitudinal Creepage
- Longitudinal Creep Force

Leading Axle, High Rail (Tread):

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

Plus:

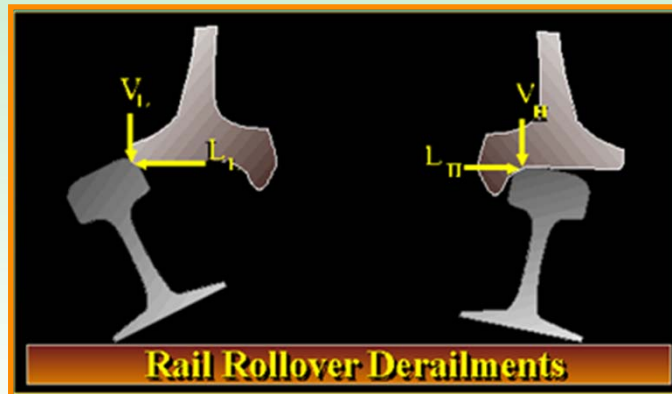
Normal force (keeps vehicle on track)
(AoA)

Leading Axle, Low Rail:

- Angle of Attack
- Primarily Lateral Creepage
- Lateral Creep Force



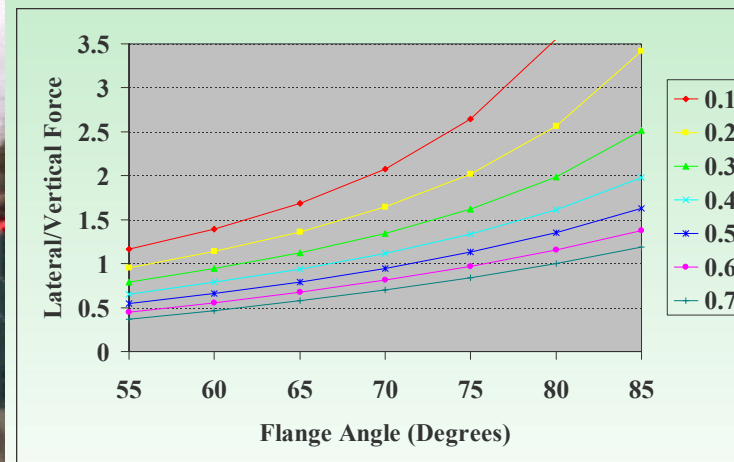
Impacts of High Lateral Loads: Rail Rollover / Track Spread Derailments



Impacts of High Lateral Loads: Plate Cutting, Gauge Widening



Impacts of High Lateral Loads: Wheel Climb Derailments



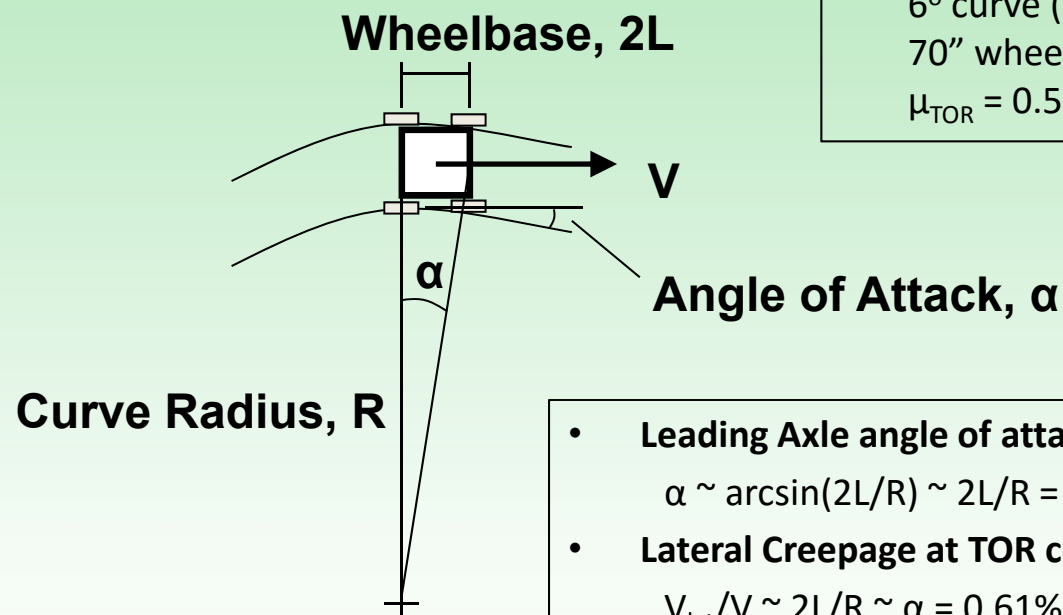
Impacts of High Lateral Loads: Fastener Fatigue / Clip Breakage



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



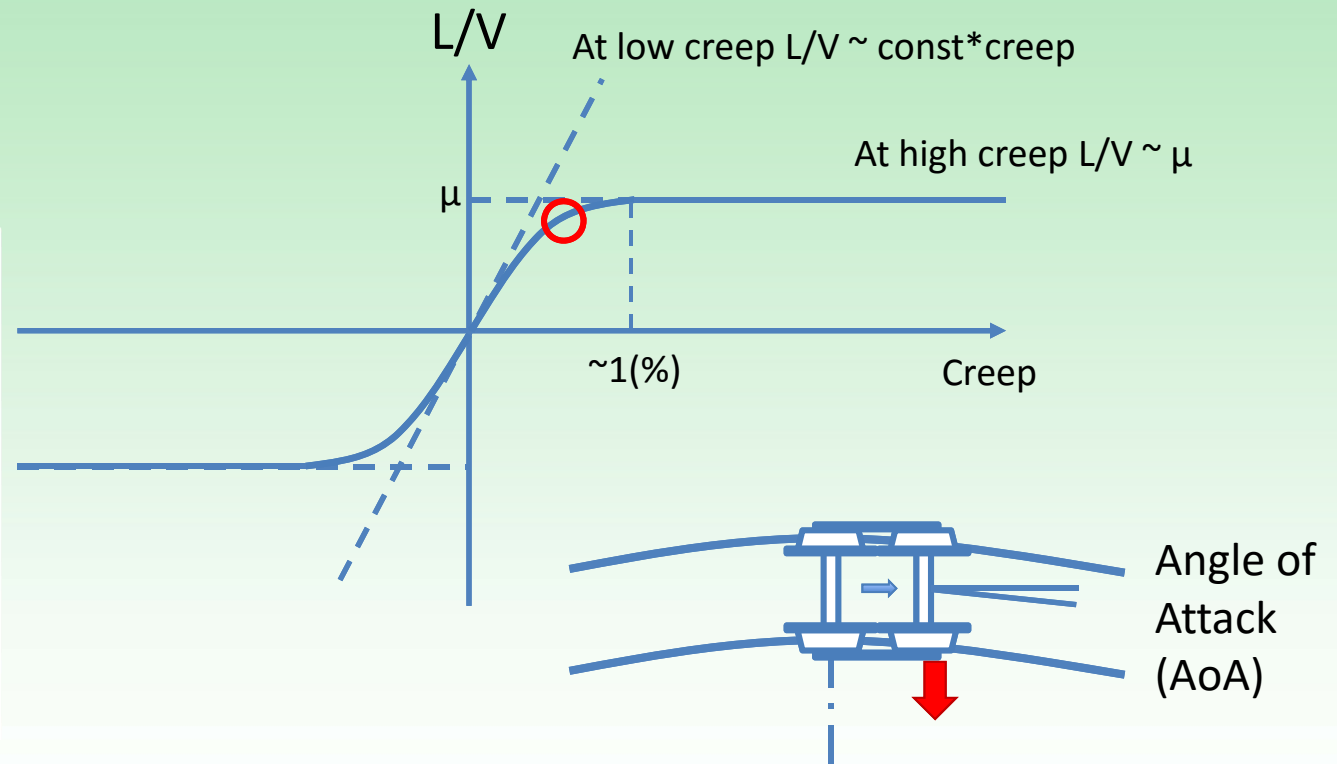
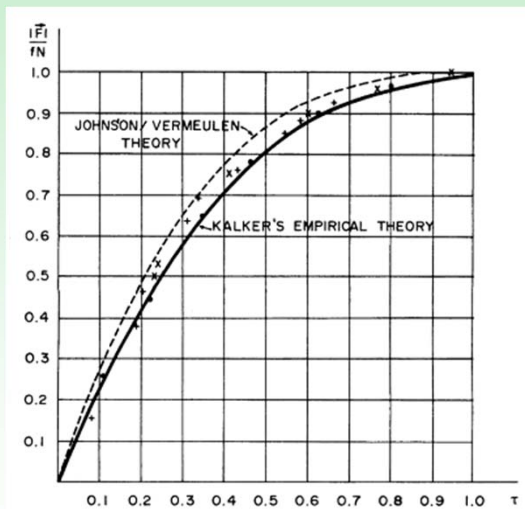
- Example:
 6° curve ($R = 955'$)
 $70''$ wheelbase ($2L = 5.83'$)
 $\mu_{\text{TOR}} = 0.5$ (dry)

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

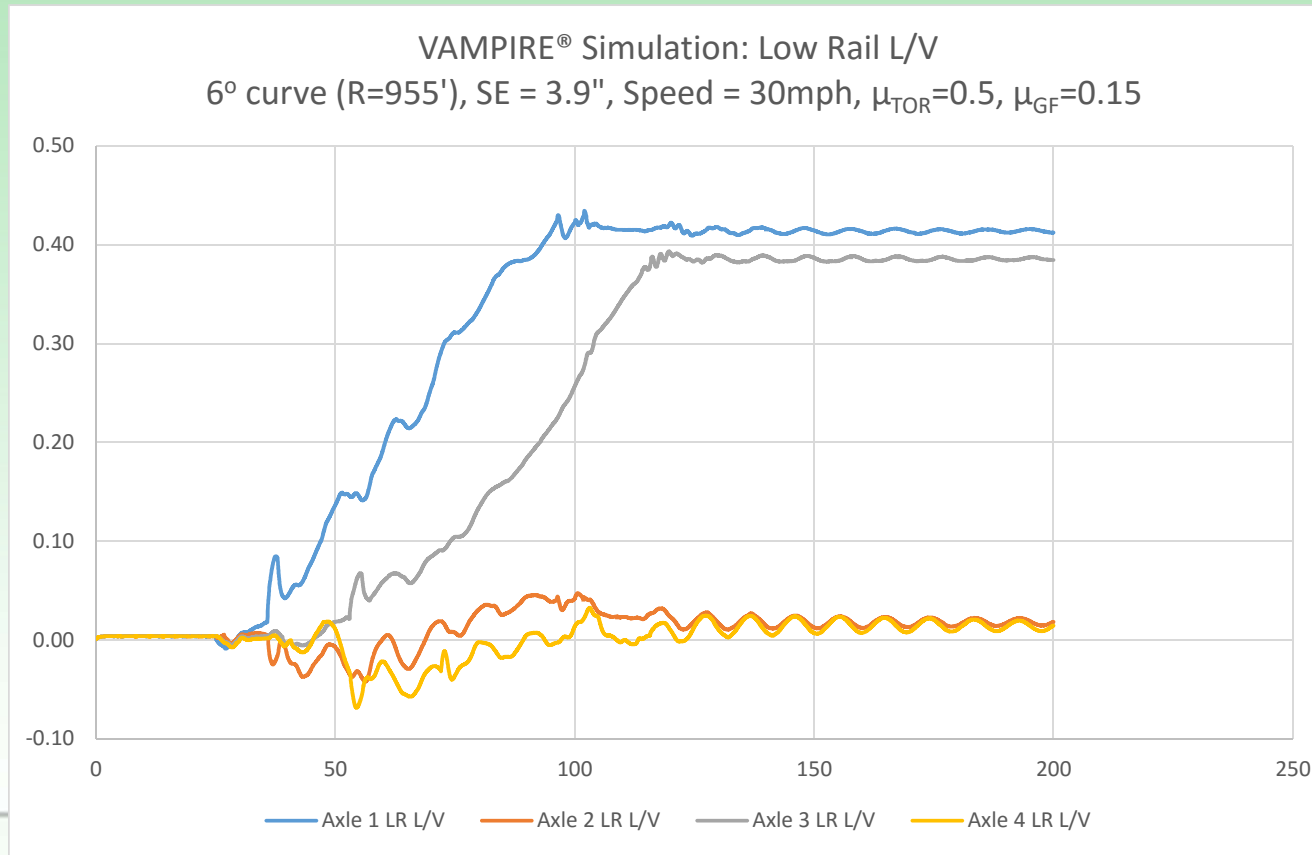


Estimating Low Rail L/V and Lateral Force

- At 0.61% creep:
 $L/V = \text{_____} \mu$

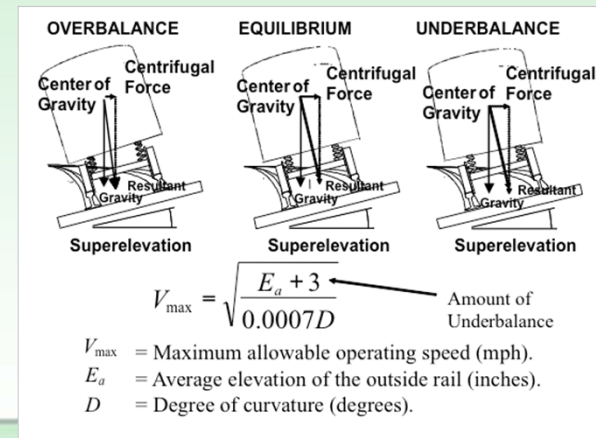
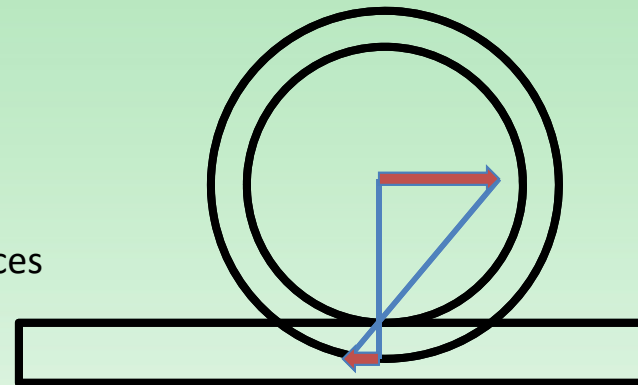


How does this compare with simulation results?



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



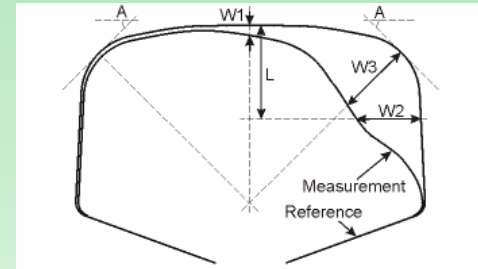
Rail and Wheel Wear



Rail and Wheel Wear

- Wear Types:

- Adhesion
- Surface Fatigue
- Abrasion
- Corrosion
- Rolling Contact Fatigue
- Plastic Flow

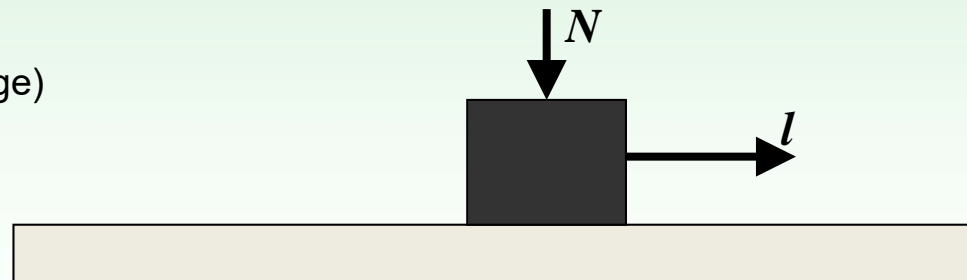


- “Archard” Wear Law:

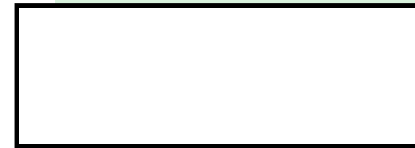
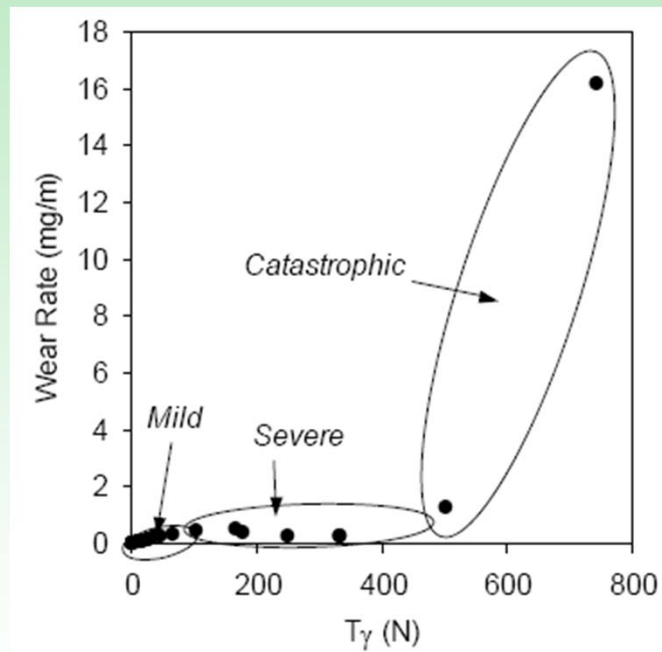
- V = volume of wear
- N = normal load
- l = sliding distance (i.e. creepage)
- H = hardness
- c = wear coefficient

$$V = c \frac{Nl}{H}$$

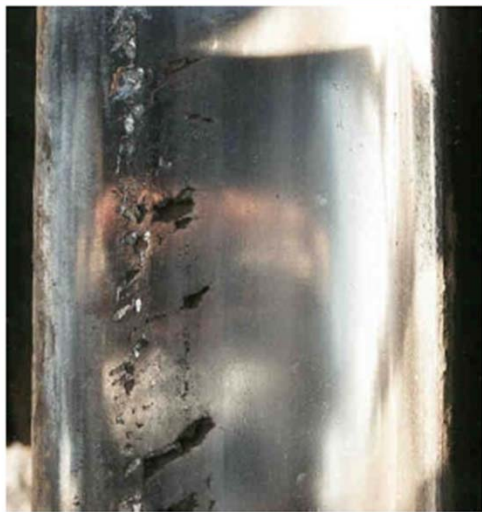
c proportional to
COF



Wear regimes

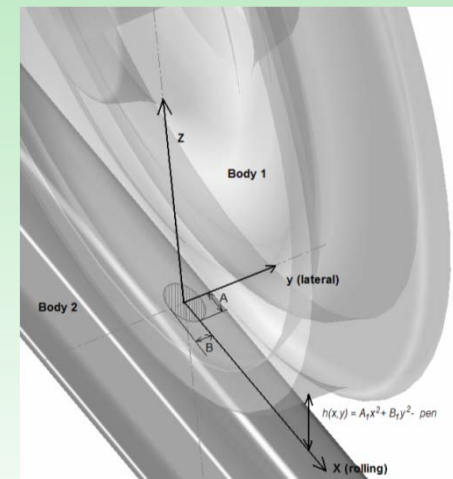
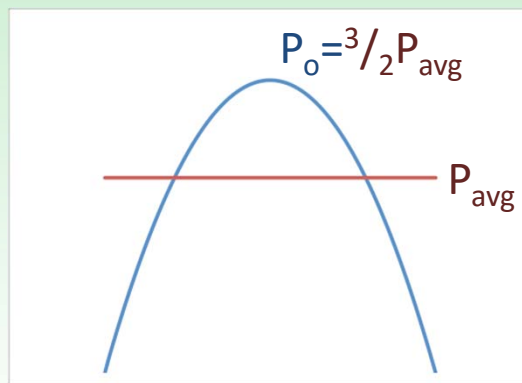


Shakedown and Rolling Contact Fatigue (RCF)

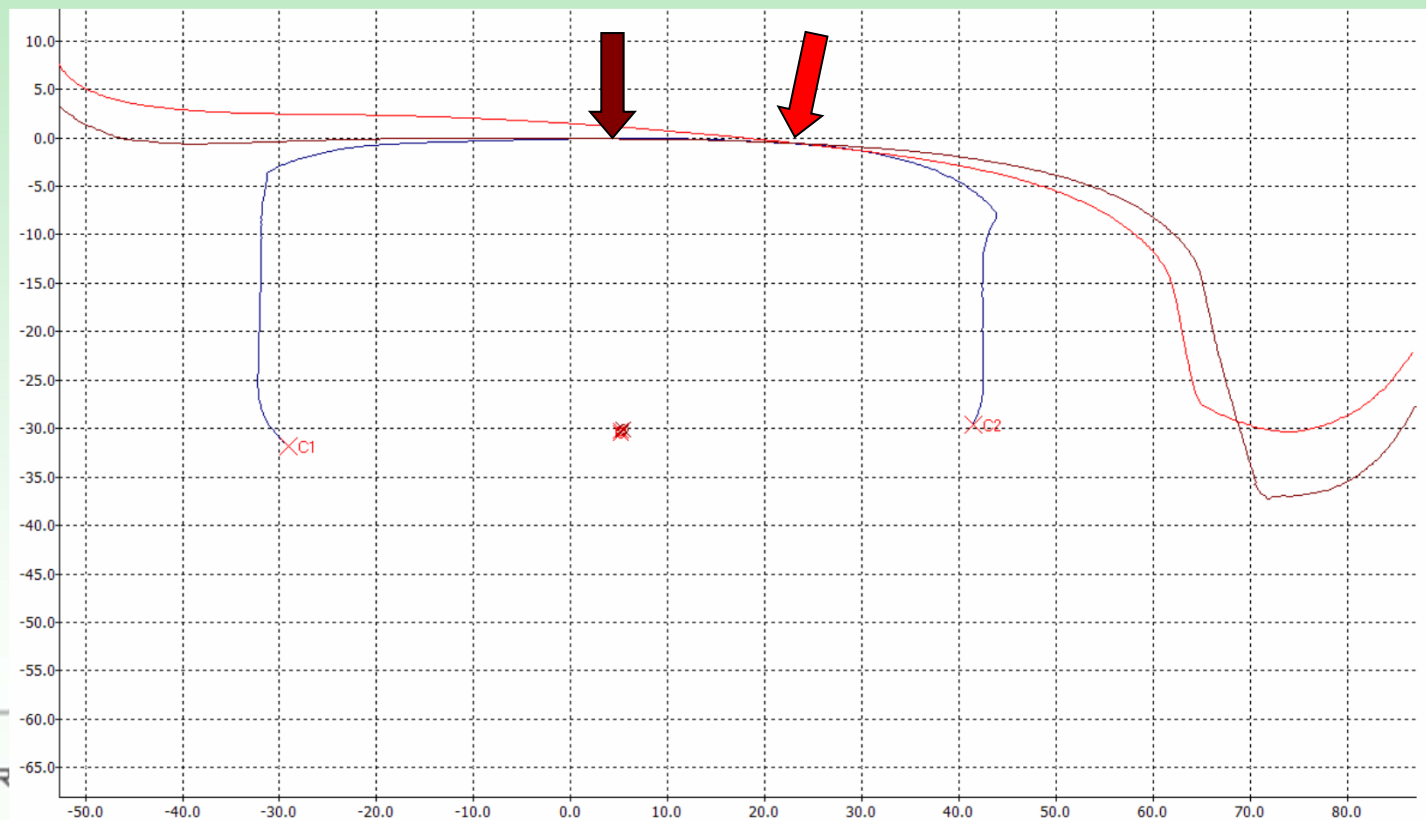


Recall: Hertzian Contact

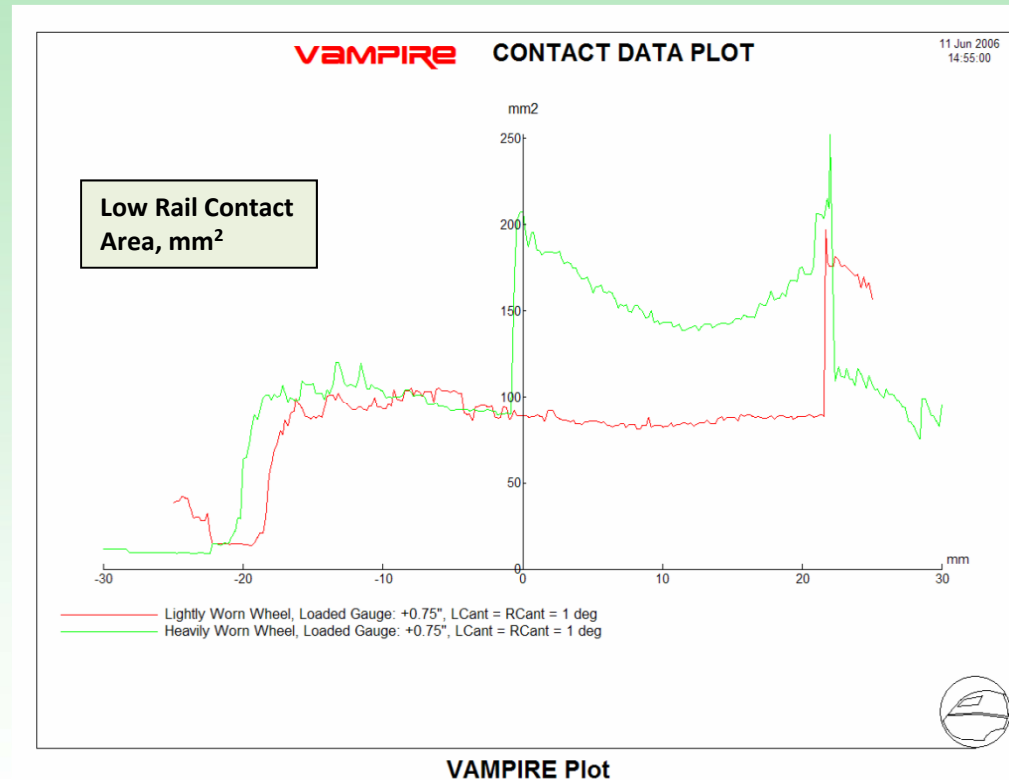
- “Contact Patches” tend to be **elliptical**
- This yields **parabolic** contact pressures



The Contact Patch and Contact Pressures



The Contact Patch and Contact Pressures



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?

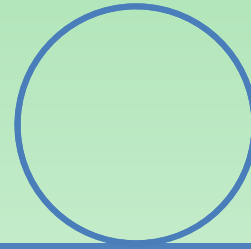
**Magel, E., Sroba, P., Sawley, K. and Kalousek, J. (2004) Control of Rolling Contact Fatigue of Rails, Proceedings of the 2004 AREMA Annual Conference, Nashville, TN, September 19-22, 2004*

| Steel | Hardness (Brinnell) | K | |
|----------------|------------------------|--------|---------|
| | | ksi | MPa |
| "Standard" | 260-280 | 65-70 | 448-483 |
| "Intermediate" | 320-340 | 80-85 | 552-587 |
| "Premium" | 340-380 | 85-95 | 587-656 |
| "HE Premium" | 380-400 | 95-100 | 656-691 |

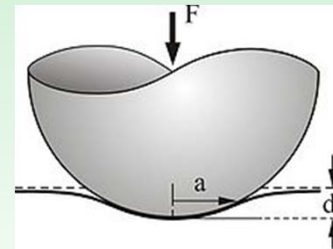




Tensile Testing (1-D loading)



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

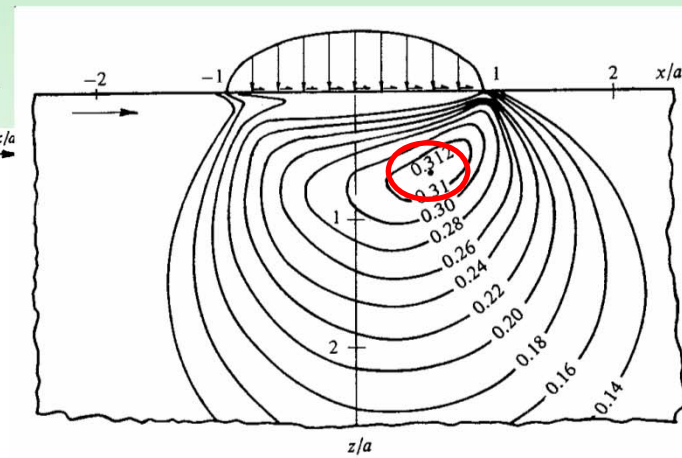
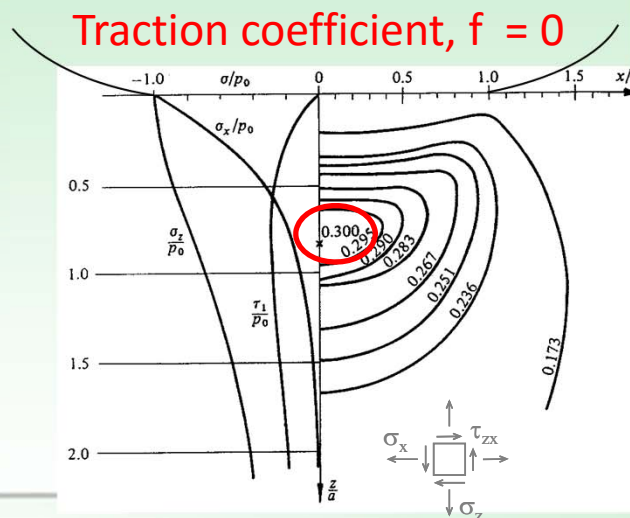


Spherical Contact with Elastic Half-Space (3-D loading)



RCF Development: Contact Pressures, Traction and Stresses

- Cylindrical contact pressure / stress distribution with no tangential traction
- Cylindrical pressure / stress distribution with tangential traction



Traction coefficient, $f = 0.2$

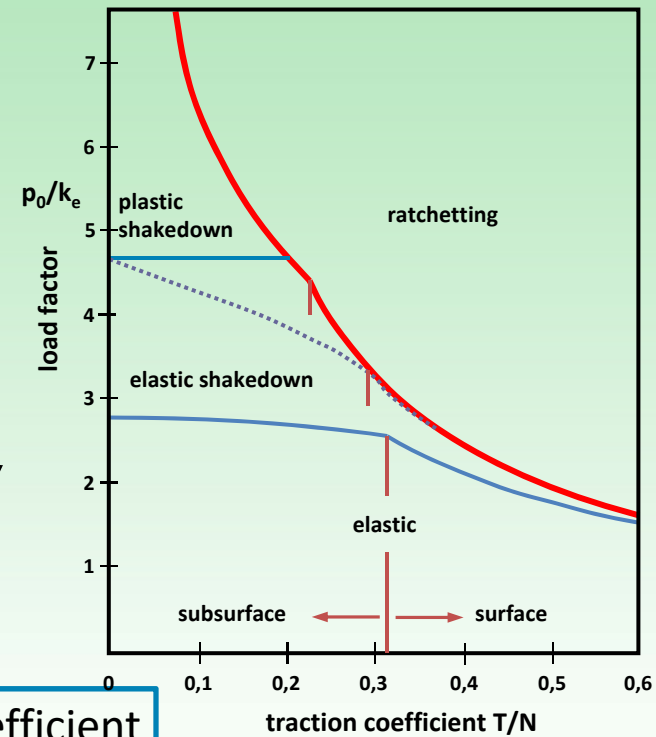


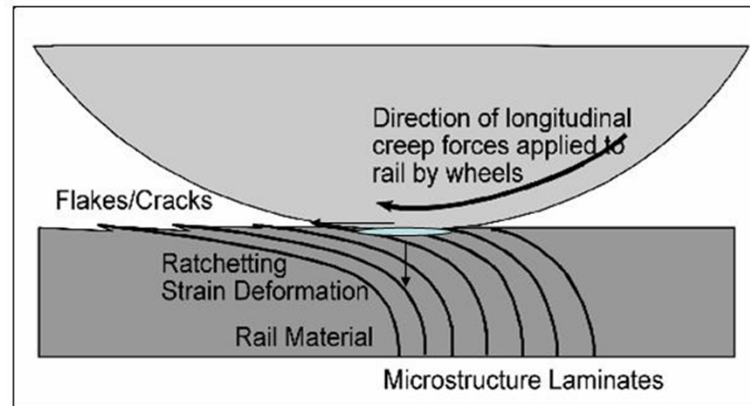
RCF Development: Shakedown

Increased Material Strength
Reduced Stress
(e.g. wheel/rail profiles)



Reduced Traction Coefficient
(e.g. reduced friction)



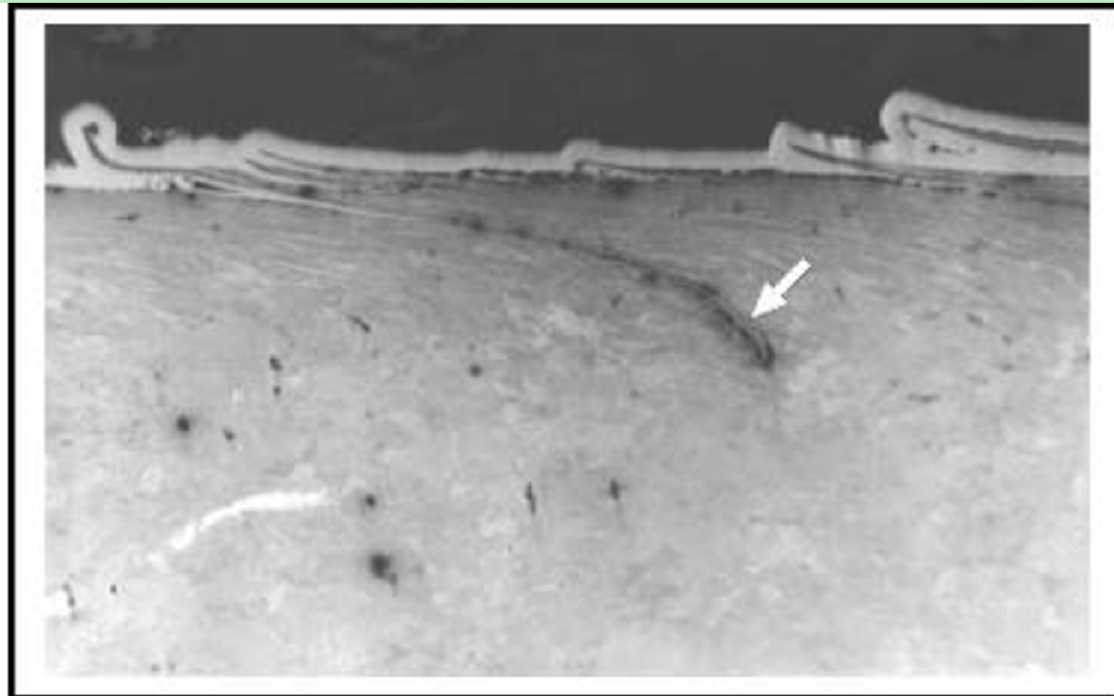


Wheel Tread

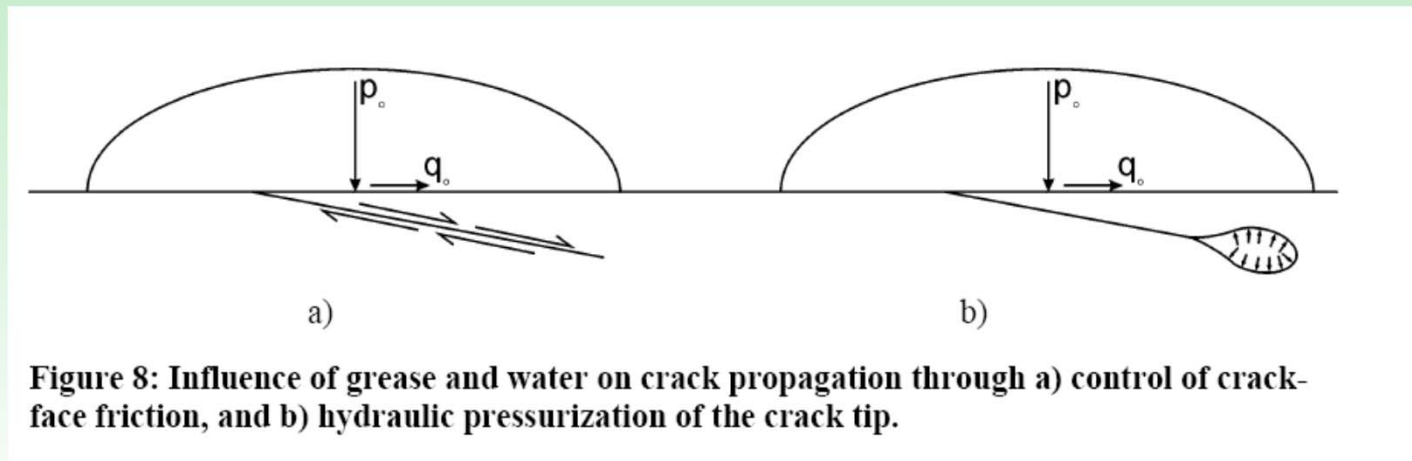


High Rail





Hydropressurization: effect of liquids on crack growth



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?



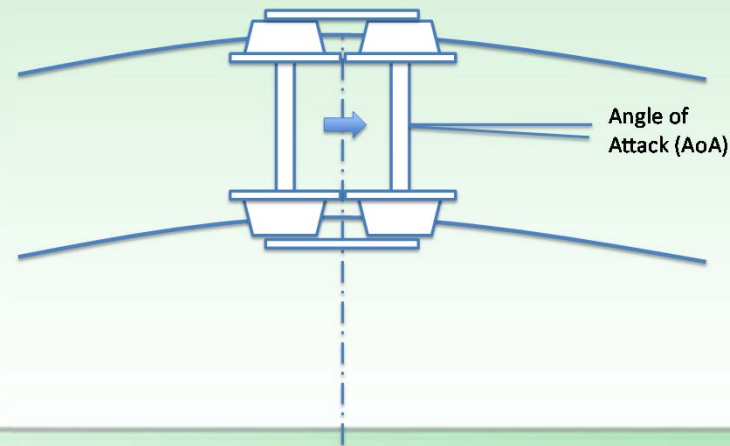
Estimating lateral creepage, traction ratio & contact pressure:

- In “mild” curving, leading axle angle of attack:

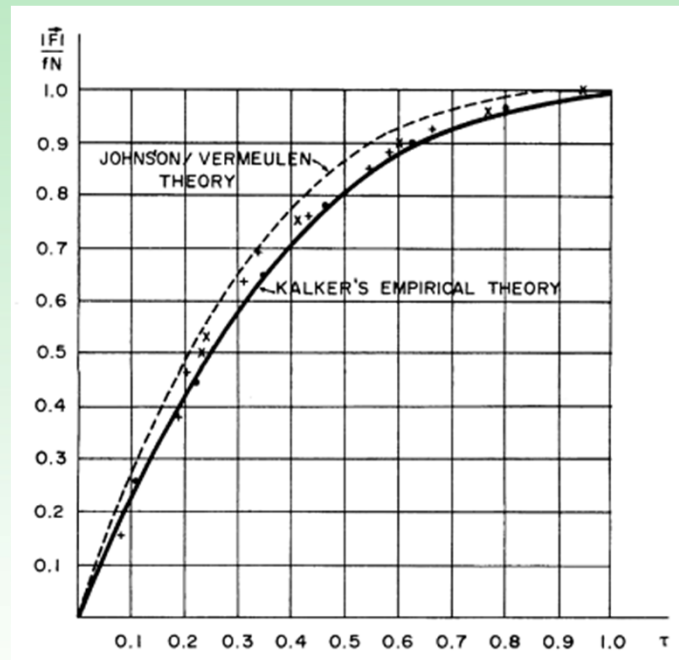
$$\alpha \sim \arcsin(L/R) \sim L/R = 0.0030 \text{ Rad (3.0 mRad)}$$

- Lateral Creepage at low rail TOR contact:

$$V_{\text{lat}}/V \sim 2L/R \sim \alpha = 0.3\%$$



Estimating the traction ratio (L/V)



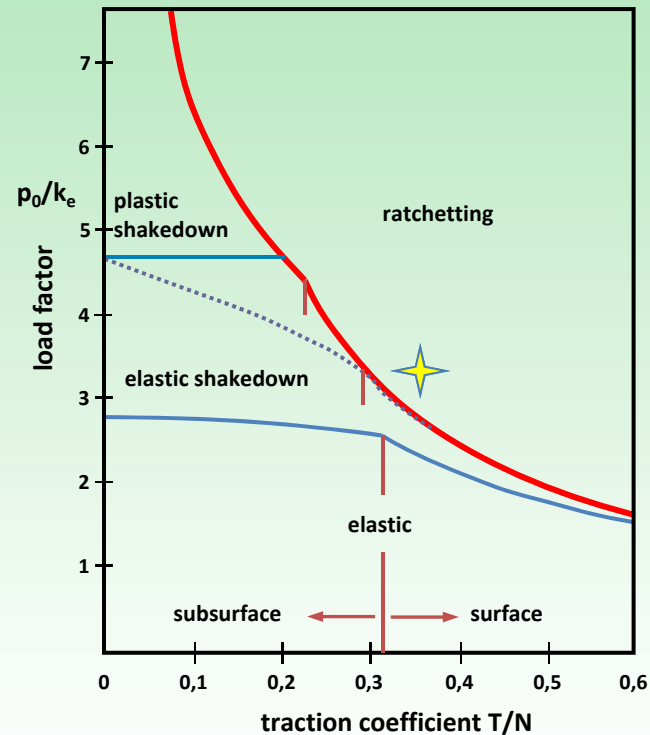
- At 0.3% creep:
 $T/N \sim 0.6 \mu$
- With $\mu = 0.6$
Traction Ratio (T/N) ~ 0.36

**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
 $P_o = 225 \text{ ksi}$
- With $K = 70 \text{ ksi}$,
 $P_o/K = 3.21$



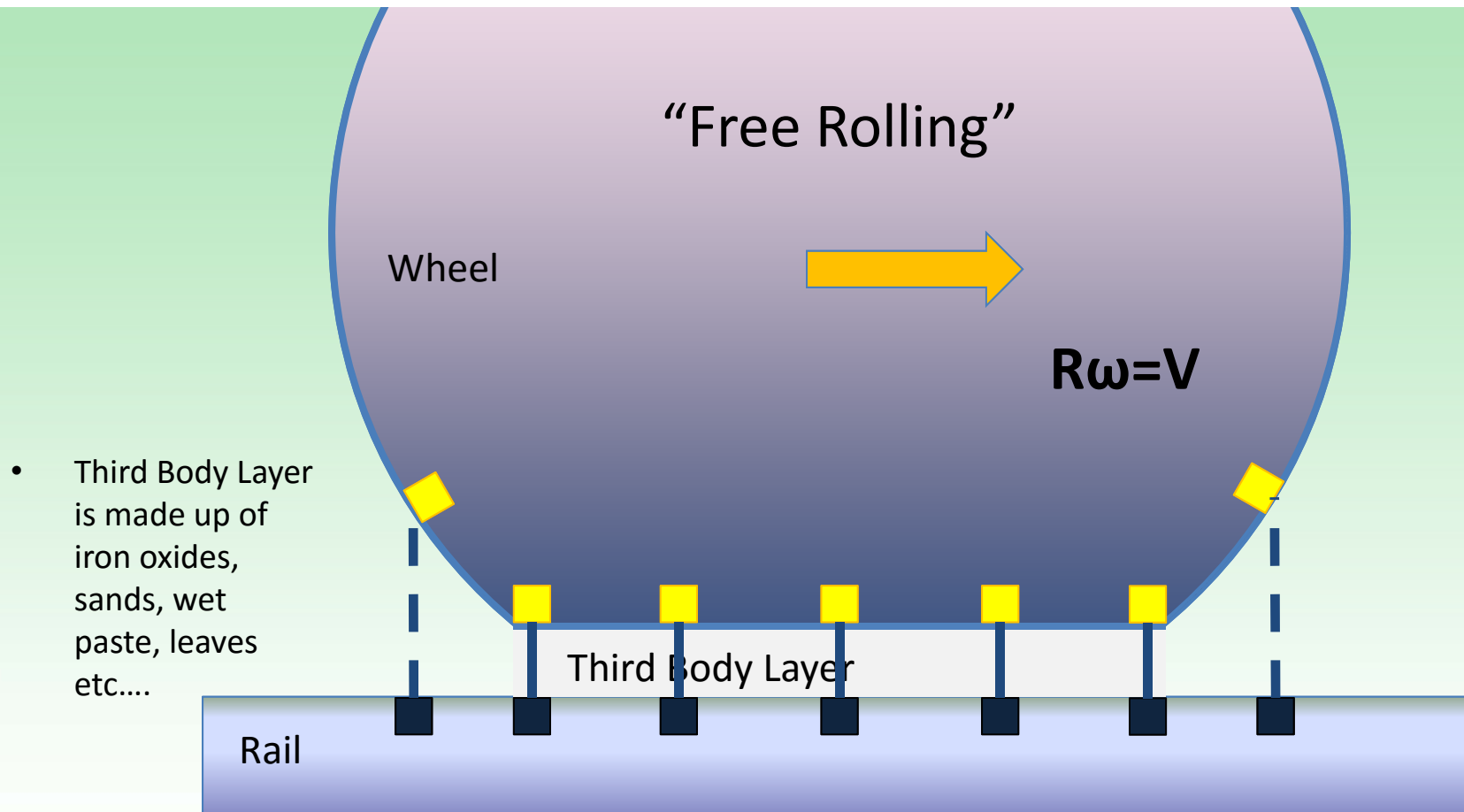
Questions & Discussion

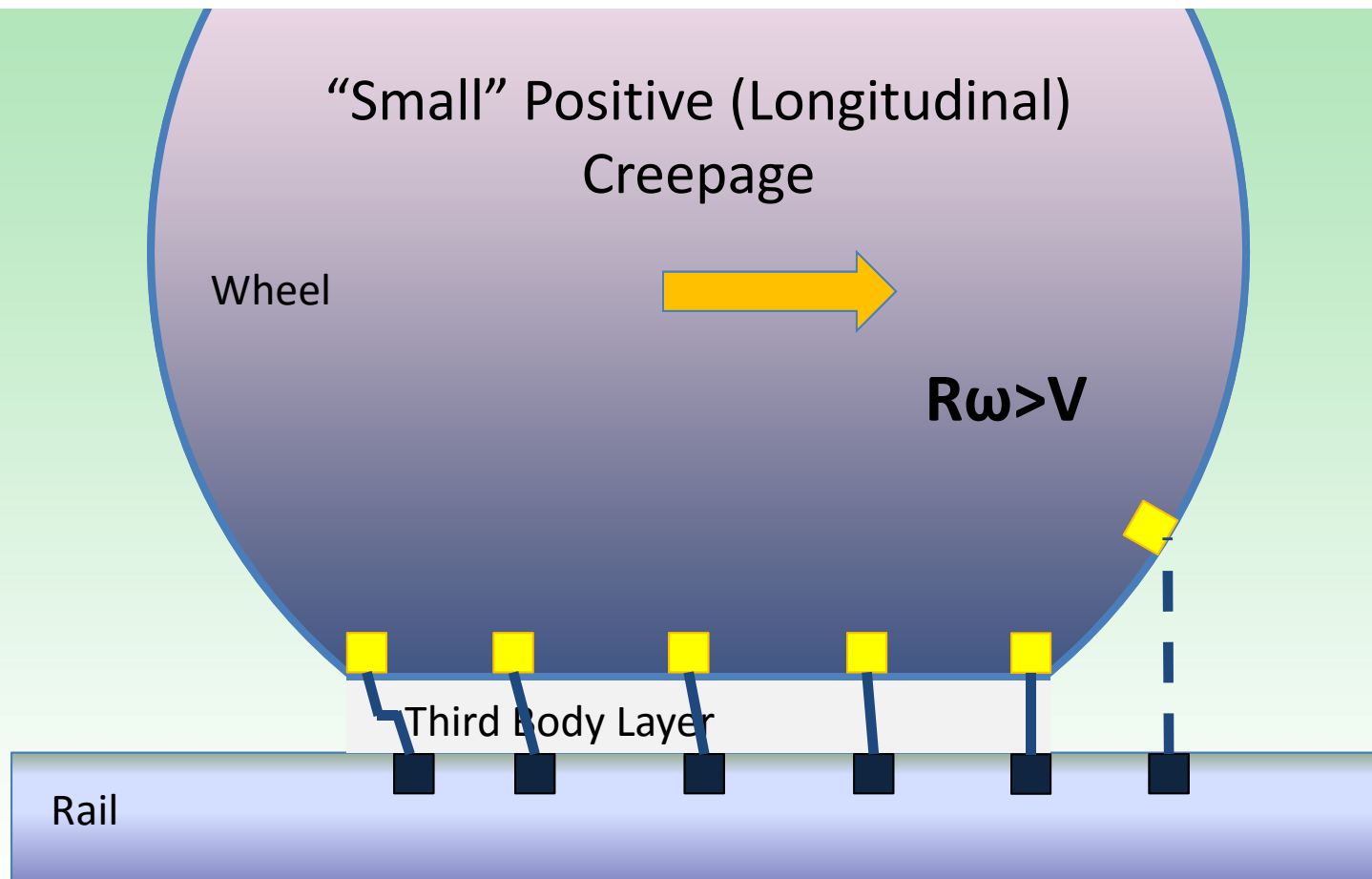


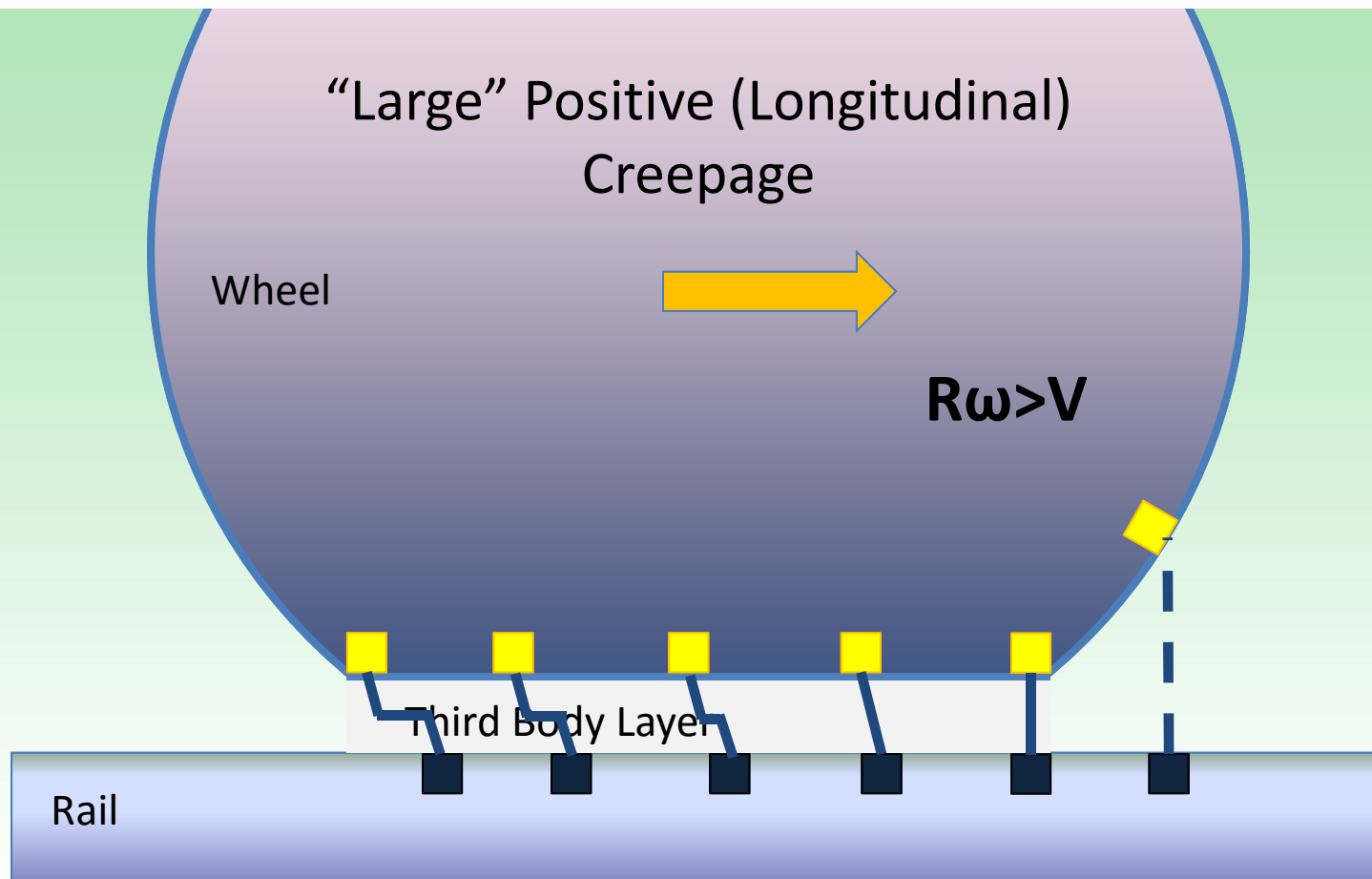
Part 3

- The Third Body Layer, Traction/Creepage and Friction Management
- Frequency Domain Phenomena: Noise and Corrugations

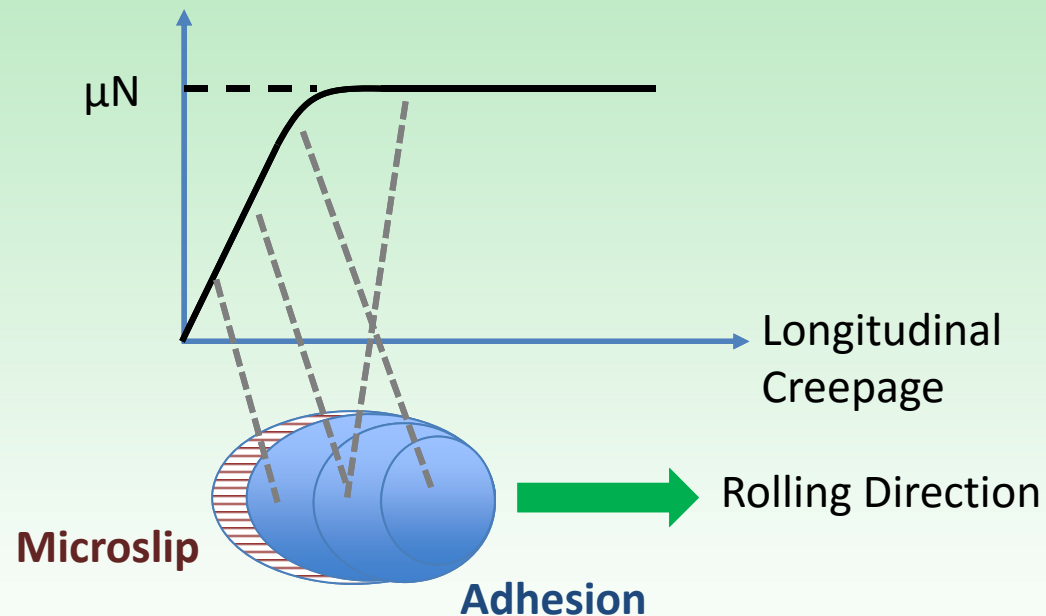






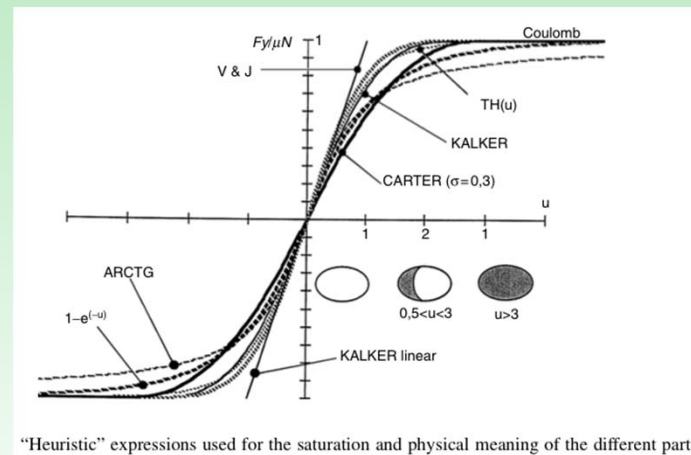
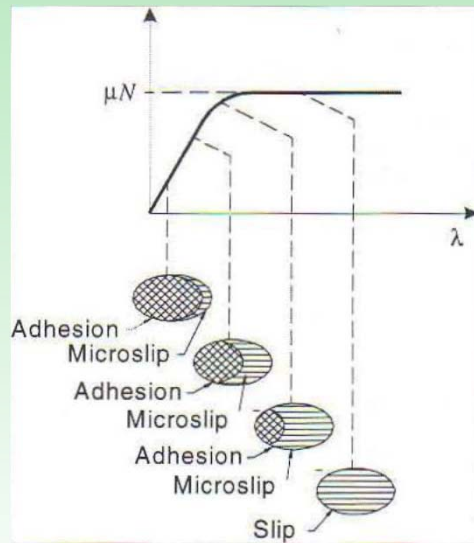


The Traction-Creepage Curve



Traction/Creepage Curves

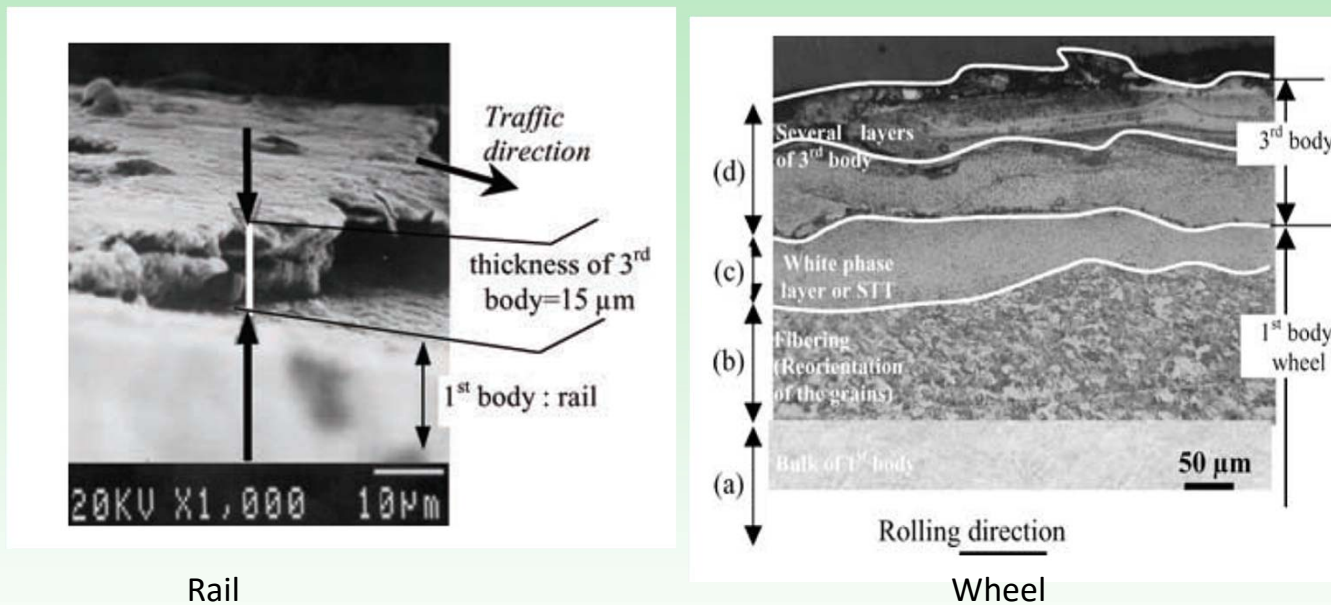
75



"Heuristic" expressions used for the saturation and physical meaning of the different parts.



Third Body Layer – Micron Scale



Y. Berthier, S. Decartes, M. Busquet et al. (2004). The Role and Effects of the third body in the wheel rail interaction. *Fatigue Fract. Eng. Mater Struct.* 27, 423-436



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.

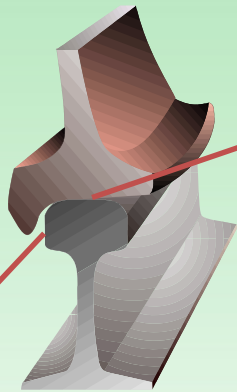


Managing friction: two distinct interfaces

1. Gauge Face / Wheel Flange Lubrication
2. Top of Rail / Wheel Tread Friction Control



Controlling Friction at the Wheel/Rail Interface



Gage Face (GF) Friction Impacts:

- Rail / Wheel Wear (Gage Face, Flange)
- RCF Development
- Fuel Efficiency
- Flange Noise
- Derailment Potential (Wheel Climb)
- Lateral Forces (indirect)

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)



Ideal Targets



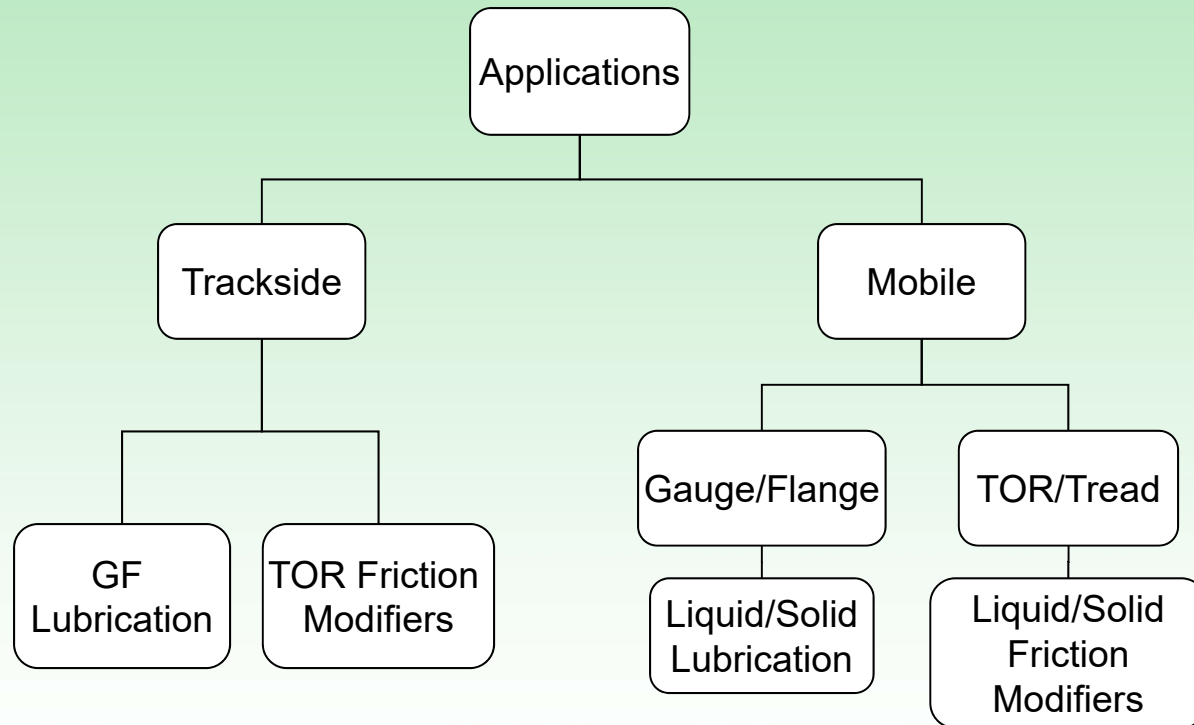
Low rail



High Rail



Friction Management Approaches



Trackside Gage Face Lubrication

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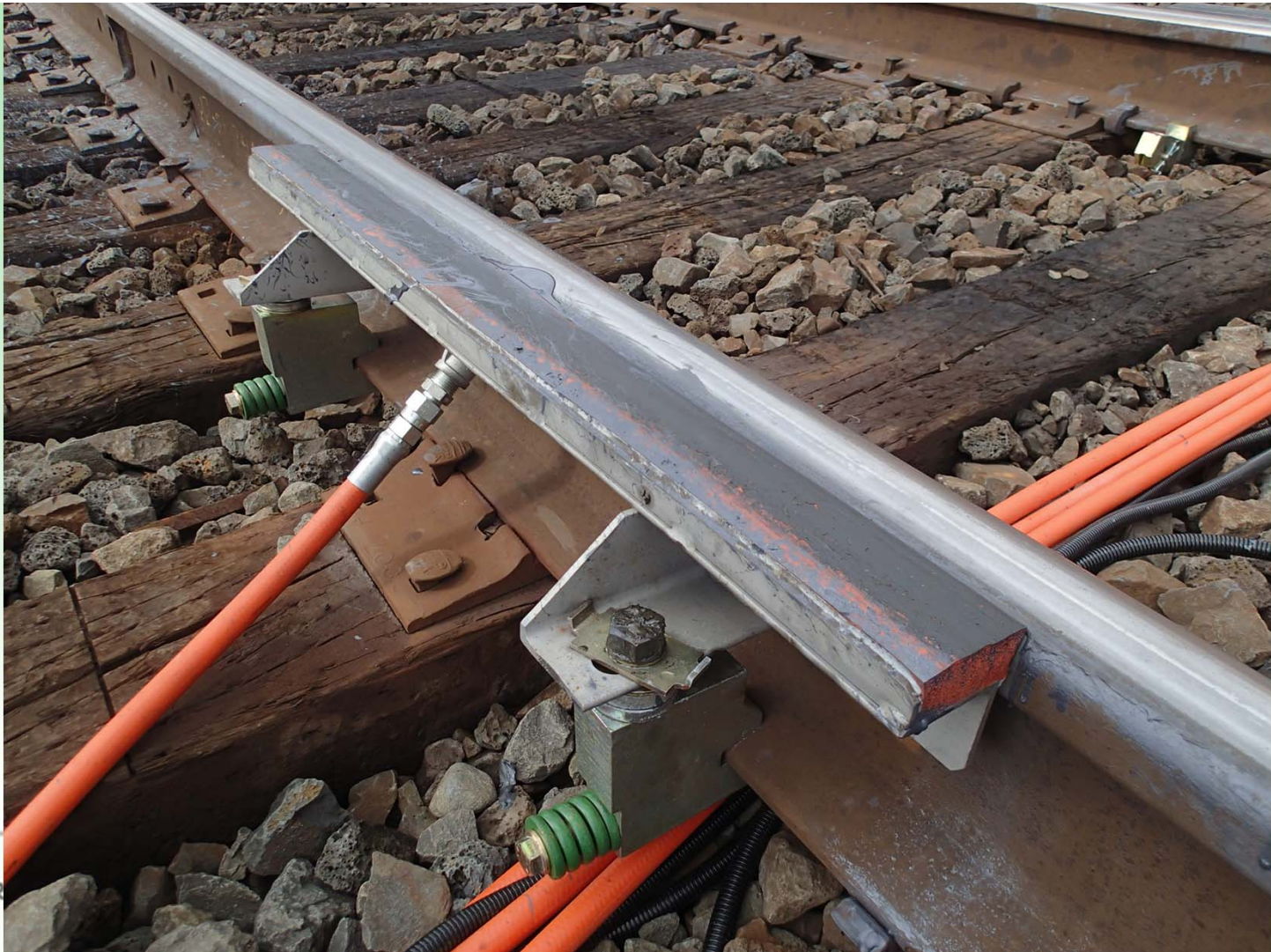
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2017



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

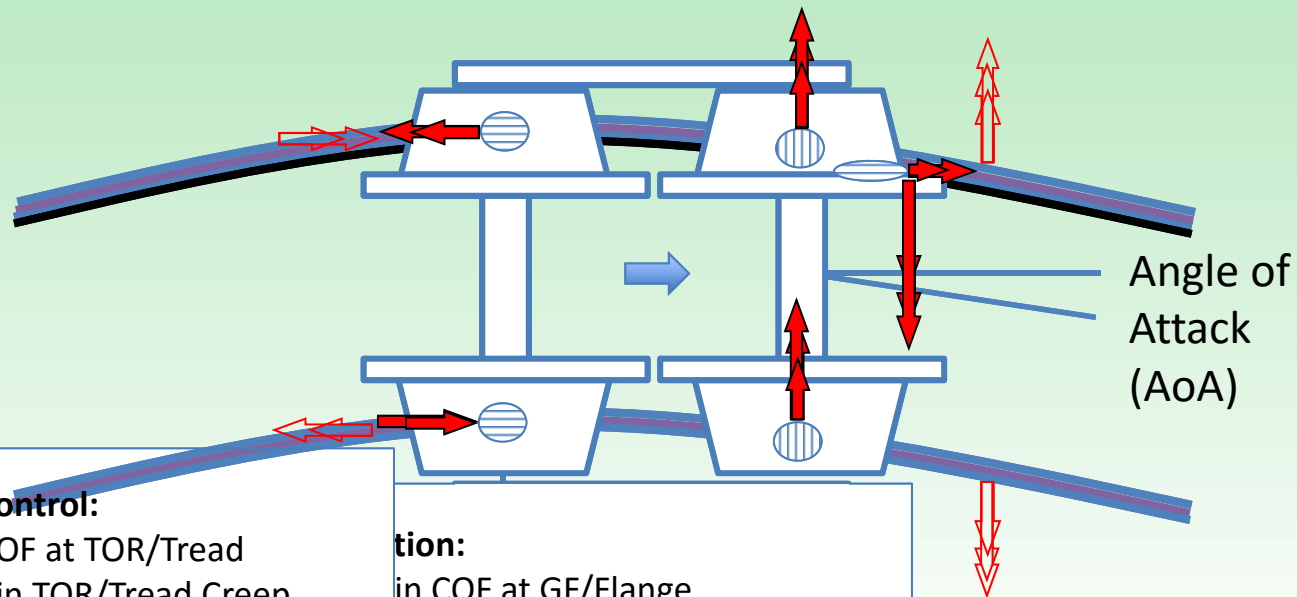


Maximizing system performance

- 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.

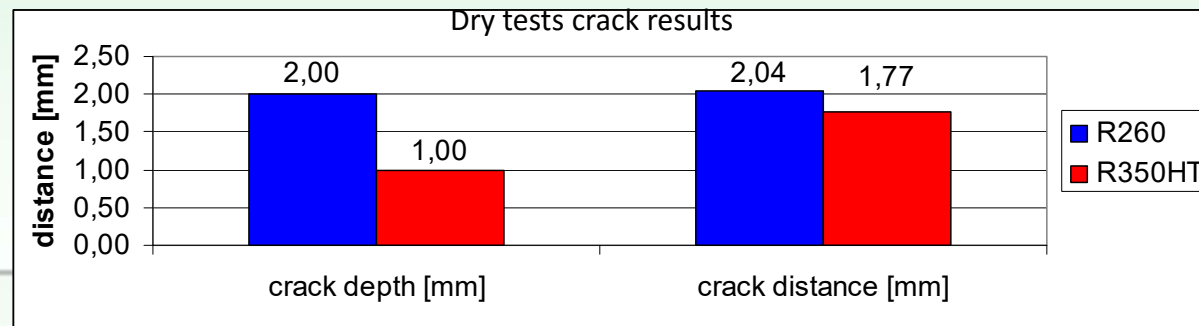
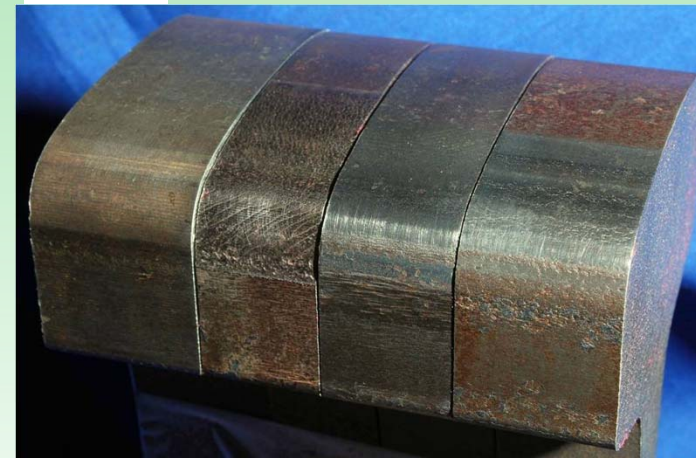
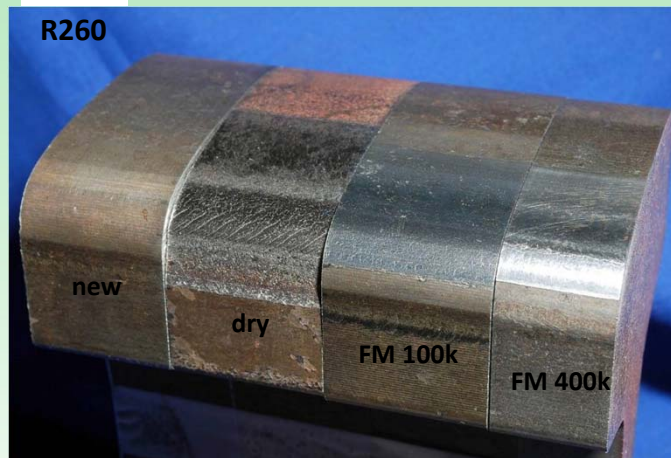
tion:

in COF at GF/Flange
 ons in wear and energy
 tion in Longitudinal Creep Force
 e Steering Moment
 crease in AoA and Lateral Forces



Example: Friction Management, Wear and RCF wheel/rail rig test results

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Curving Noise



Spectral range for different noise types

| <u>Noise type</u> | <u>Frequency range, Hz</u> |
|---------------------------------|----------------------------|
| Rolling | 30 -2500 |
| Rumble (including corrugations) | 200 - 1000 |
| Flat spots | 50 -250 (speed dependant) |
| Ground Borne Vibrations | 30 - 200 |
| Top of rail squeal | 1000 - 5000 |
| Flanging noise | 5000 – 10000 |



Top of rail wheel squeal noise

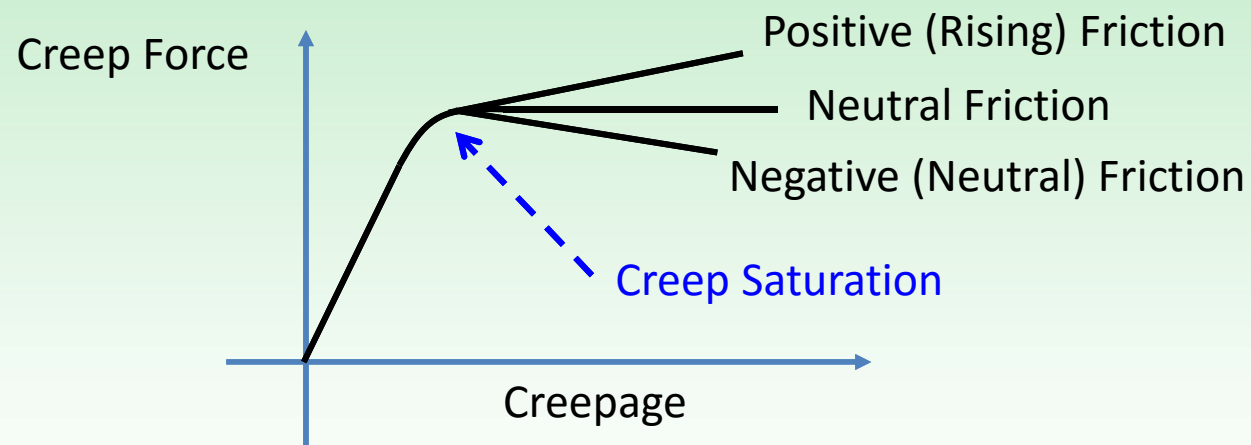
- High pitched, tonal squeal (predominantly 1000 – 5000 Hz)
- Prevalent noise mechanism in “problem” curves, usually < 300m radius
- Related to both **negative friction** characteristics of Third Body at tread / top of rail interface and **absolute friction** level
 - Stick-slip oscillations

Flanging noise

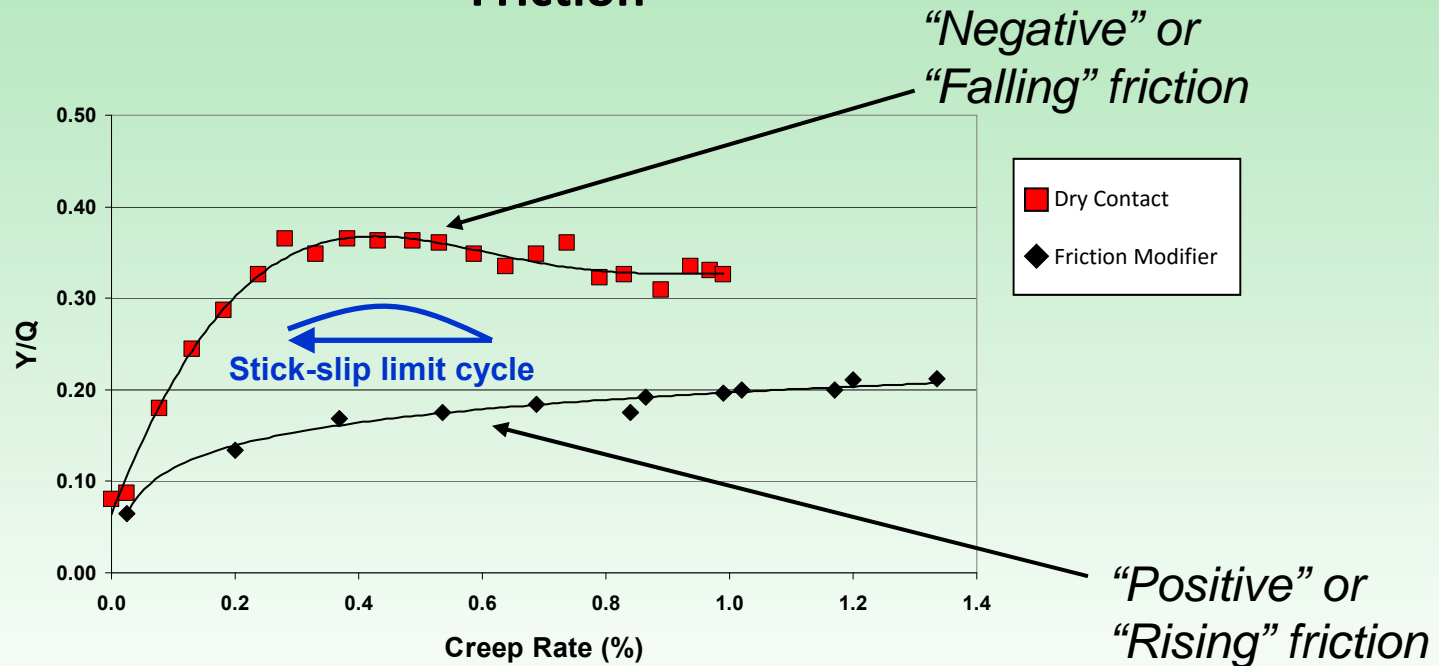
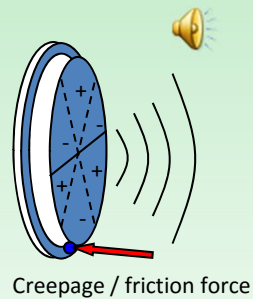
- Typically a “buzzing” OR “hissing” sound, characterized by broadband high frequency components (>5000 Hz)
- Affected by:
 - Lateral forces: related to **friction on the top of the low rail**
 - Flanging forces: related to friction on **top of low and high rails**
 - Friction at the flange / gauge face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



The Traction-Creepage Curve: Positive (Rising) and Negative (Falling) Friction



Absolute Friction Levels and Positive/Negative Friction

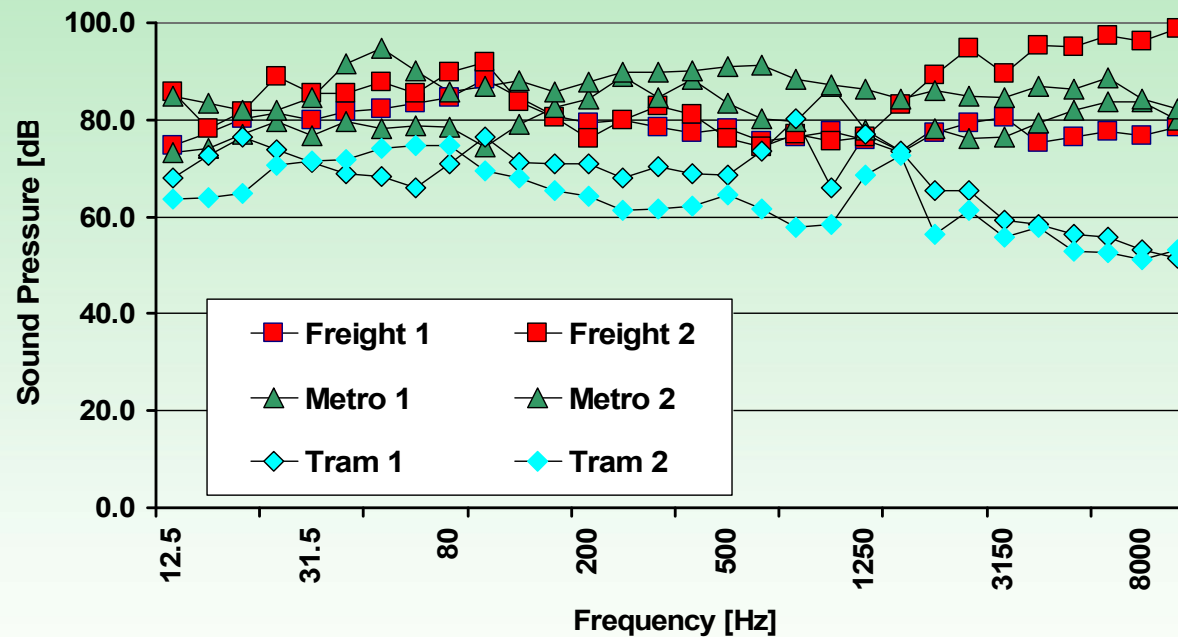


* Replotted from: "Matsumoto a, Sato Y, Ono H, Wang Y, Yamamoto Y, Tanimoto M & Oka Y, Creep force characteristics

between rail and wheel on scaled model, *Wear*, Vol 253, Issues 1-2, July 2002, pp 199-203



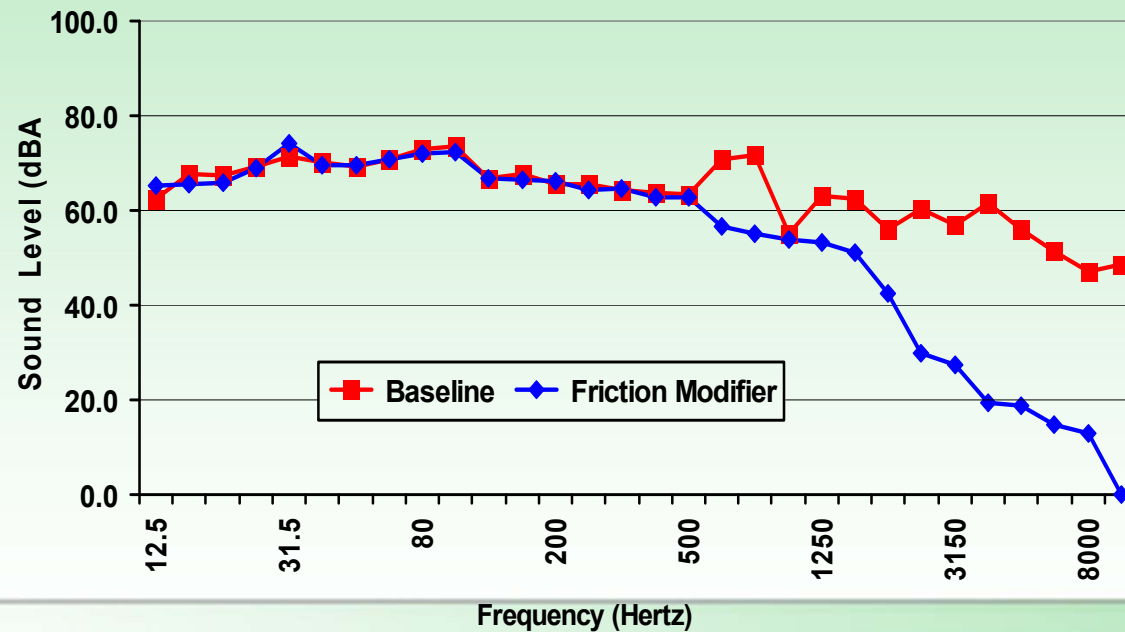
Sound spectral distribution for different wheel / rail systems



Effect of friction characteristics on spectral sound distribution: Trams



Effect of friction characteristics on spectral sound distribution: Trams



“Low Frequency” Stick-Slip / Noise

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** Video used with
permission, Brad
Kerchof, Norfolk
Southern*



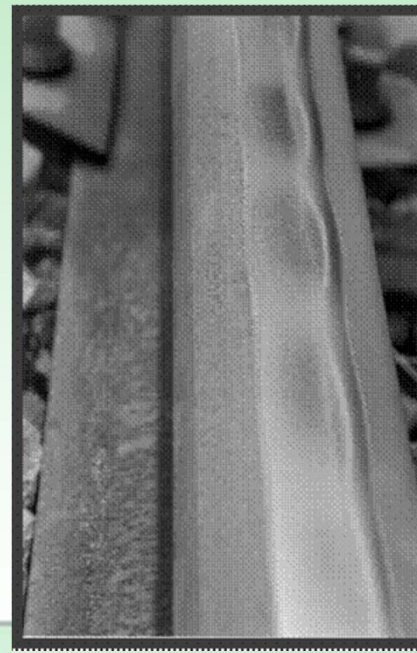
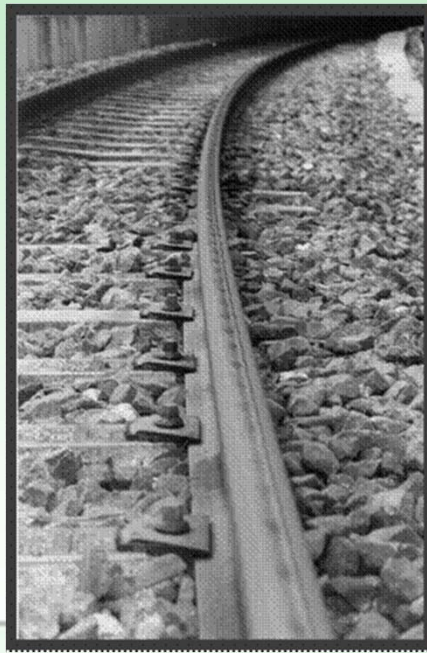
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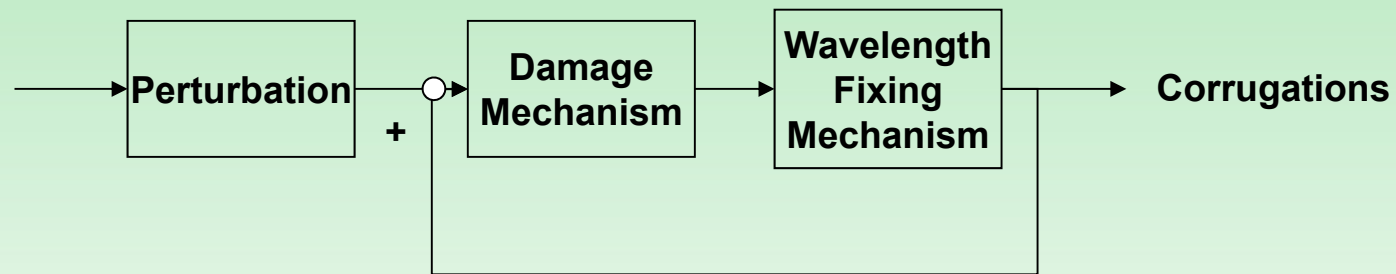
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Corrugations (Short Pitch)



Corrugation formation: common threads



$$\lambda = v/f$$

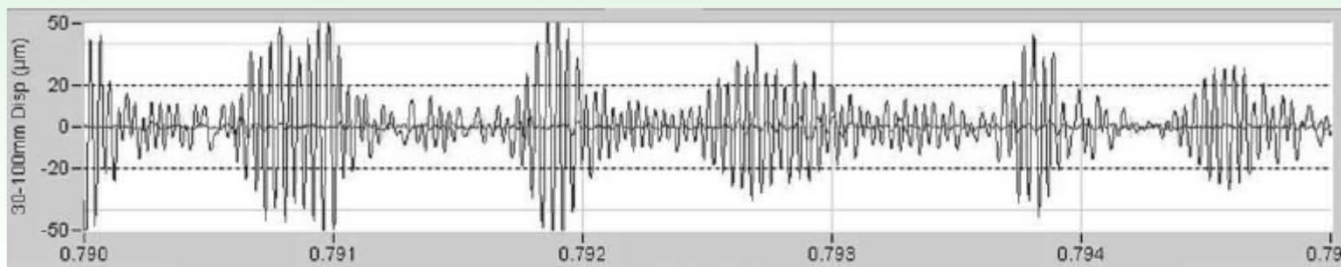


| Type | Wavelength-fixing mechanism | Where? | Typical frequency (Hz) | Damage mechanism | Relevant figures | References | Treatments ¹ | |
|---|--|---------------------------------------|------------------------|-------------------------|------------------|---------------|---|---|
| | | | | | | | Demonstrably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



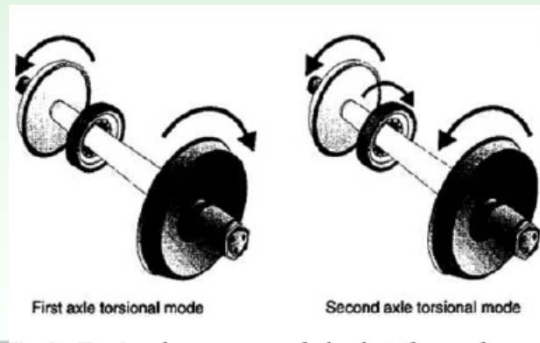
Pinned-Pinned corrugation (“roaring rail”)

- 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



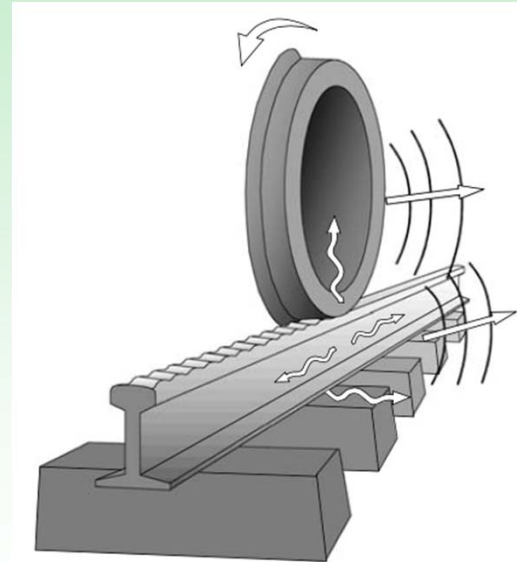
Rutting

- 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

