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

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

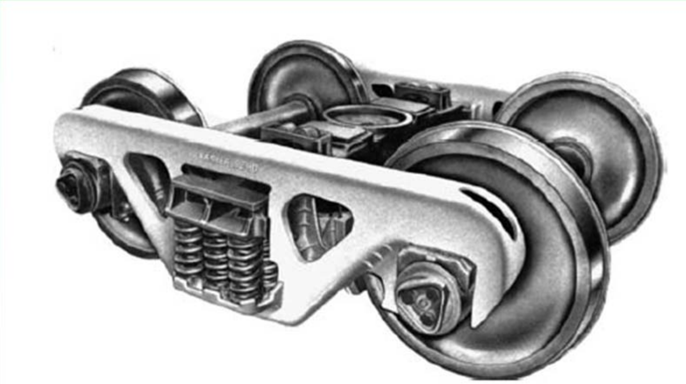
- **Part 3**
  - The Third Body Layer, Traction/Creepage and Friction Management
  - Frequency Domain Phenomena: Noise and Corrugations

Part 1

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

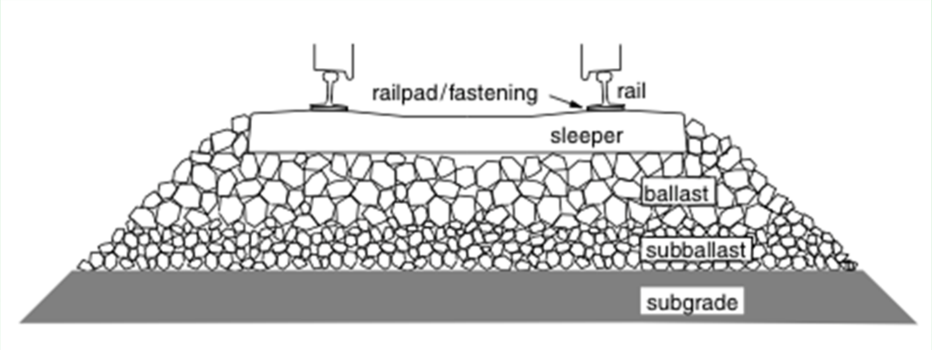
(Very) Basic Vehicle Running Gear Anatomy

- Wheels
- Wheelsets
- Axleboxes
- Suspension
- Frame



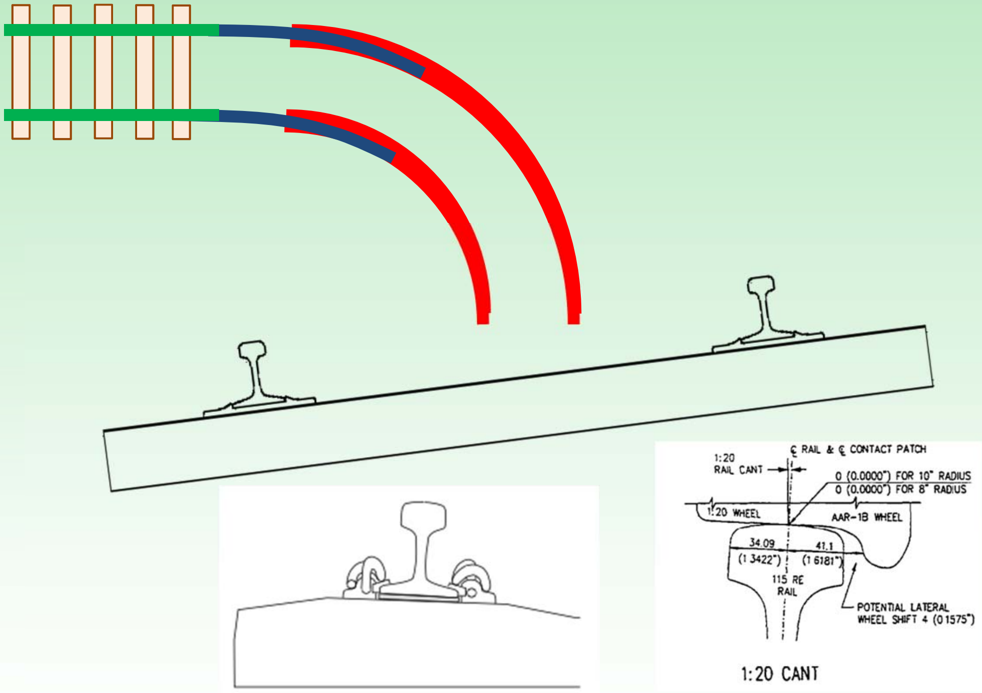
(Very) Basic Track Anatomy

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

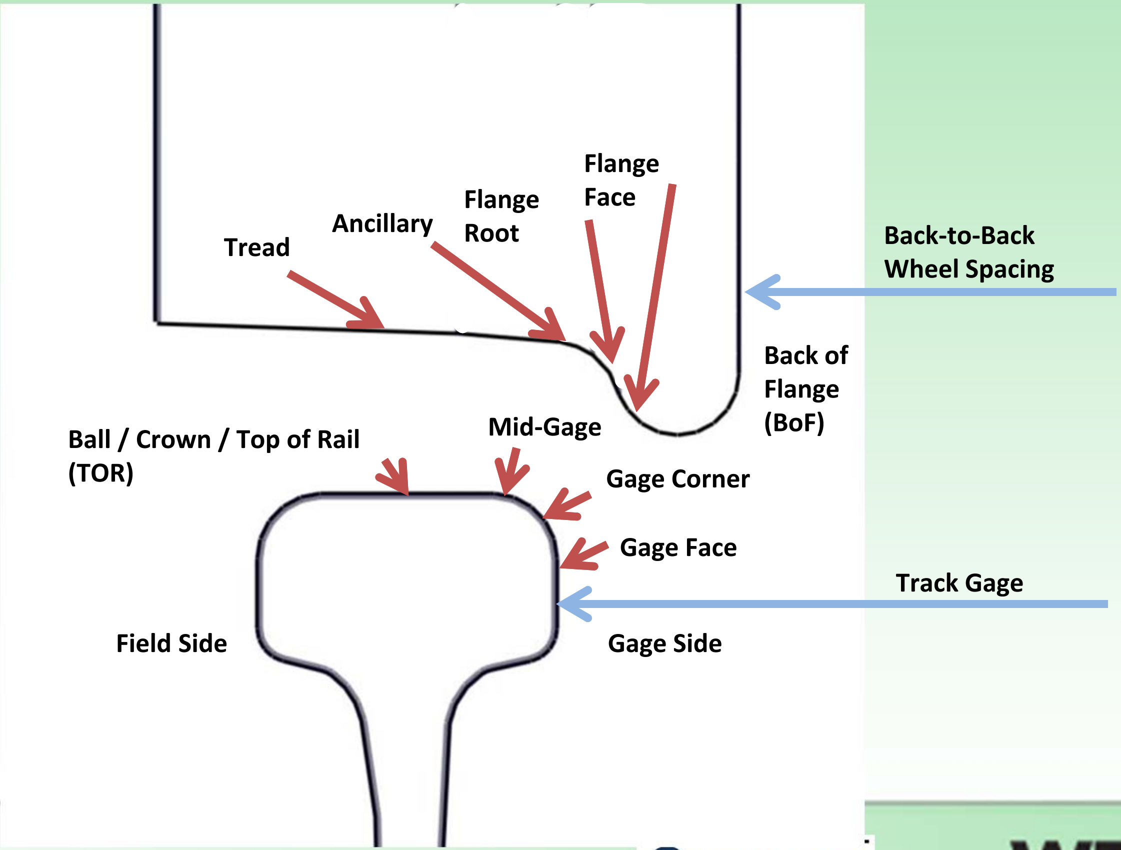


Recalling a few track geometry basics…

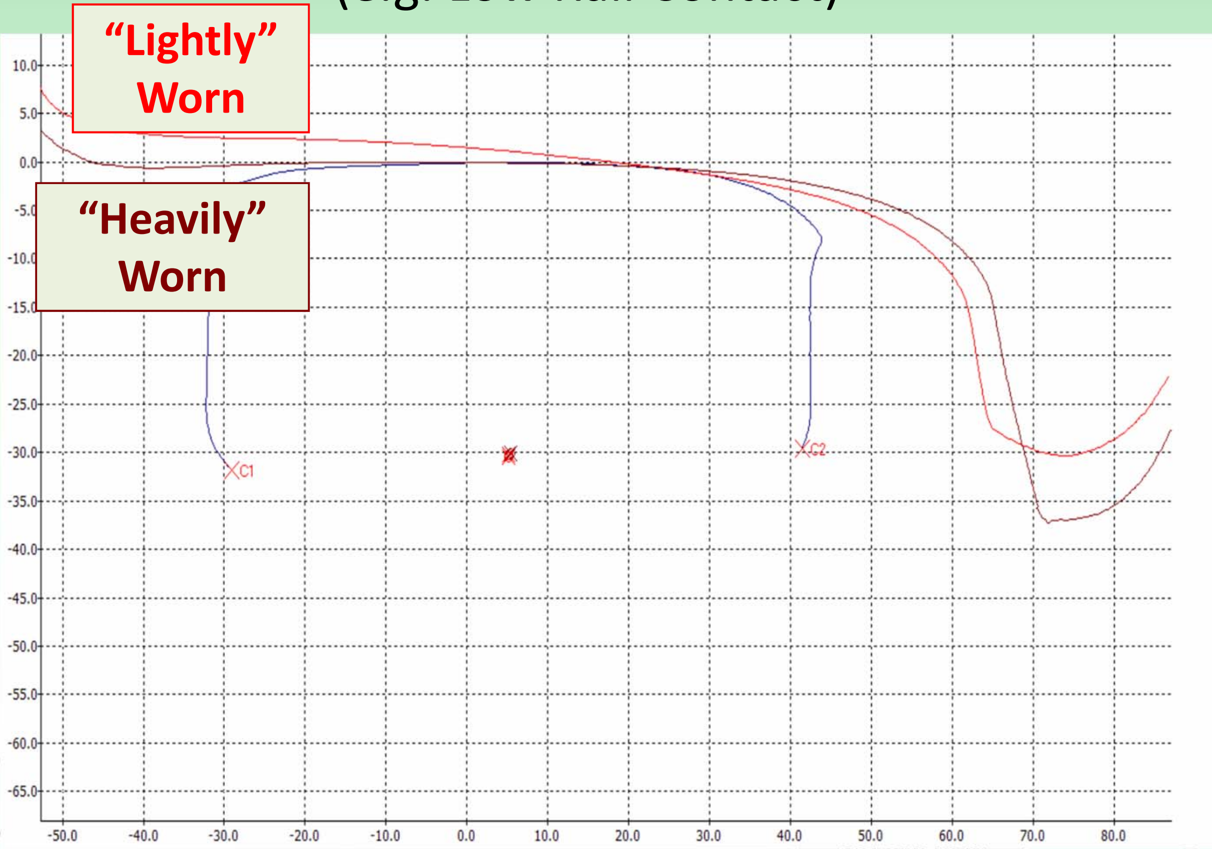
- Tangent
- Curve
- Spiral
- High Rail
- Low Rail
- Superelevation (aka Cant)
- Rail Cant



The Wheel / Rail Interface and Key Terminology



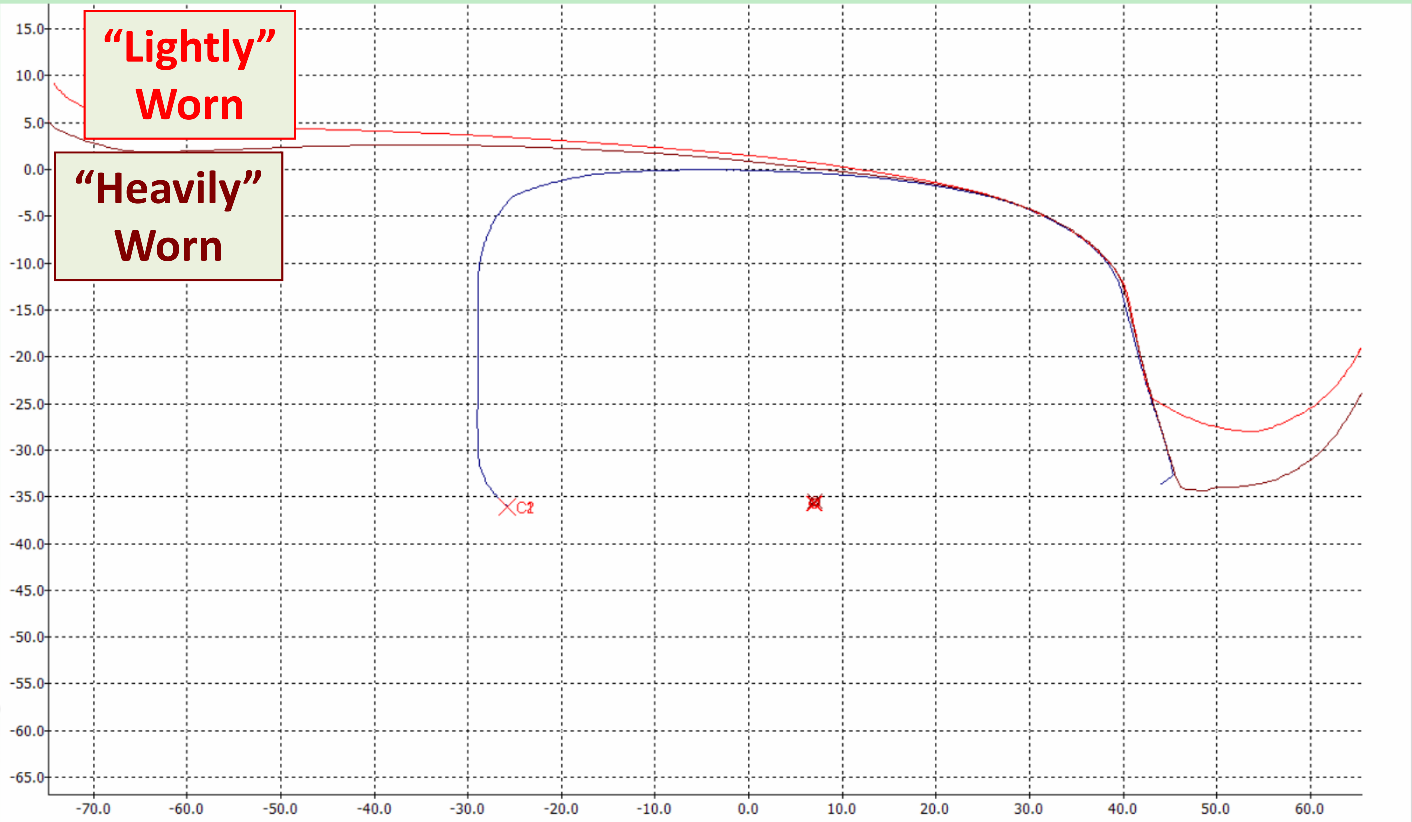
The Wheel / Rail Interface and Key Terminology (e.g. Low Rail Contact)



"Lightly" Worn

"Heavily" Worn

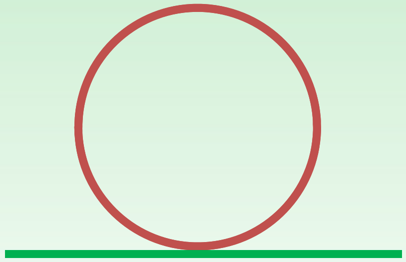
The Wheel / Rail Interface and Key Terminology
(e.g. High Rail Contact)


“Lightly” Worn

“Heavily” Worn

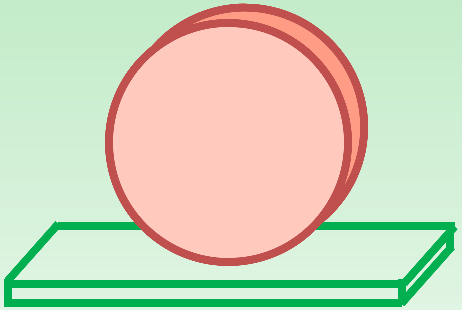
The Contact Patch and Contact Pressures

- 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?

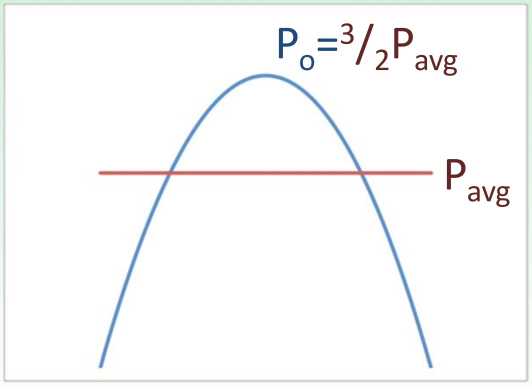


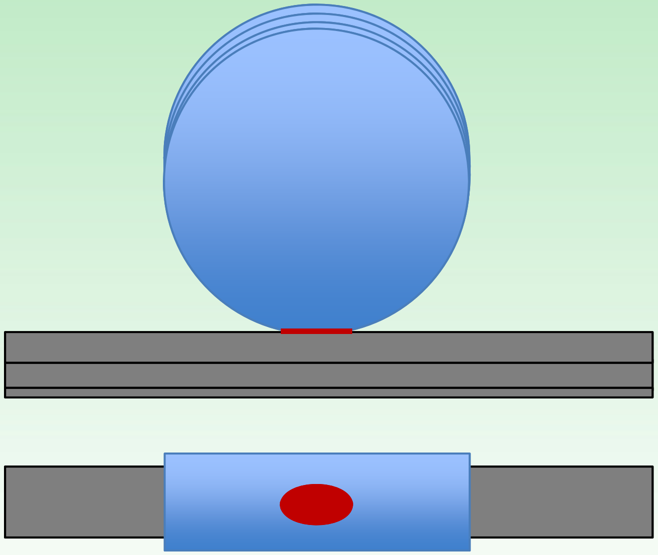
- Question #2: Given Force and Area, how do we calculate pressure?

- 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?

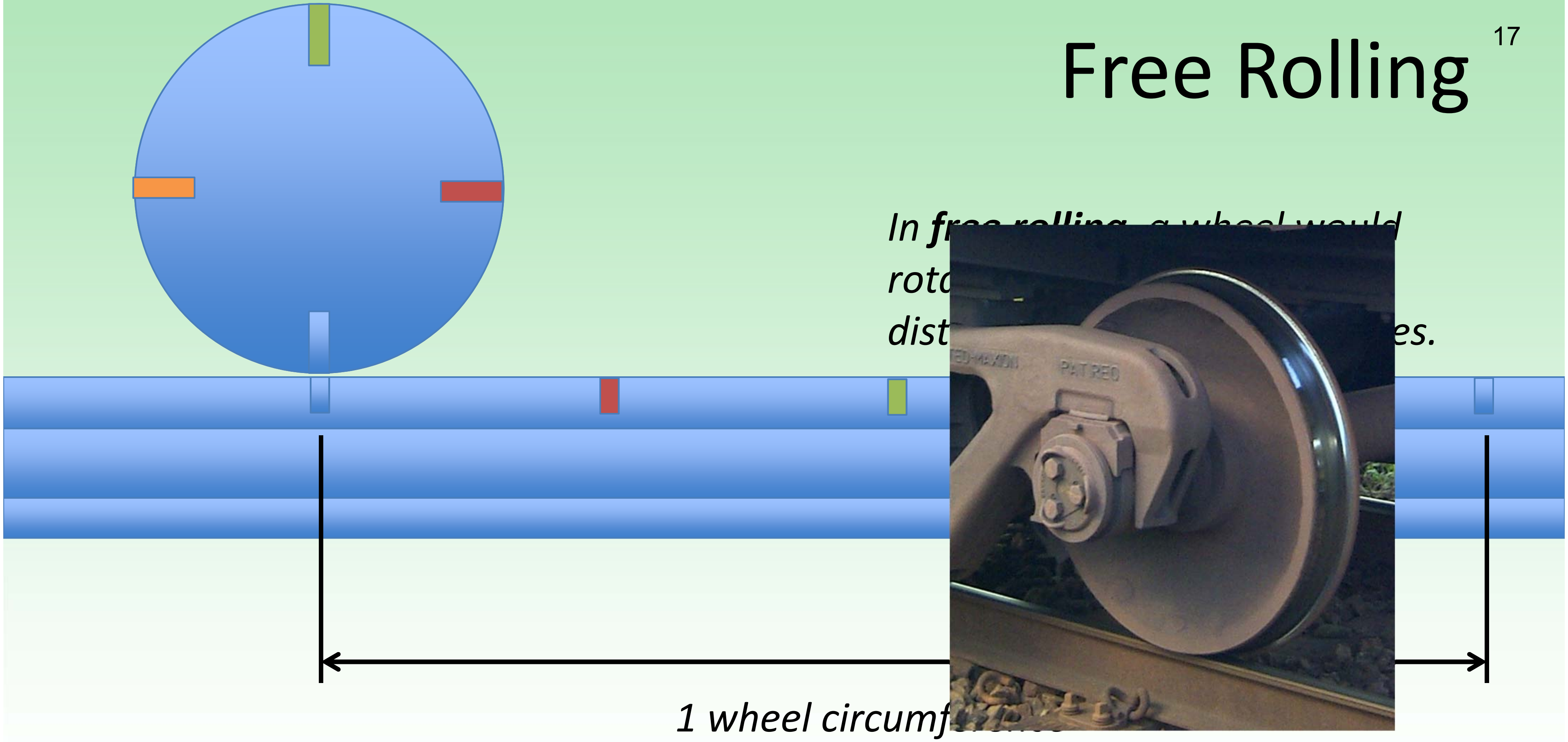
- Creepage at the wheel-rail interface is fundamentally related to all of the following (as examples):
  - Locomotive adhesion
  - Braking
  - Vehicle steering
  - Curving forces
  - Wheel and rail wear
  - Rolling contact fatigue
  - Thermal defects
  - Noise
  - Corrugations

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 Rolling



In free rolling, a wheel would

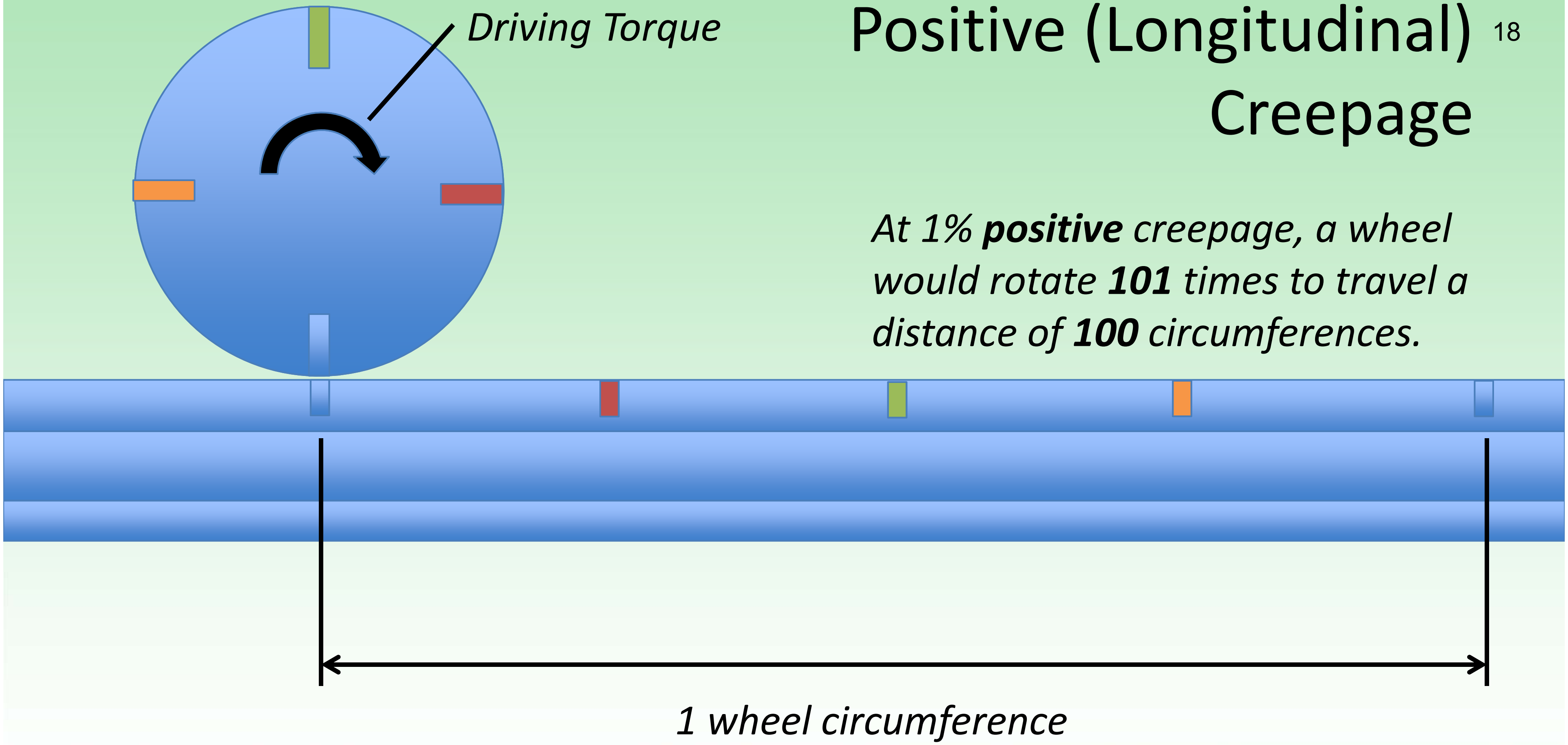
rot

dist

es.

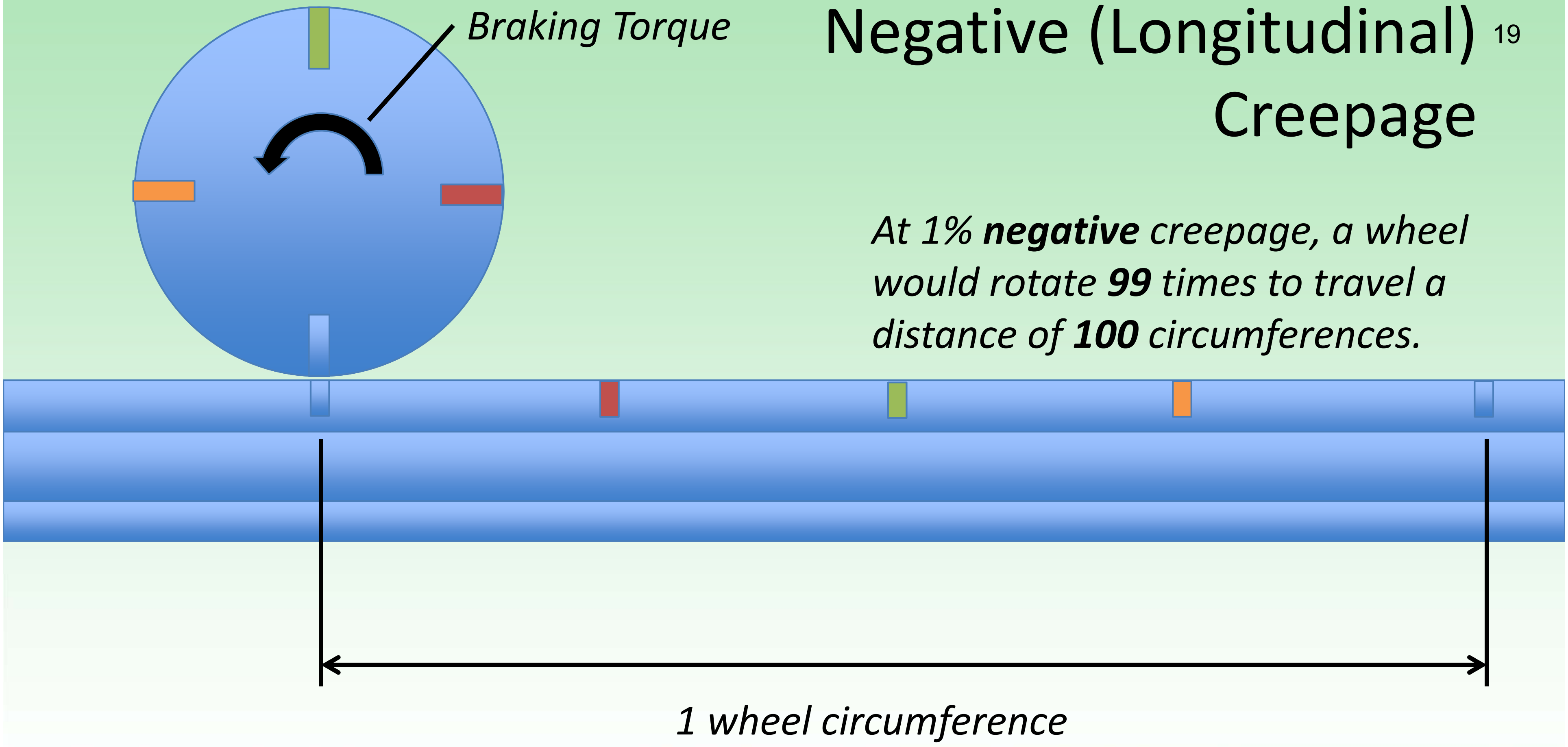
1 wheel circumference

Positive (Longitudinal) Creepage



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

Negative (Longitudinal) Creepage

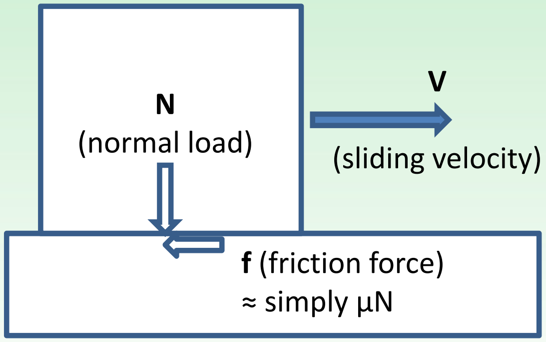


*At 1% **negative** creepage, a wheel would rotate **99** times to travel a distance of **100** circumferences.*

Rolling vs. Sliding Friction

They are not the same!

μ: coefficient of (sliding) friction



N
(normal load)

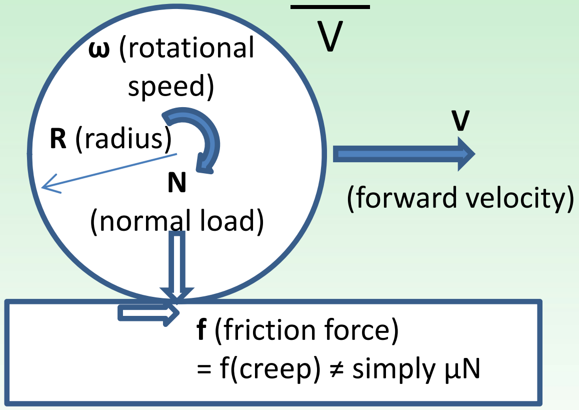
V
(sliding velocity)

f (friction force)
≈ simply μN

friction force shown as
acting on block for
positive sliding velocity

creep:

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



ω (rotational speed)

R (radius)

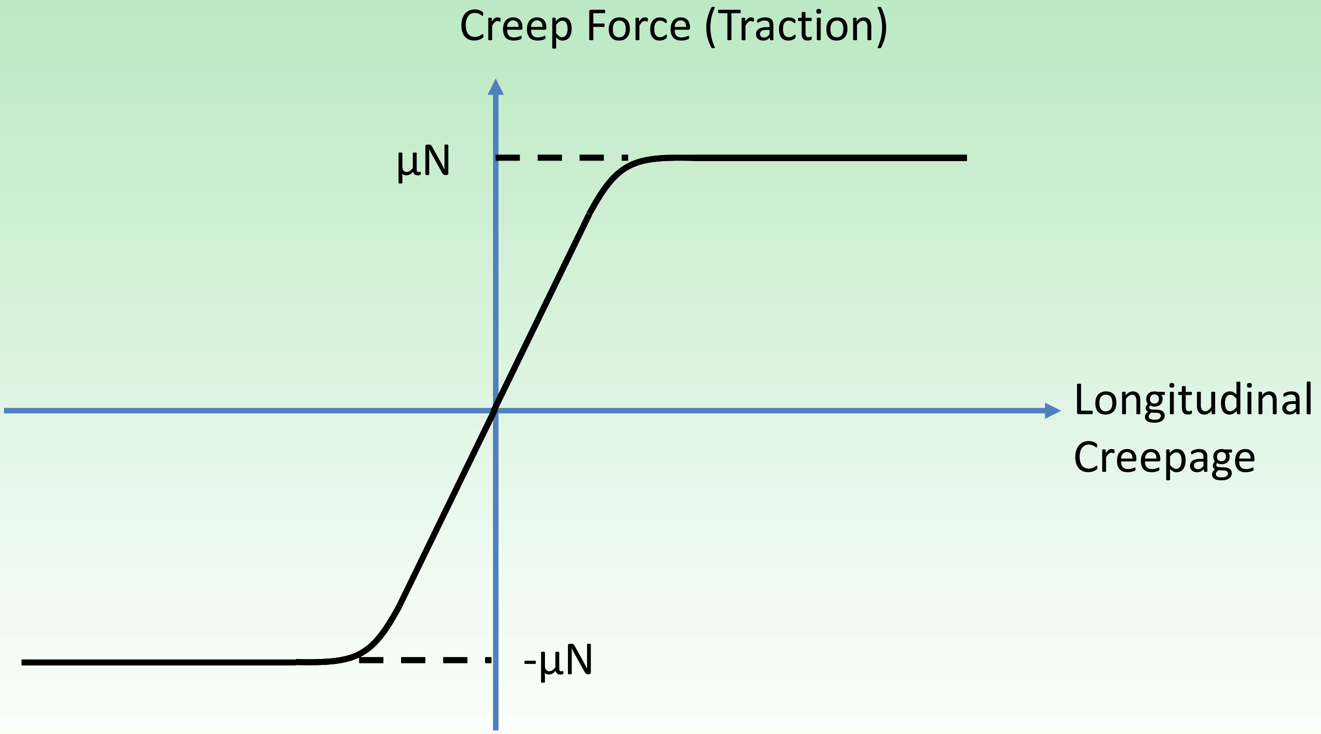
N
(normal load)

V
(forward velocity)

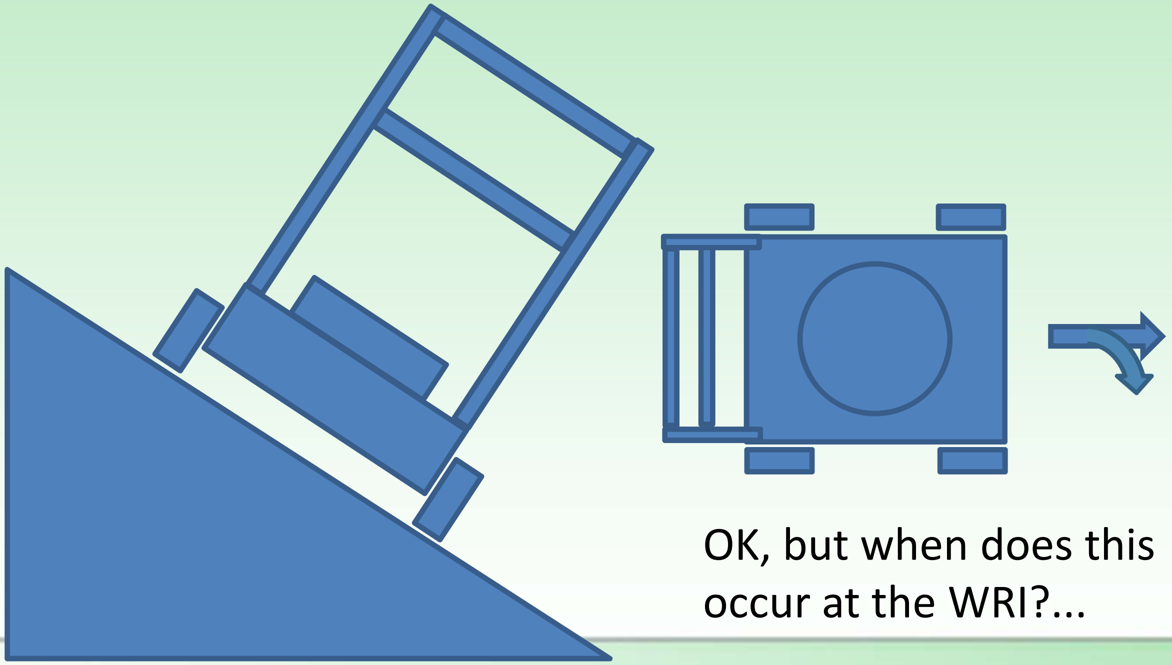
f (friction force)
= f(creep) ≠ simply μN

friction force shown as
acting on wheel for
positive creep

The Traction-Creepage Curve

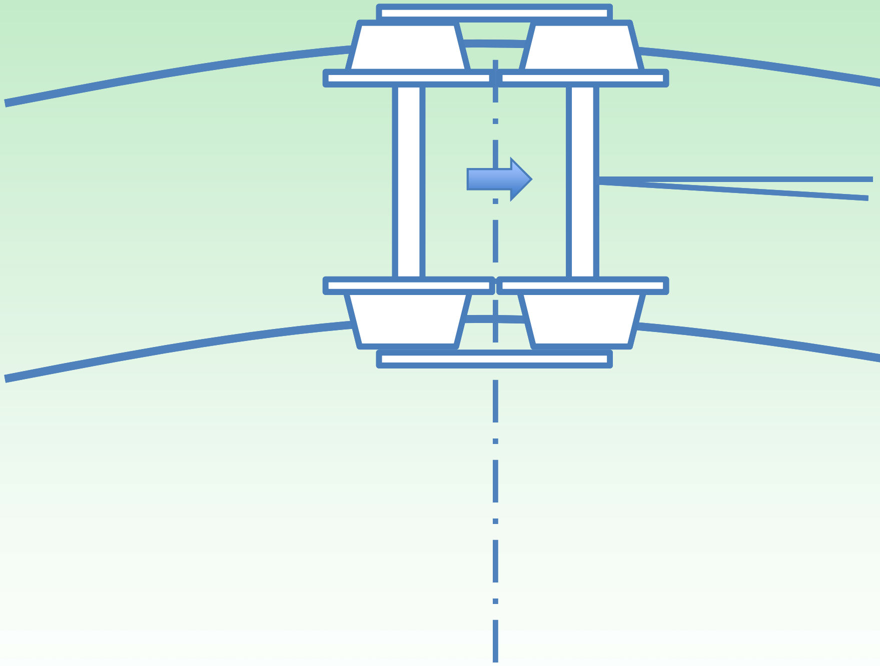


Lateral creepage
Imagine pushing a lawnmower across a steep slope…



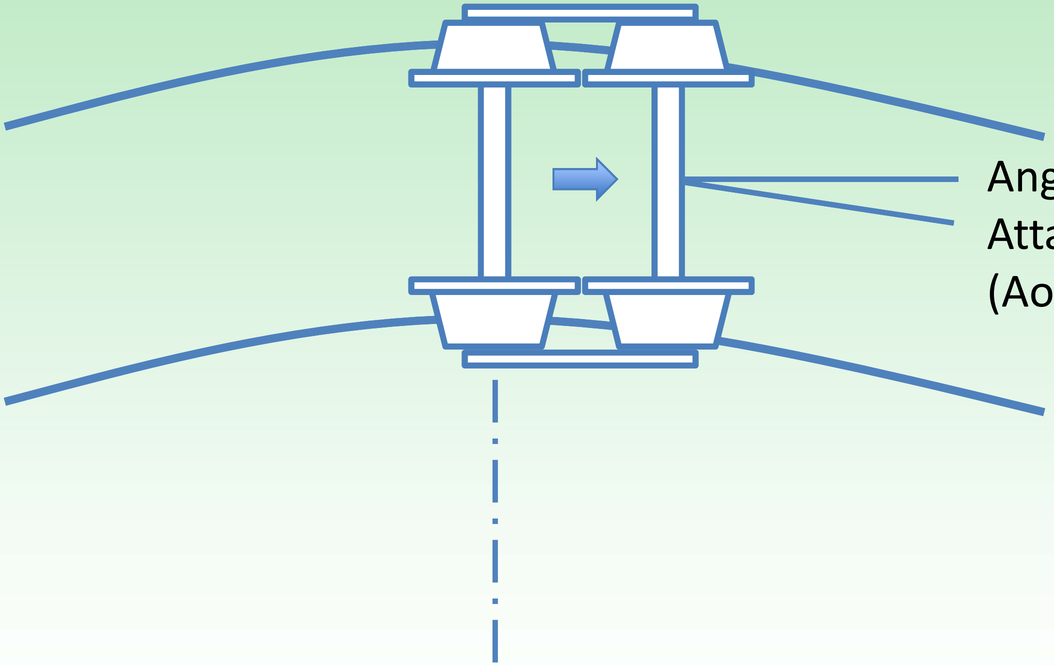
OK, but when does this occur at the WRI?...

Steering in "Steady State" Curving ("Mild" Curves)



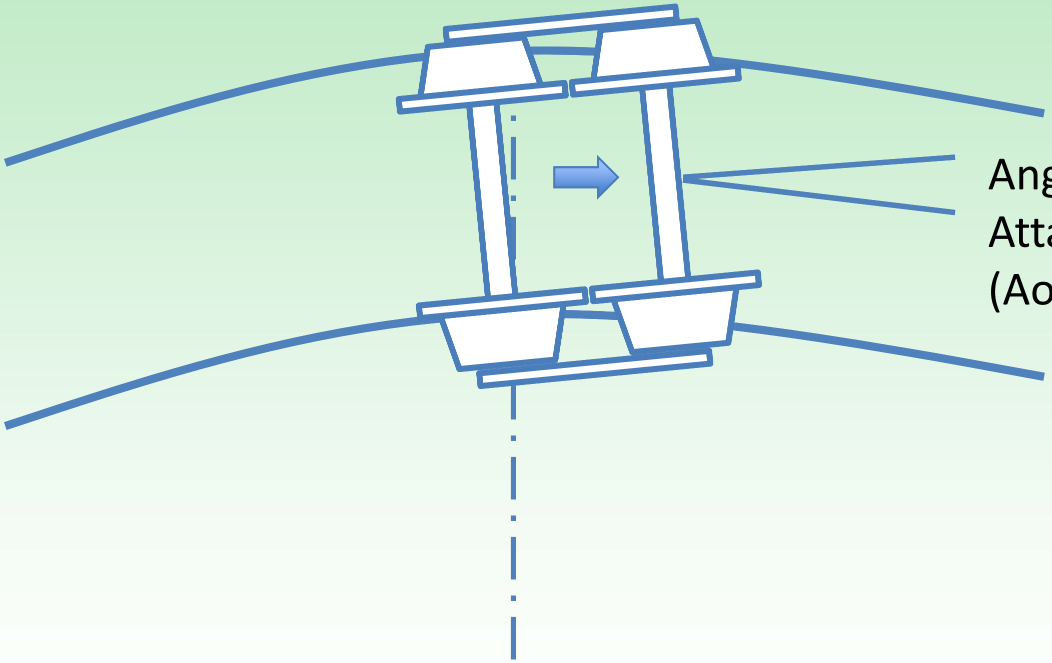
Angle of Attack (AoA)

Steering in "Steady State" Curving ("Sharp" Curves)



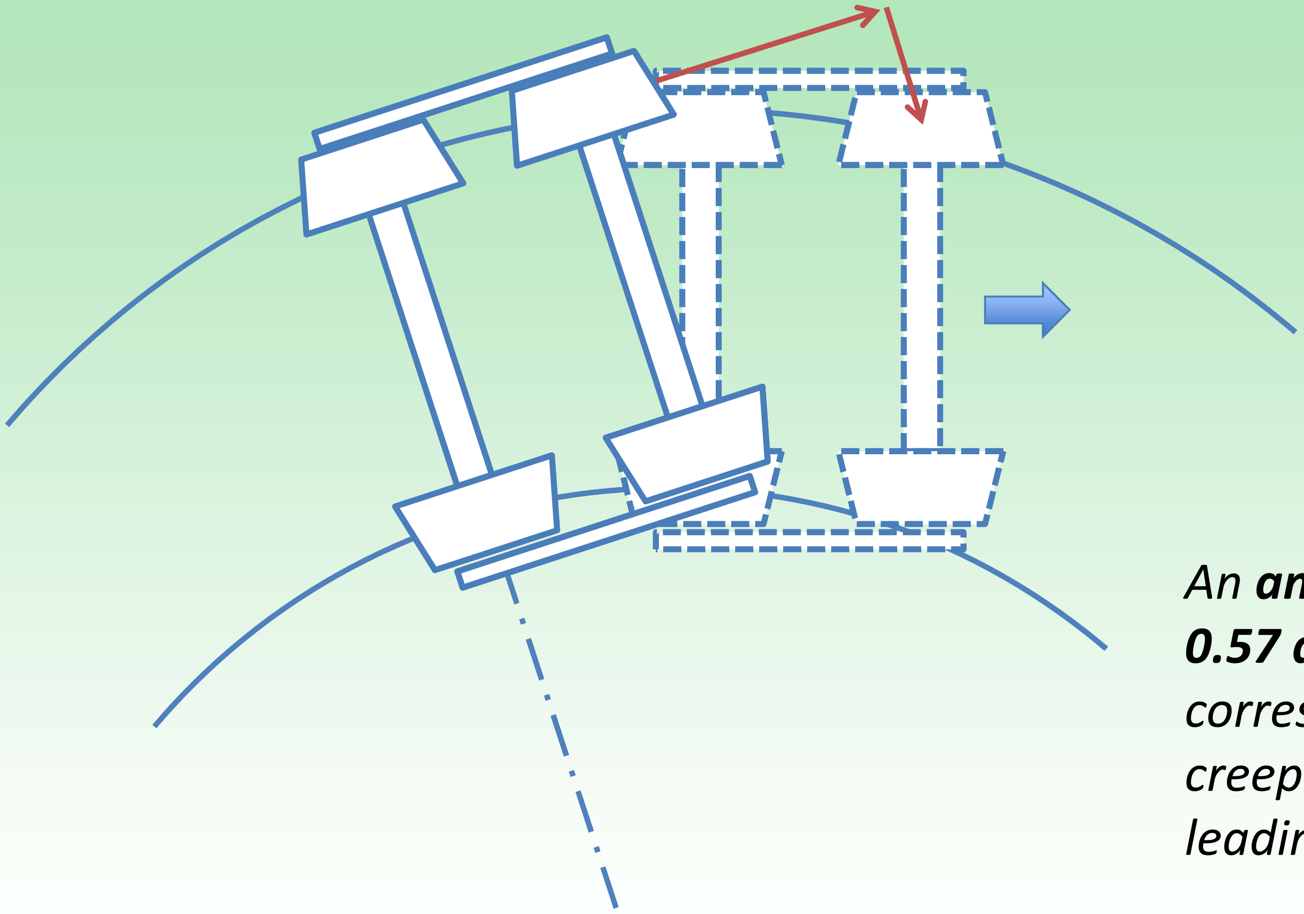
Angle of Attack (AoA)

Steering in "Steady State" Curving ("Very Sharp" Curves)



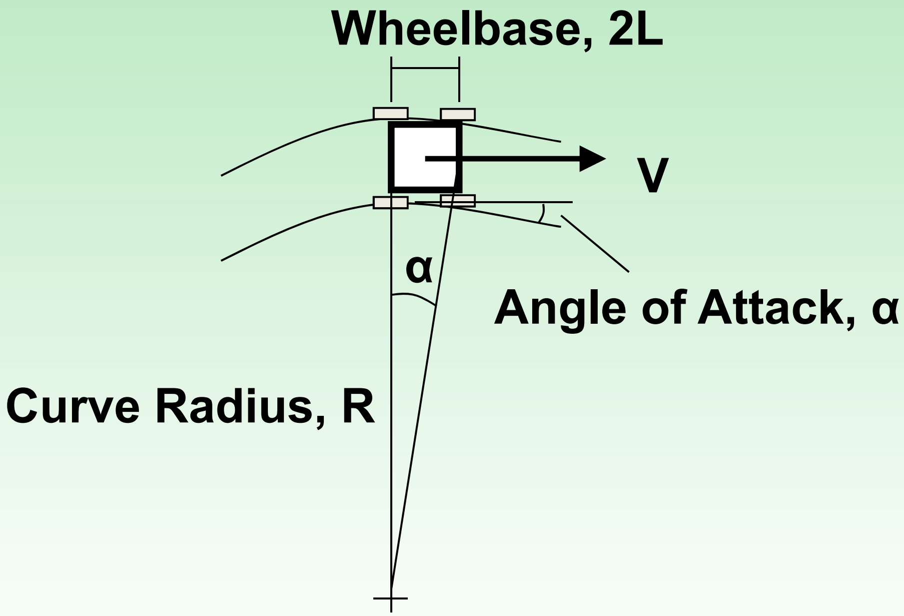
Angle of Attack (AoA)

Lateral Creepage



*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 ($2L = 5.83'$)

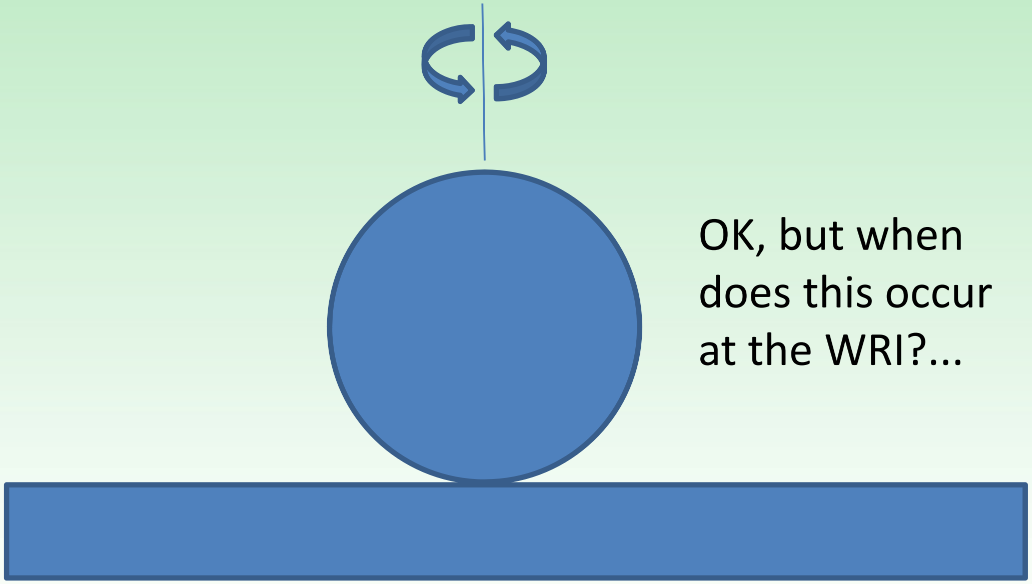
LEADING AXLE ANGLE OF ATTACK:

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

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

Spin Creepage

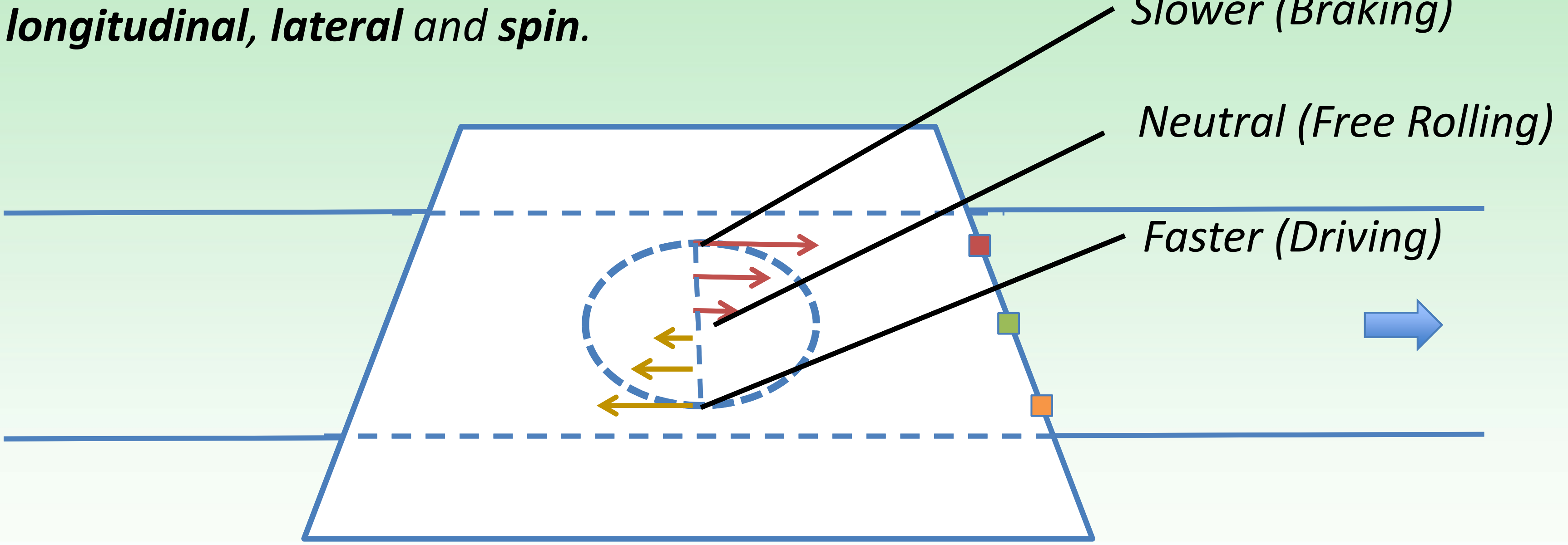
Think of spinning a coin on a tabletop….



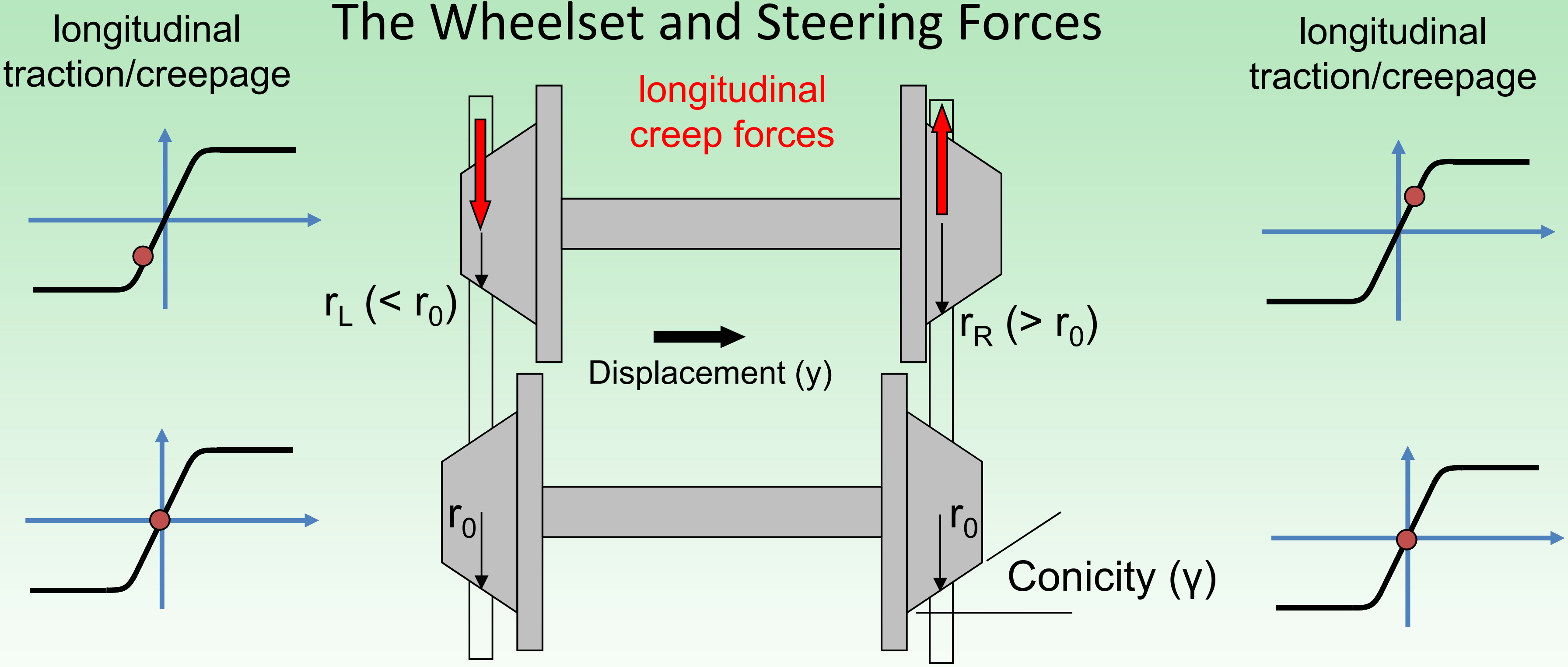
OK, but when does this occur at the WRI?...

Spin Creepage

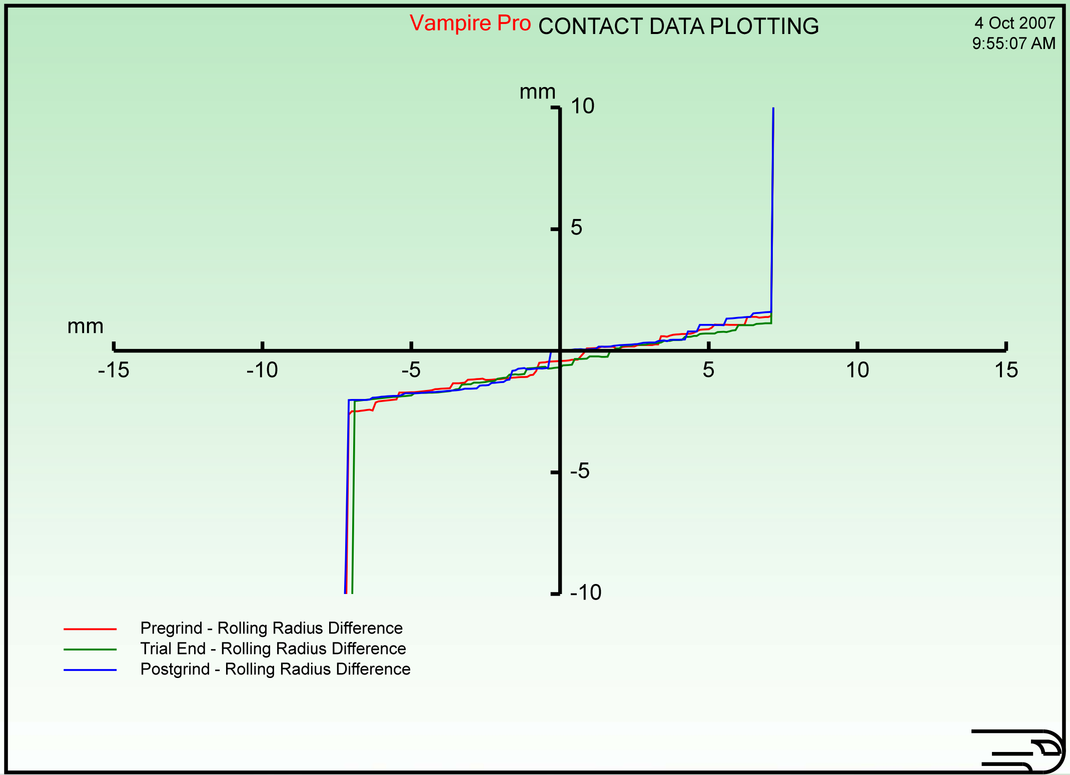
*The **net creepage** vector at the wheel/rail interface is (in general) a combination of **longitudinal**, **lateral** and **spin**.*



The Wheelset and Steering Forces

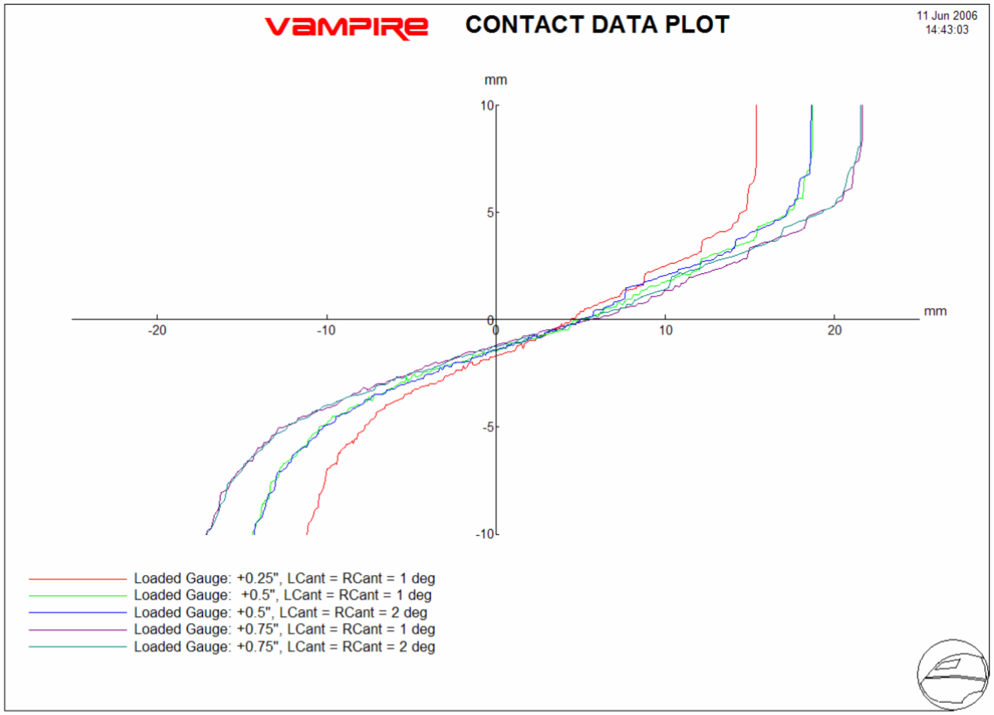


Effective Conicity



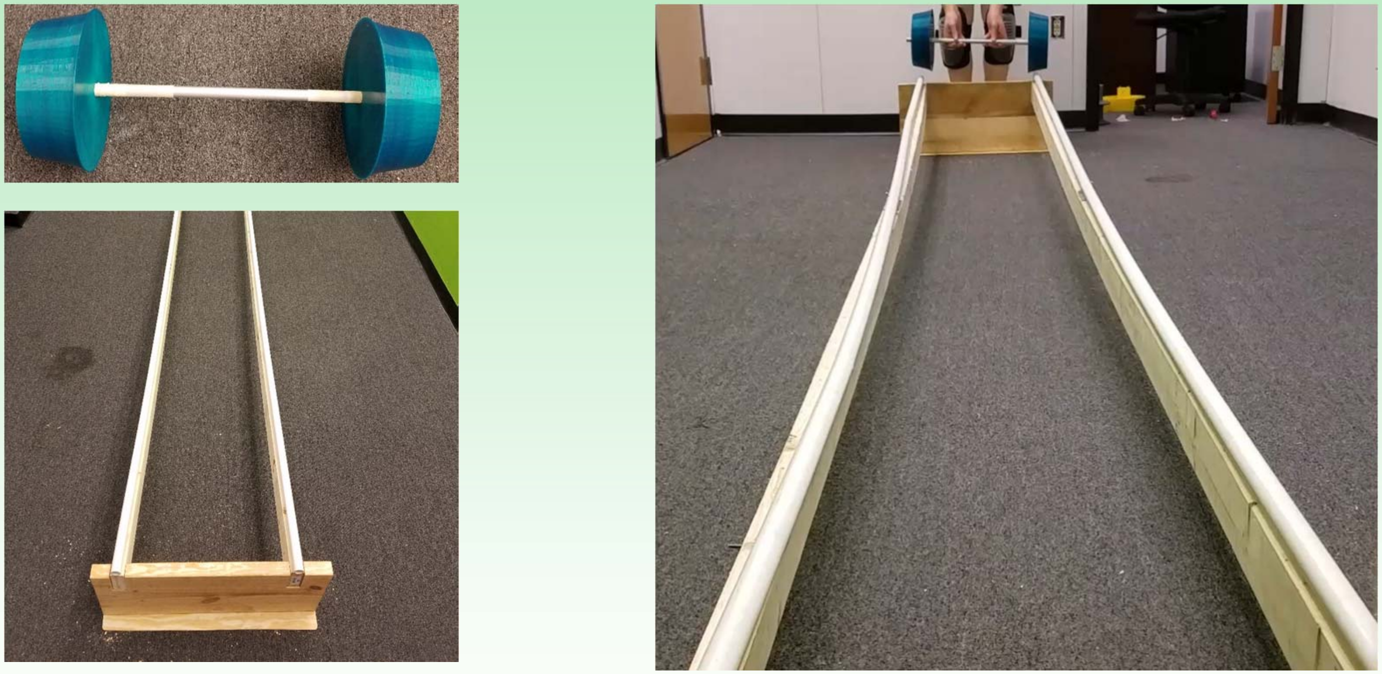
Rolling Radius Difference

Effective Conicity (Worn Wheels)



VAMPIRE Plot

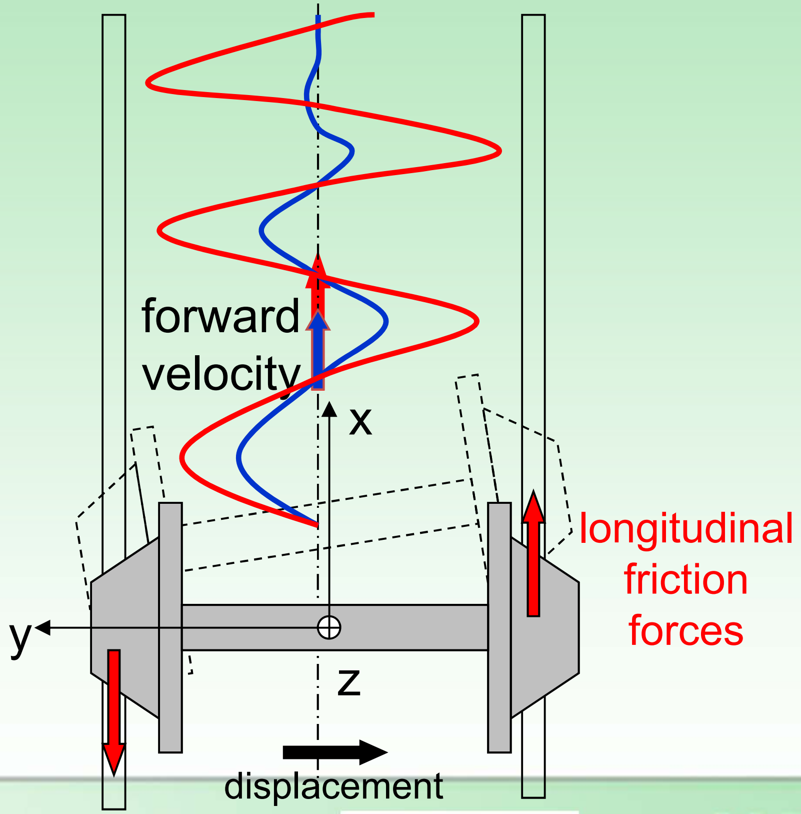
Demonstration*: Steering forces in tangent track



* 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.

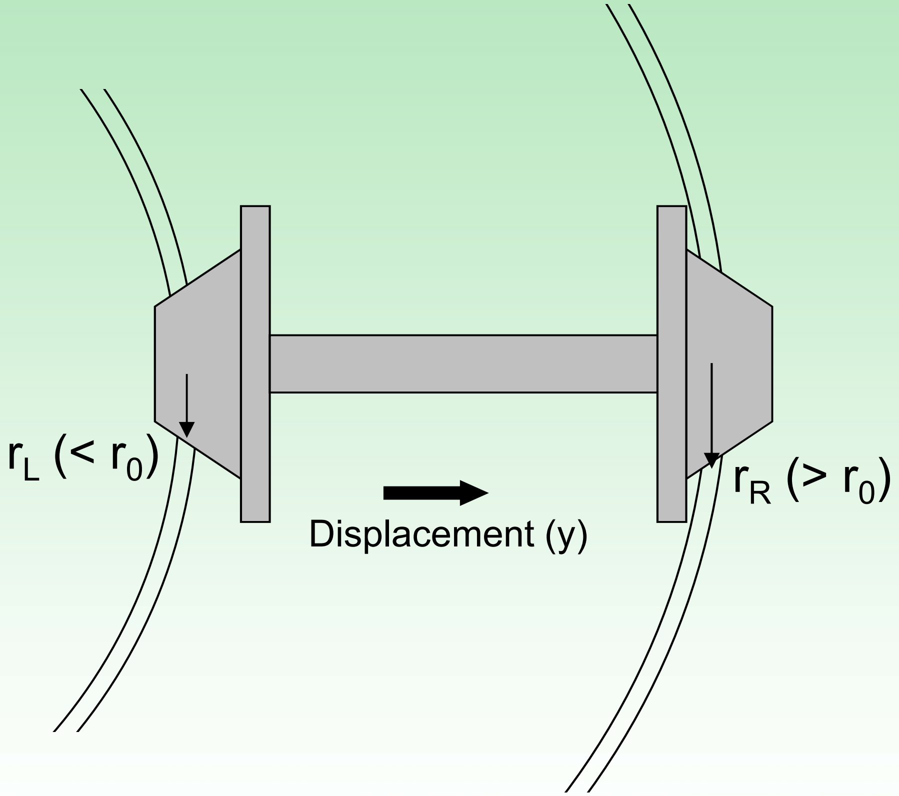


Questions & Discussion

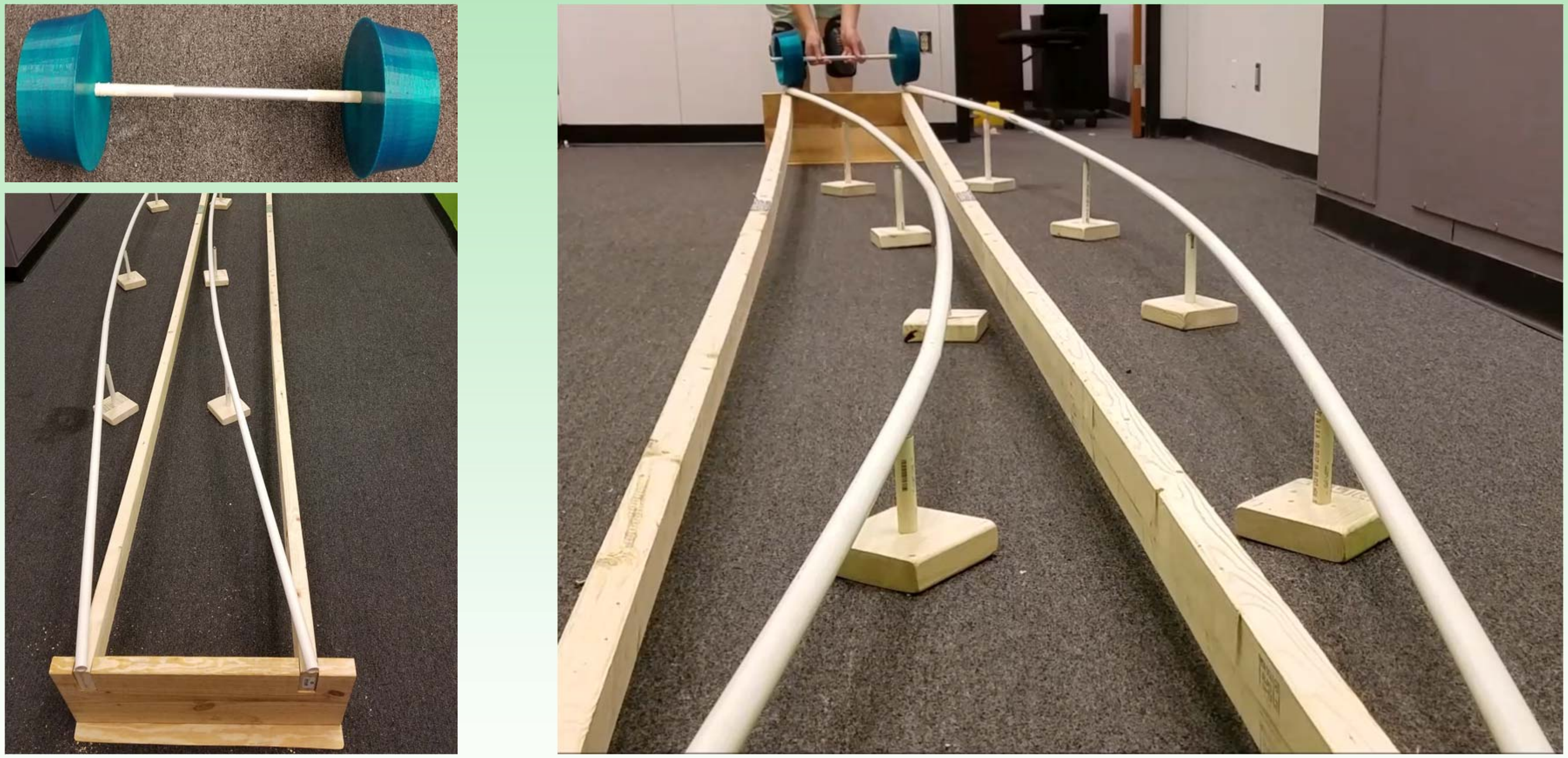
Part 2

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

Curving and Theoretical Equilibrium



Demonstration*: Steering forces in curved track

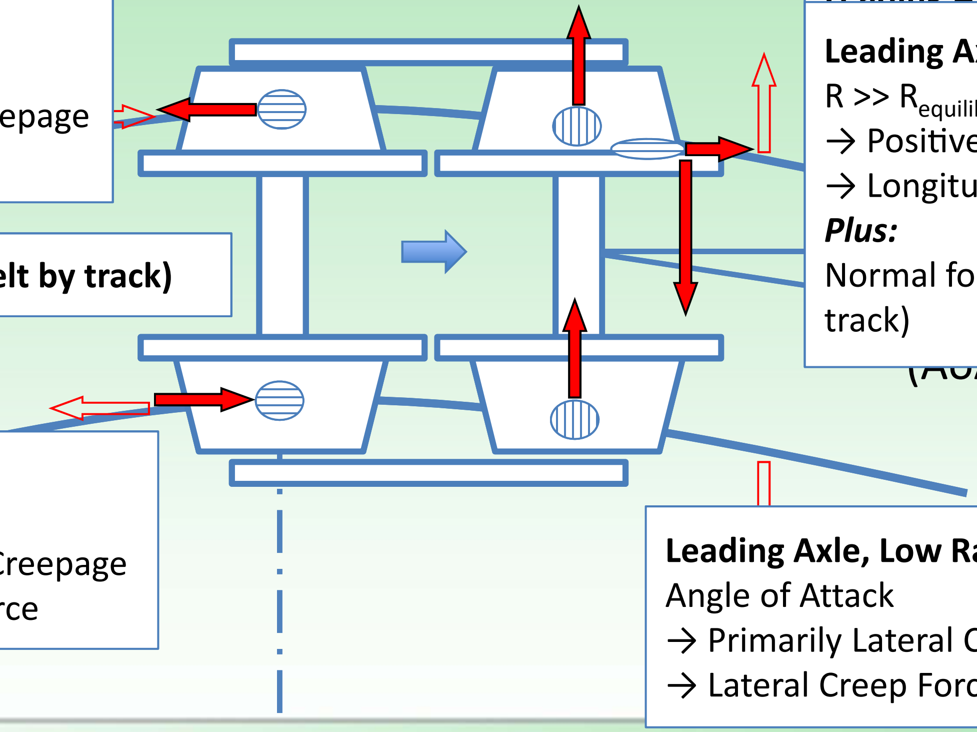


* Wheel / rail demonstration rig, images and videos prepared by **Josh Rychtarczyk**

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:
$R < R_{equilibrium}$
→ Negative Longitudinal Creepage
→ Longitudinal Creep Force

Reaction Forces (felt by track)

Leading Axle, High Rail (Tread):

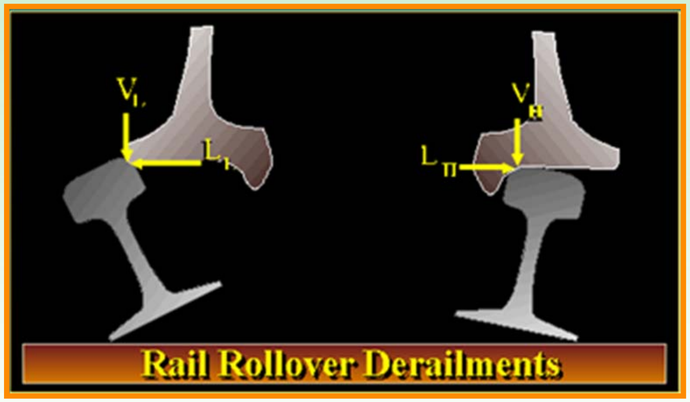
Leading Axle, High Rail (Flange):
$R >> R_{equilibrium}$
→ Positive Longitudinal Creepage
→ Longitudinal Creep Force
Plus:
Normal force (keeps vehicle on track)

(AOA)

Trailing Axle, Low Rail:
$R > R_{equilibrium}$
→ Positive Longitudinal Creepage
→ Longitudinal Creep Force

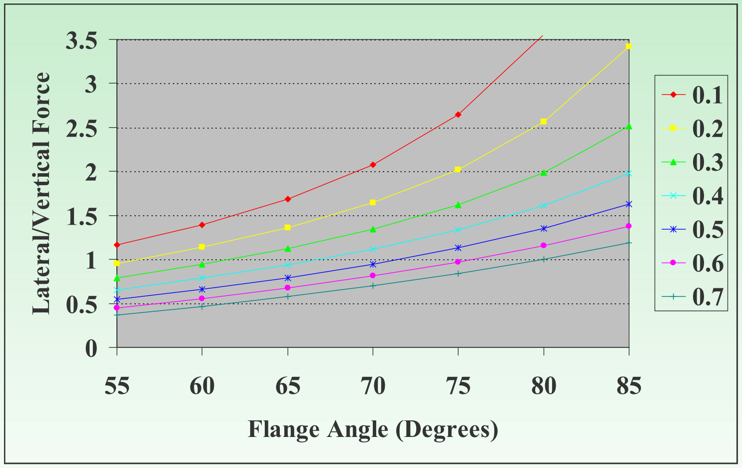
Leading Axle, Low Rail:
Angle of Attack
→ Primarily Lateral Creepage
→ Lateral Creep Force

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



Impacts of High Lateral Loads:
Plate Cutting, Gauge Widening

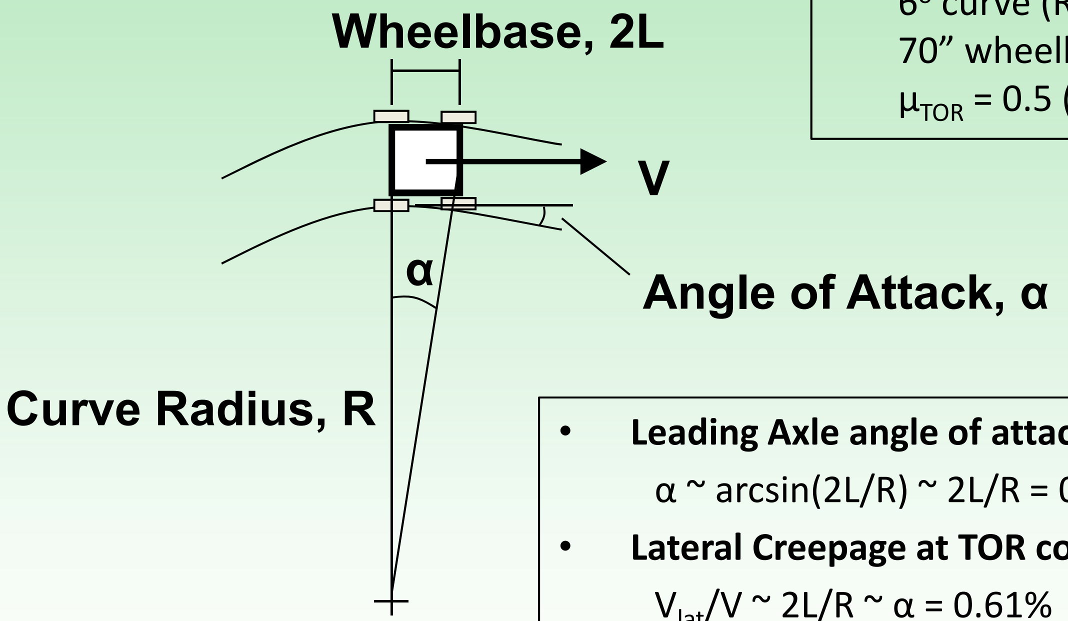
Impacts of High Lateral Loads:
Wheel Climb Derailments



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

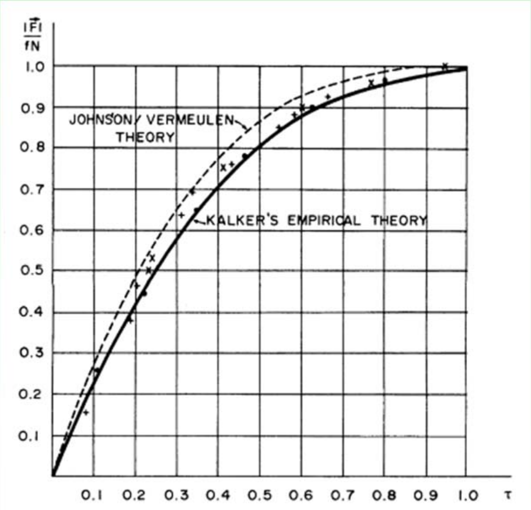


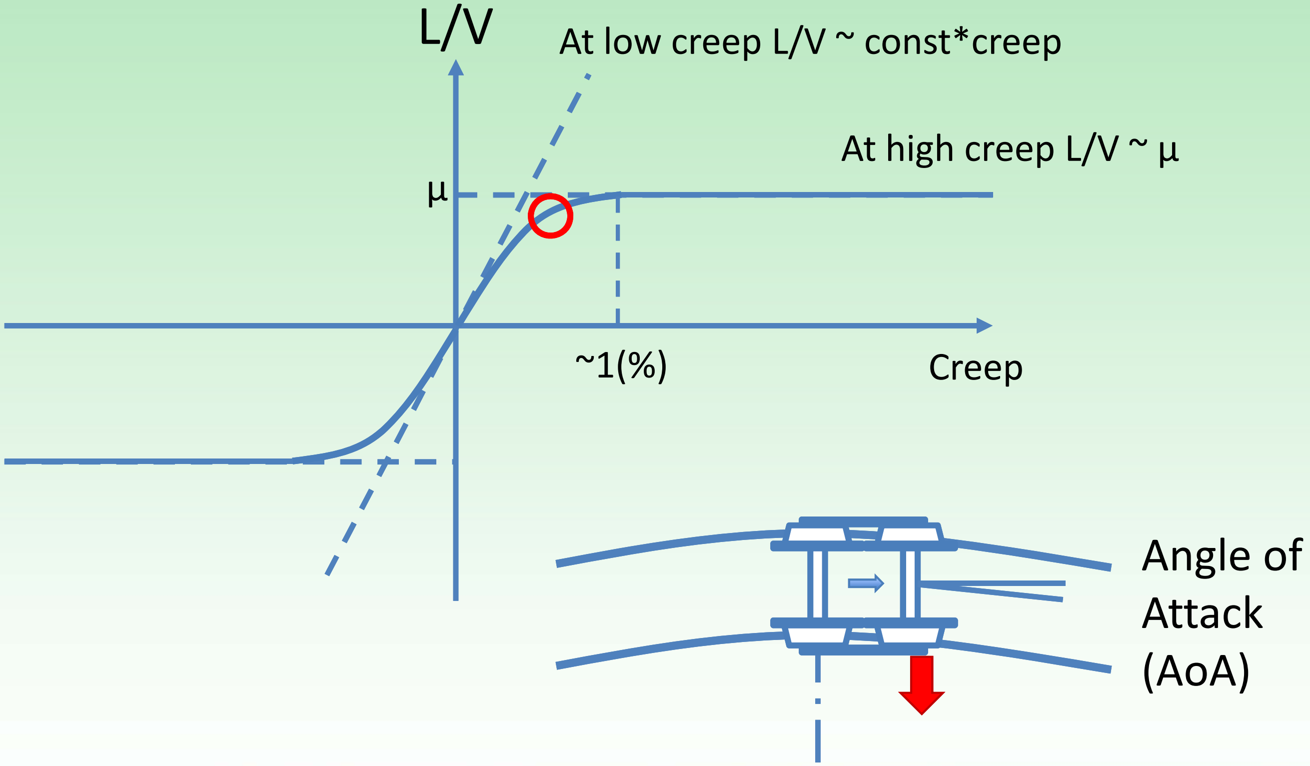
- Example:
  6° curve (R = 955')
  70" wheelbase (2L = 5.83')
  μ_{TOR} = 0.5 (dry)

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

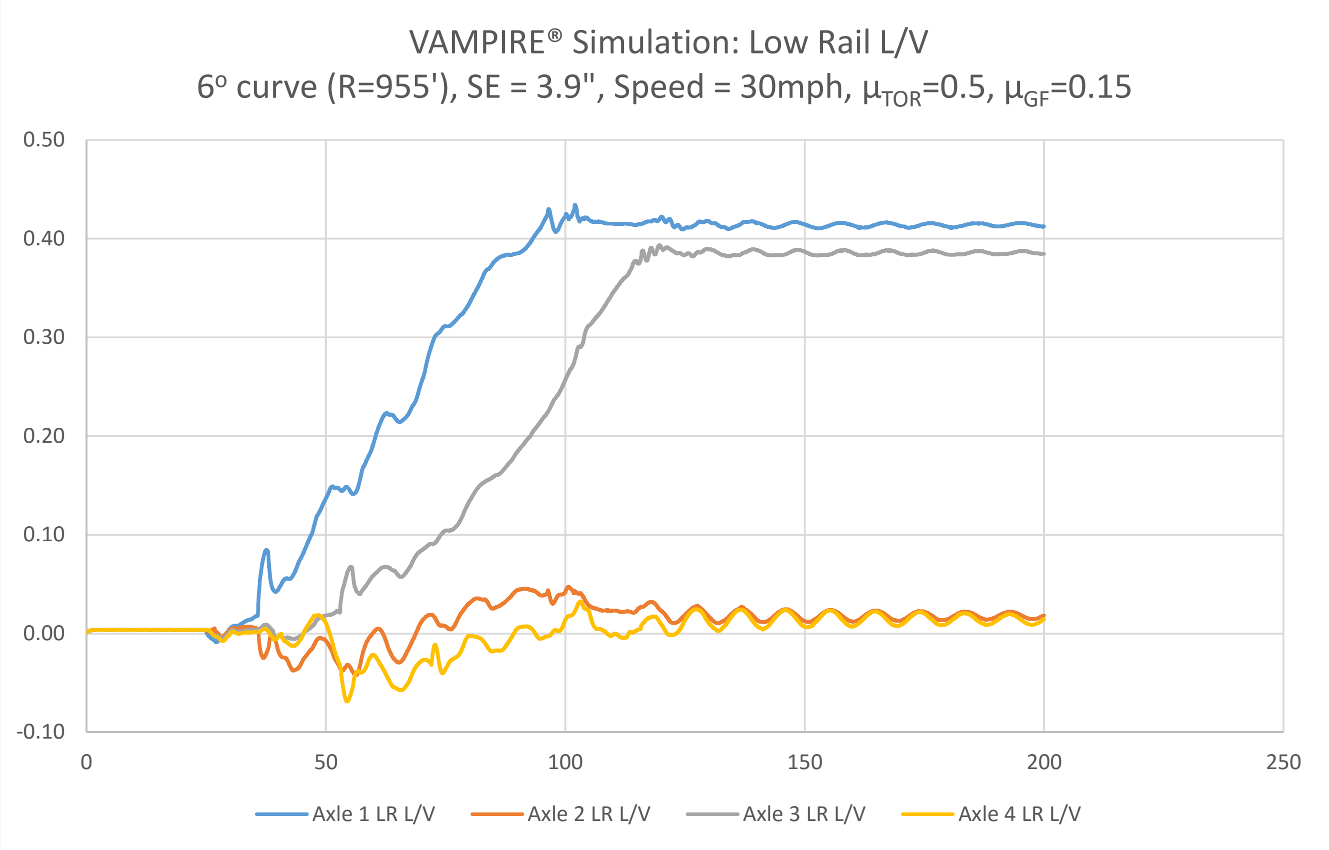
Estimating Low Rail L/V and Lateral Force

- At 0.61% creep:
  L/V = _______ μ



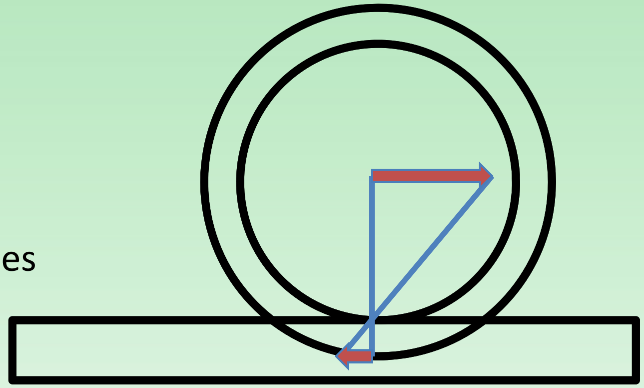


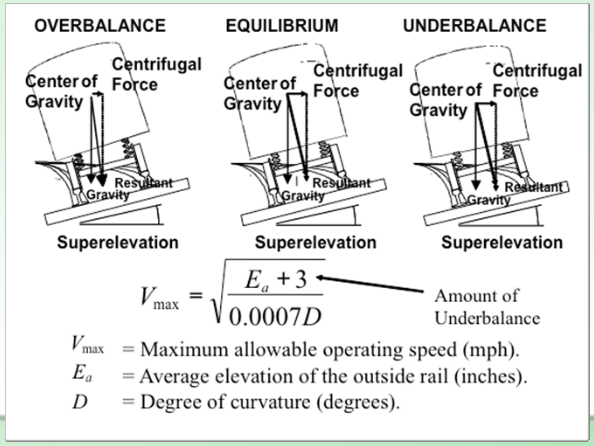
How does this compare with simulation results?



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





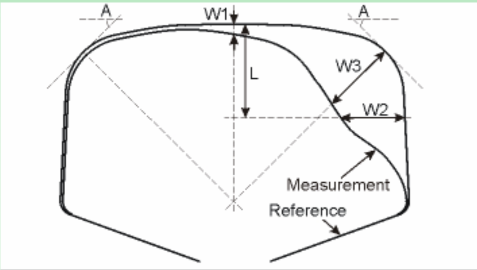
$$V_{\max} = \sqrt{\frac{E_a + 3}{0.0007D}}$$

$V_{\max}$ = Maximum allowable operating speed (mph).
E_a = 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

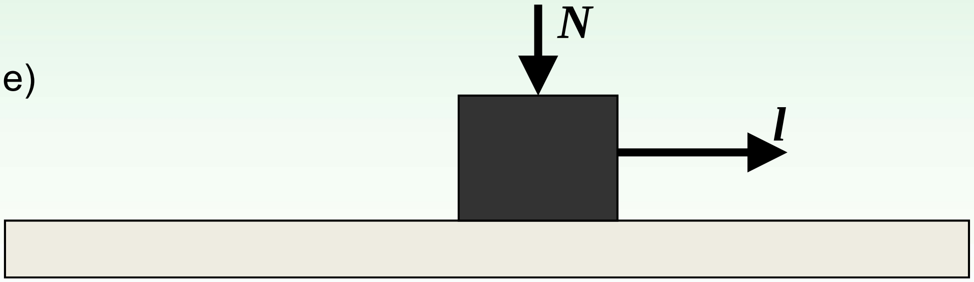


- “Archard” Wear Law:

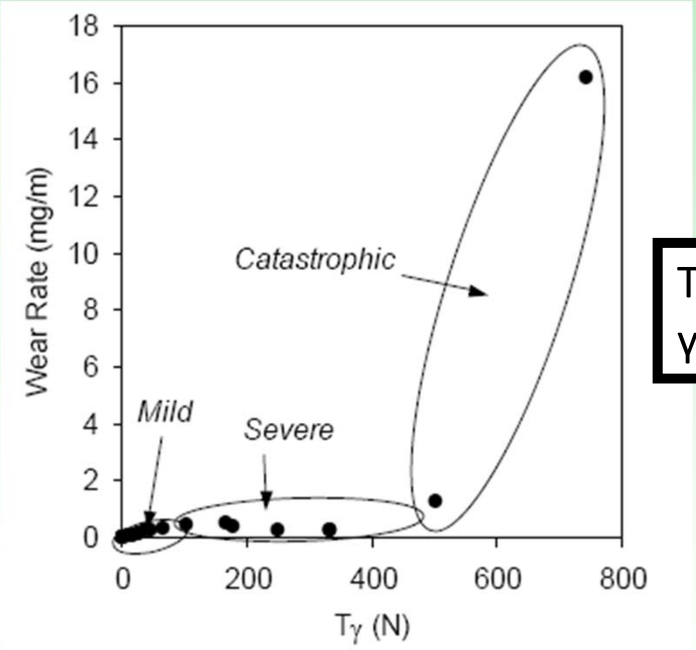
$$V = \boxed{c}\frac{Nl}{H}$$

c proportional to COF

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



Wear regimes

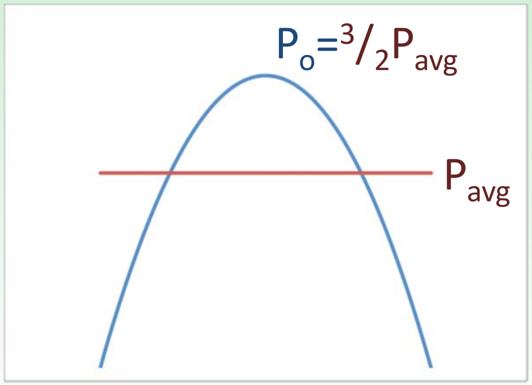


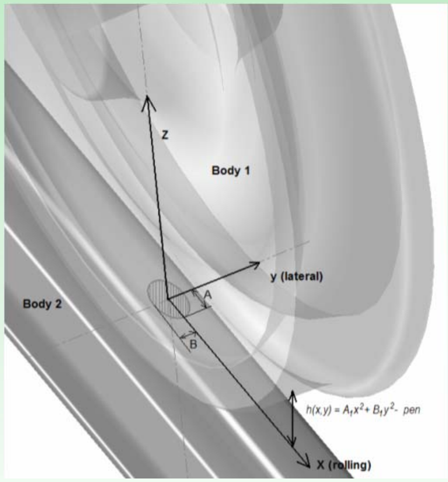
T = Tractive force
γ = Slip

Shakedown and Rolling Contact Fatigue (RCF)

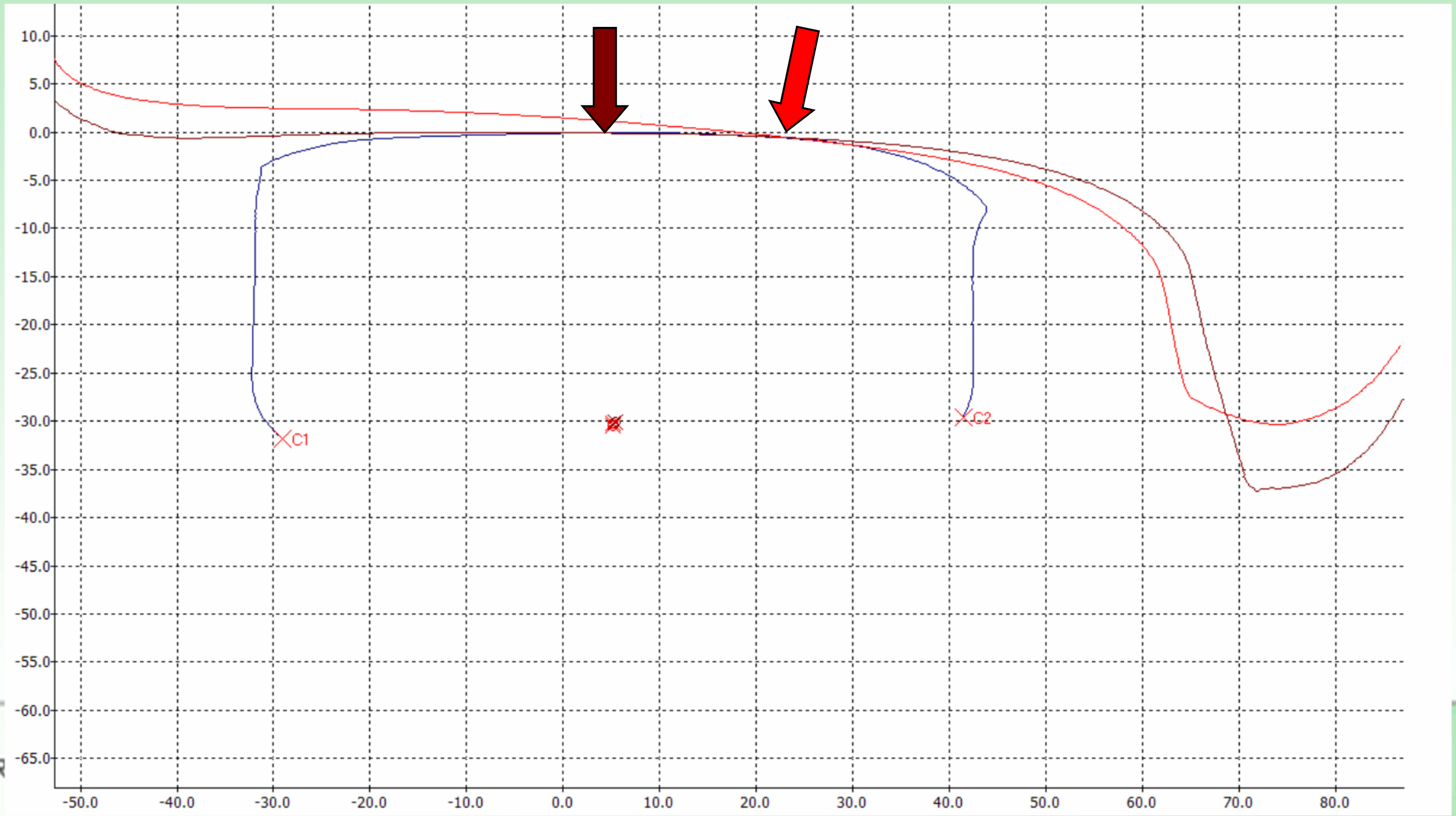
Recall: Hertzian Contact

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

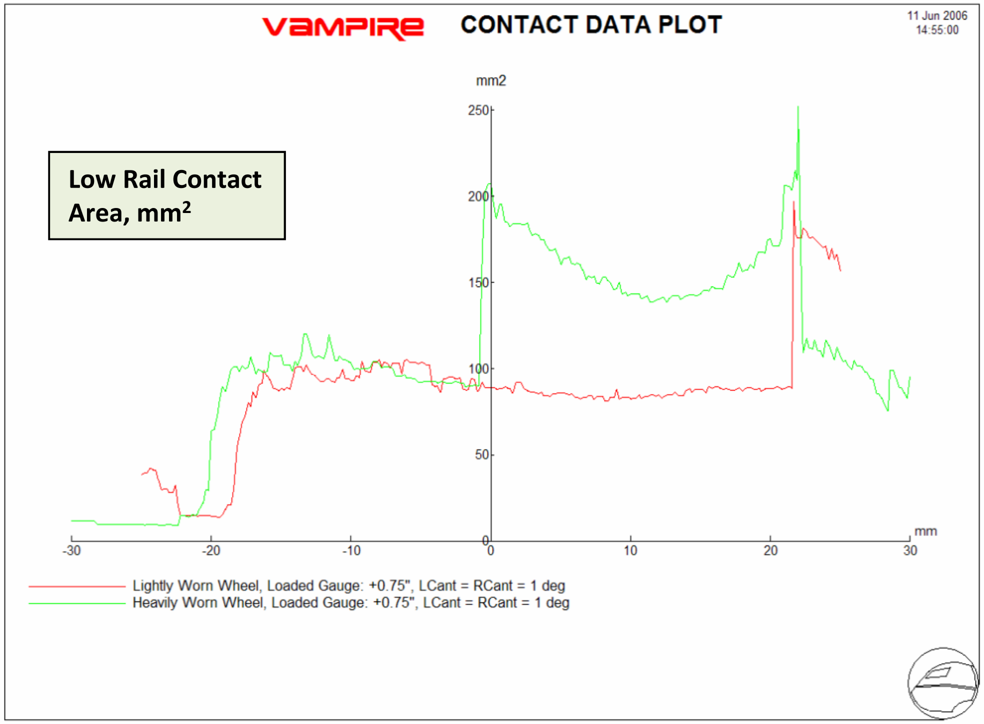




The Contact Patch and Contact Pressures



The Contact Patch and Contact Pressures



VAMPIRE Plot

Example calculation: Average and Peak Pressure

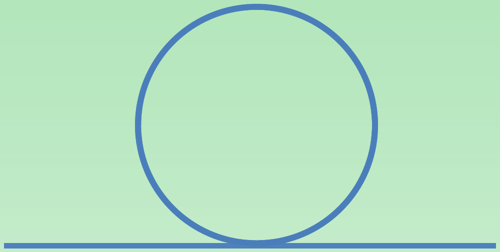
- Let’s assume a circular contact patch, with a radius of **0.28” (7 mm)**
- The contact area is then: **0.24 in^2 (154 mm^2)**
- Assuming a HAL vehicle weight (gross) of 286,000 lbs, we have a nominal wheel load of 35,750 lbs, i.e. **35.75 kips (159 kN)**
- The resulting average contact pressure (Pavg) 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?

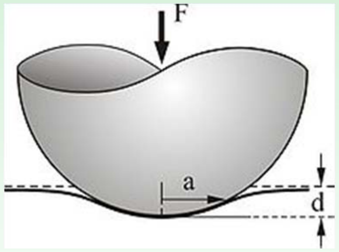
Steel	Hardness (Brinnell)	K	
		ksi	MPa
“Standard”	260-280	65-70	448-483
“Intermediate”	320-340	80-85	552-587
“Premium”	340-380	85-95	587-656
“HE Premium”	380-400	95-100	656-691

**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*

Tensile Testing (1-D loading)



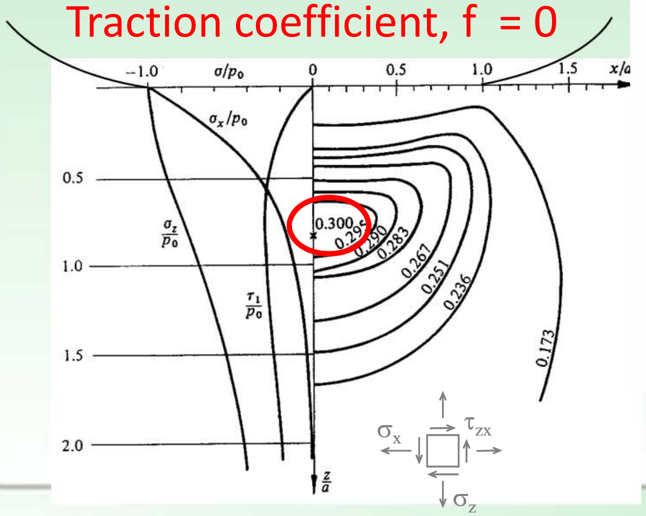
Cylindrical Contact with Elastic Half-Space (2-D loading)



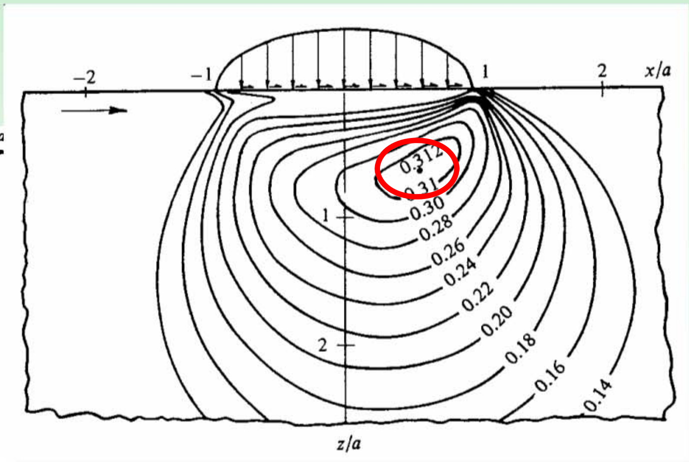
Spherical Contact with Elastic Half-Space (3-D loading)

RCF Development:
Contact Pressures, Tractions and Stresses

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



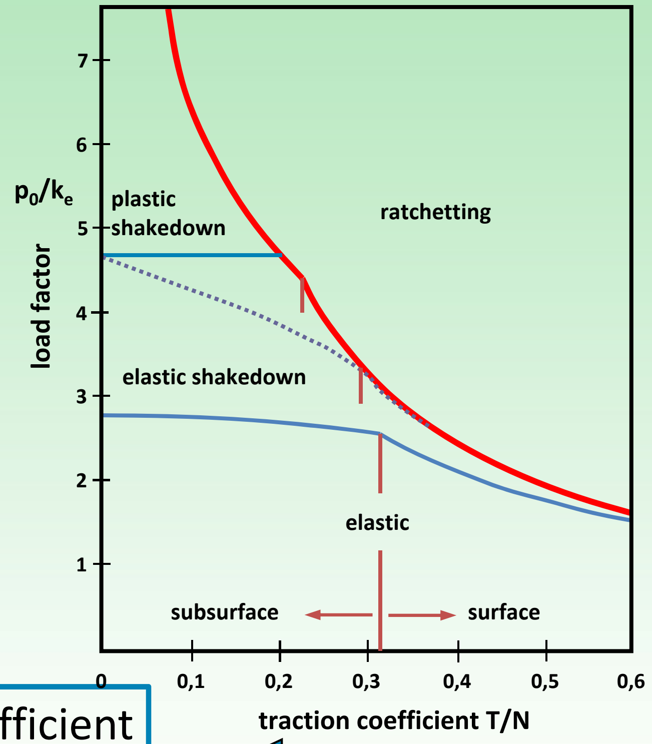
Traction coefficient, f = 0



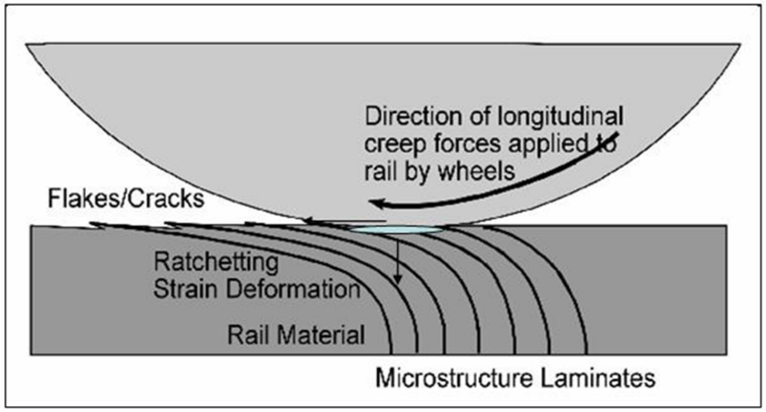
Traction coefficient, f = 0.2

RCF Development: Shakedown

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

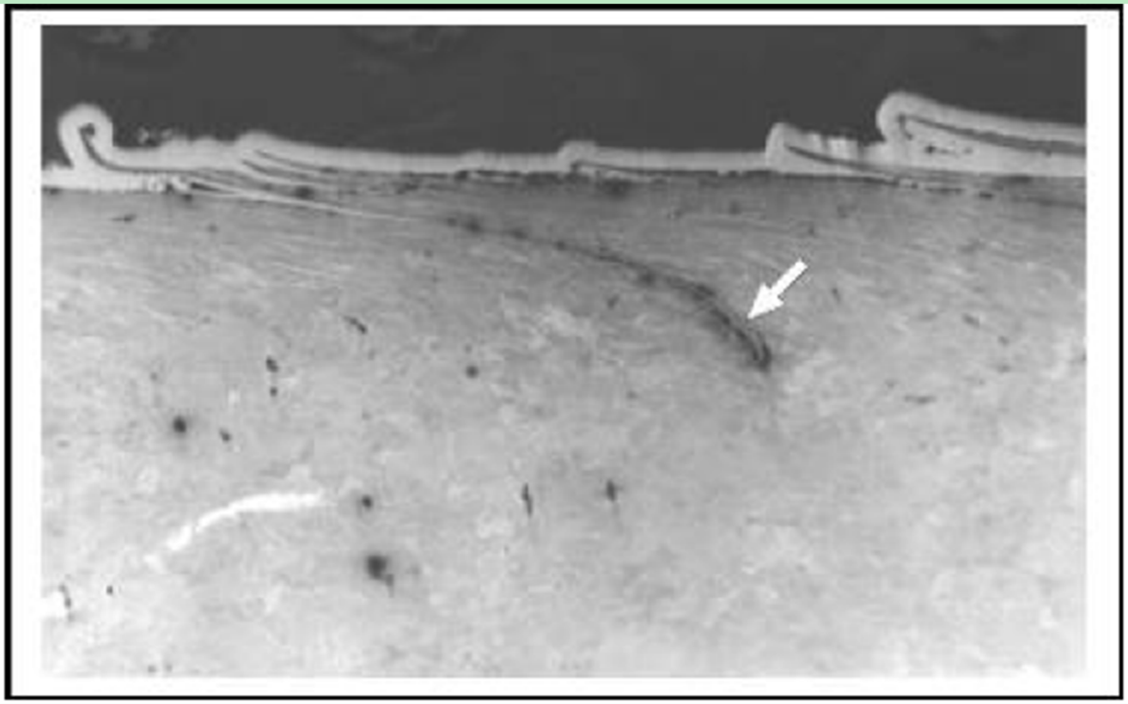


Reduced Traction Coefficient
(e.g. reduced friction)

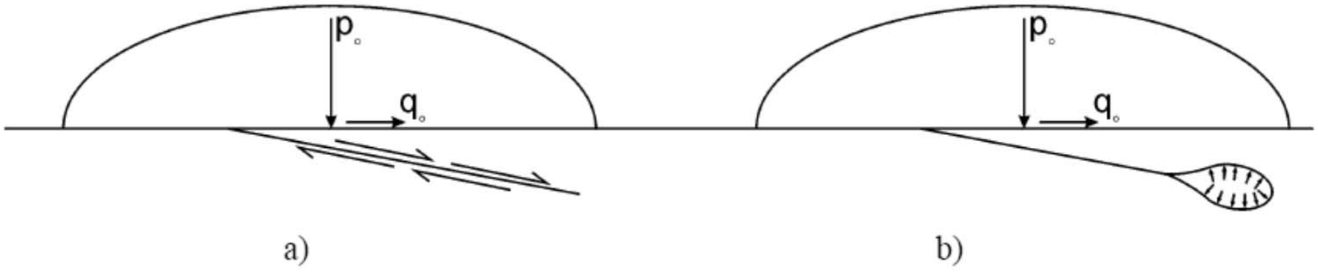

Direction of longitudinal creep forces applied to rail by wheels
Flakes/Cracks
Ratchetting Strain Deformation
Rail Material
Microstructure Laminates

Wheel Tread


←MLN1 ON 13m 25½ch High rail
High Rail



Hydropressurization: effect of liquids on crack growth



a) b)

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 **μ = 0.6**
- How would you assess the risk of **low rail** RCF formation and growth under these conditions?

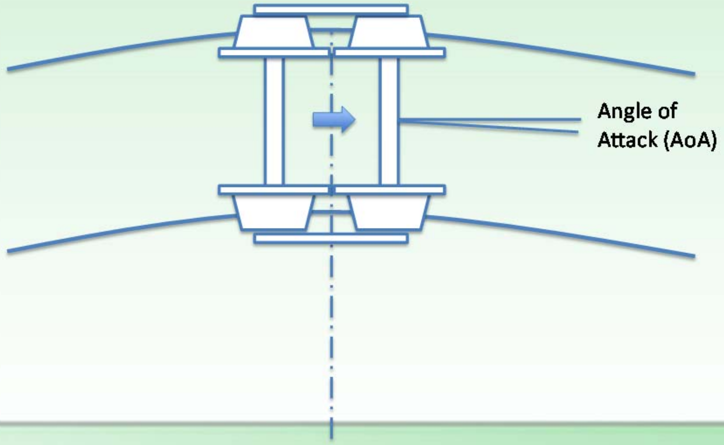
Estimating lateral creepage, traction ratio & contact pressure:

- **In "mild" curving, leading axle angle of attack:**

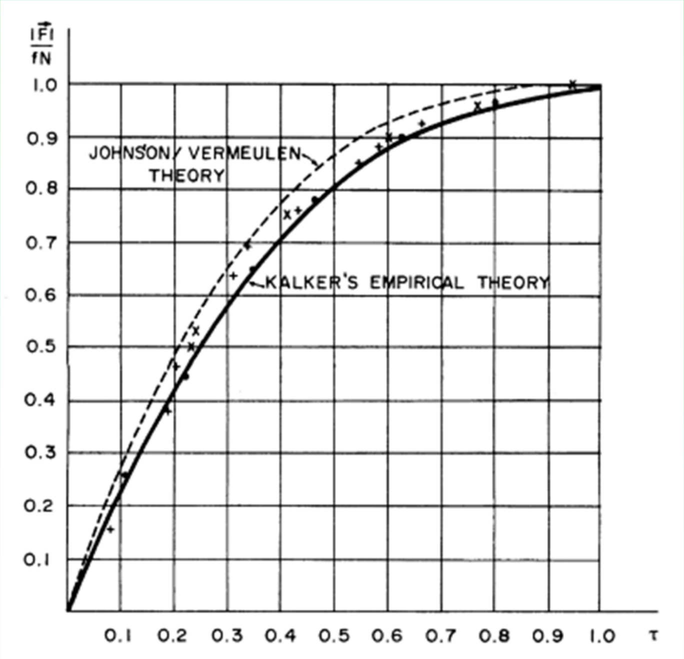
  $\alpha \sim \arcsin(L/R) \sim L/R = 0.0030$ Rad (3.0 mRad)

- **Lateral Creepage at low rail TOR contact:**

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



Estimating the traction ratio (L/V)

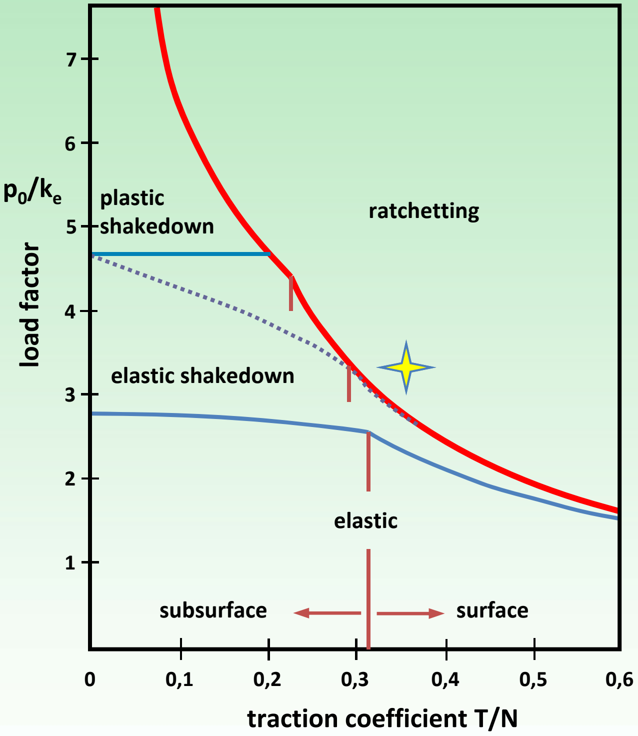


- At 0.3% creep:
  T/N ~ 0.6 µ
- With µ = 0.6
  Traction Ratio (T/N) ~ 0.36

**Note, we have neglected longitudinal and spin creep…*

Where are we on the shakedown map?

- From the previous slide
  T/N ~0.36
- We previously calculated
  Po = 225 ksi
- With K = 70ksi,
  Po/K = 3.21

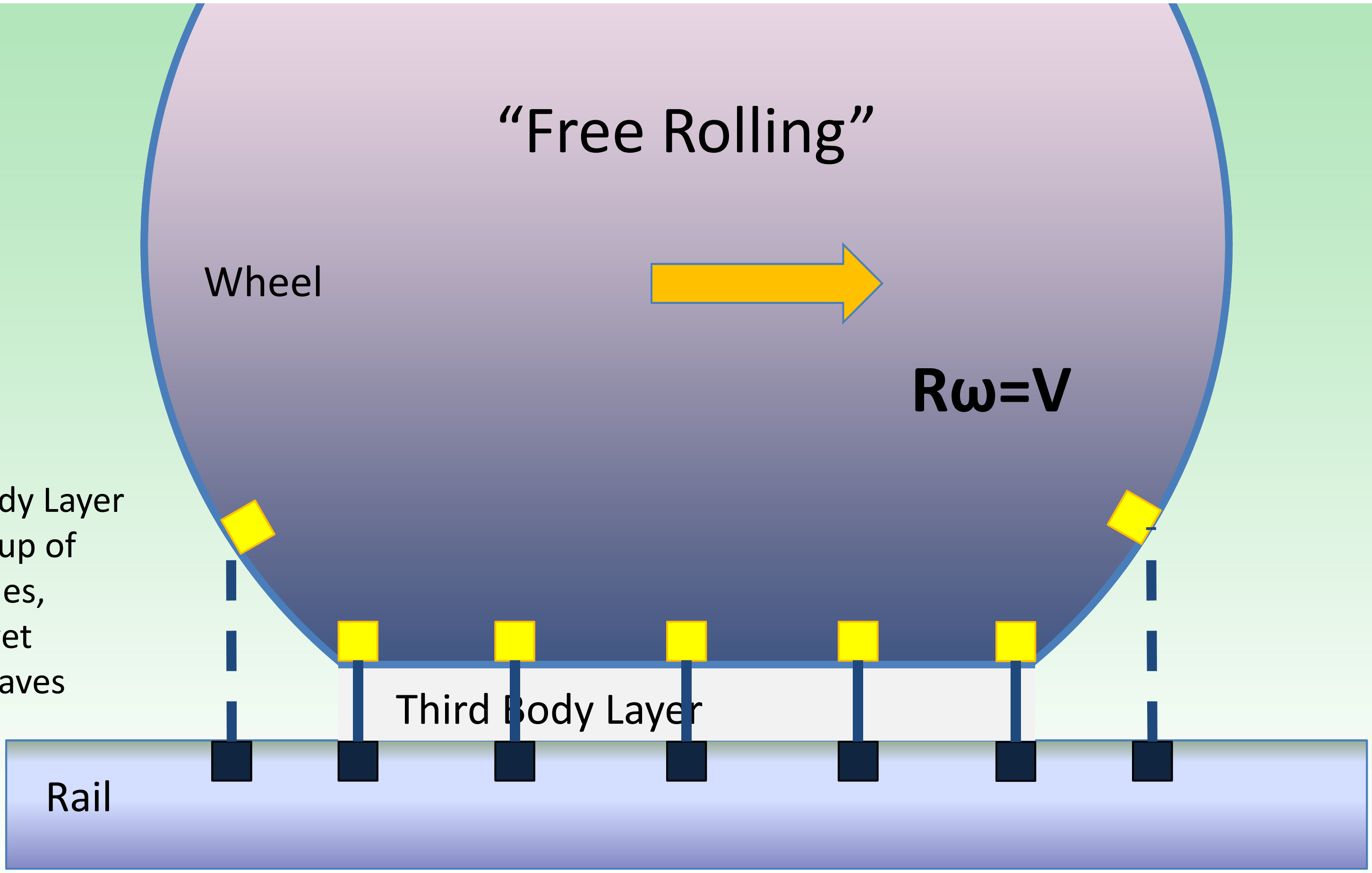


Questions & Discussion

Part 3

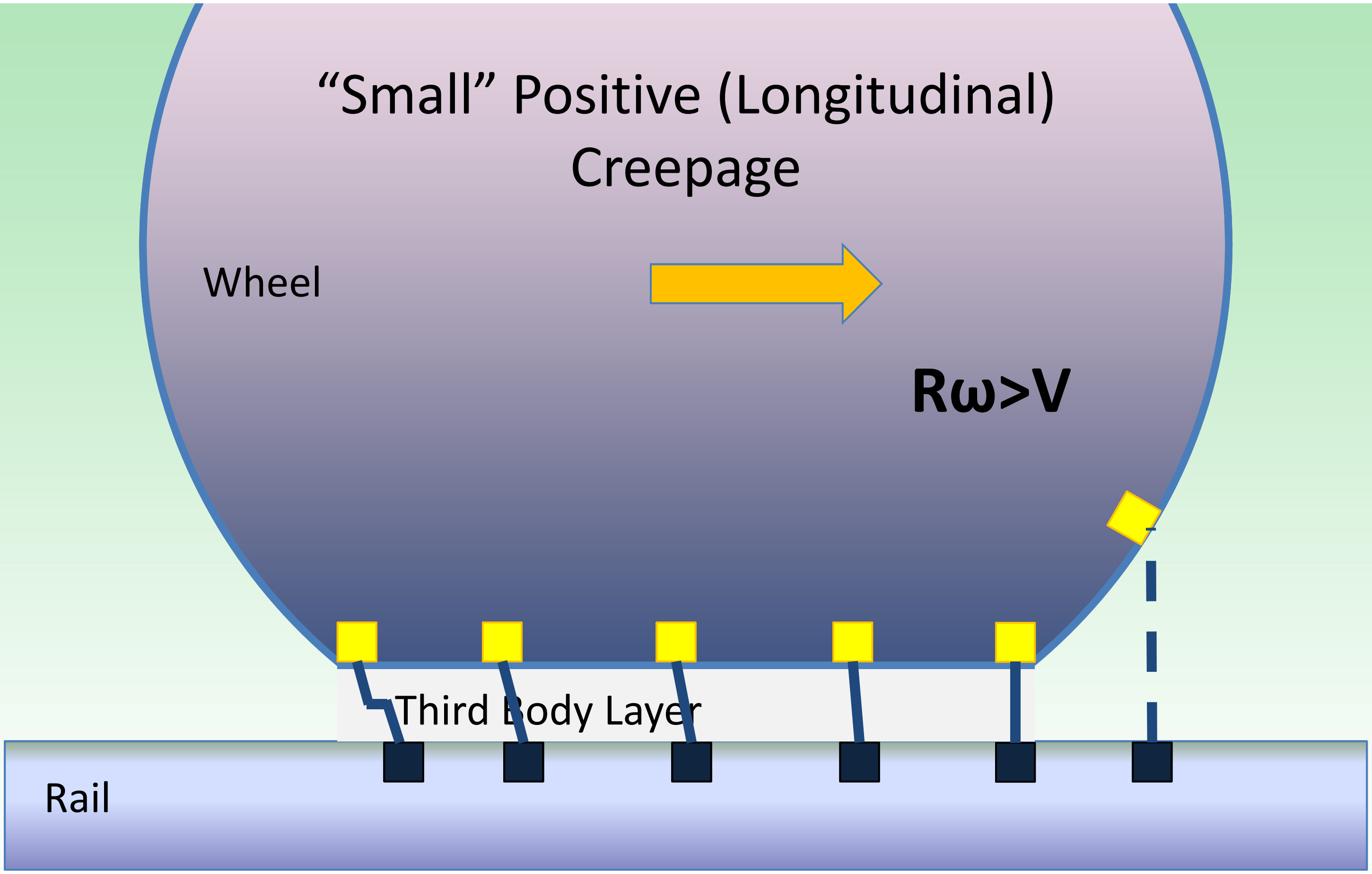
- The Third Body Layer, Traction/Creepage and Friction Management
- Frequency Domain Phenomena: Noise and Corrugations

“Free Rolling”



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

“Small” Positive (Longitudinal) Creepage



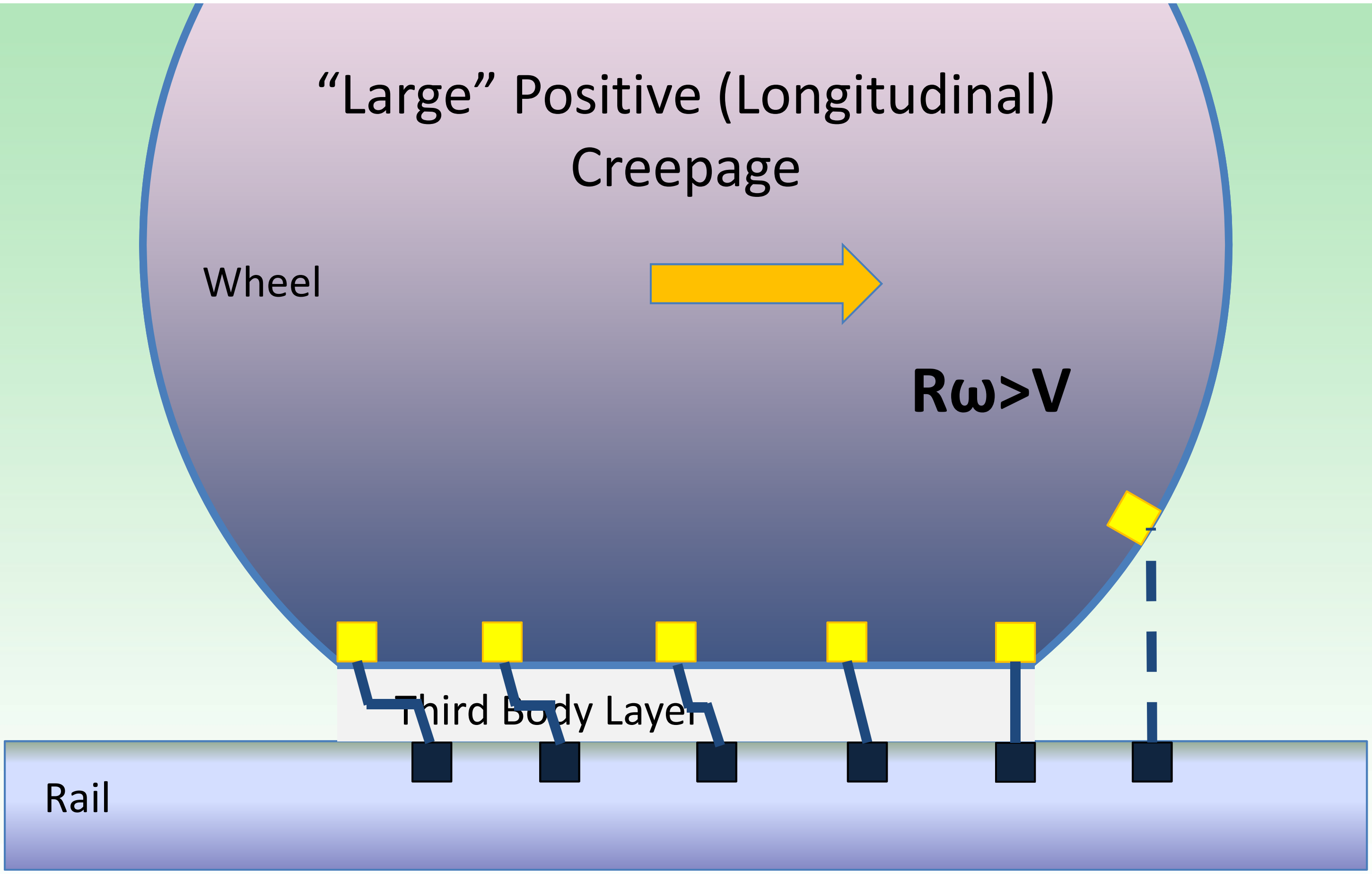
Wheel

Rω>V

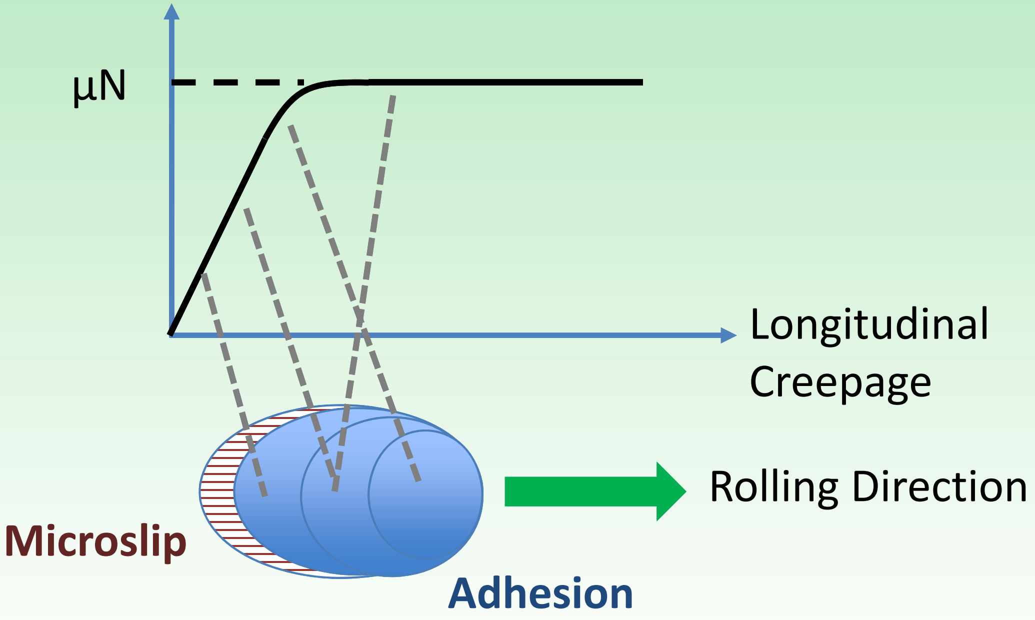
Third Body Layer

Rail

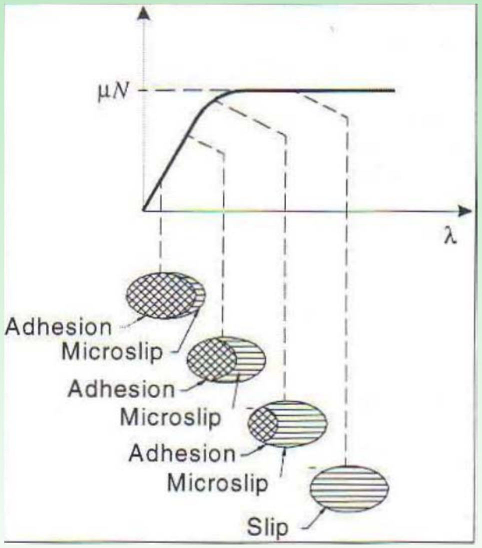
"Large" Positive (Longitudinal) Creepage

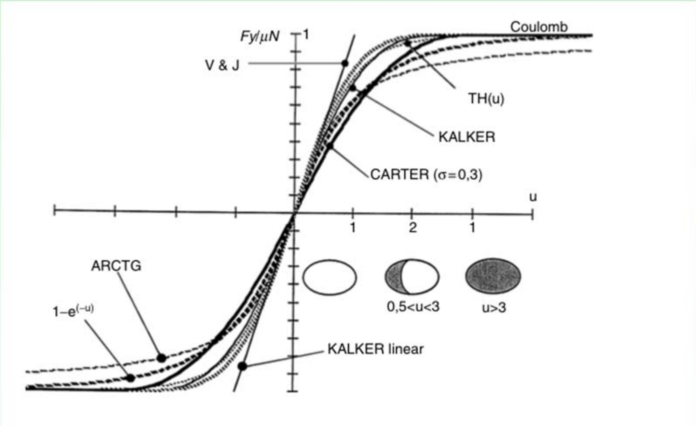


The Traction-Creepage Curve



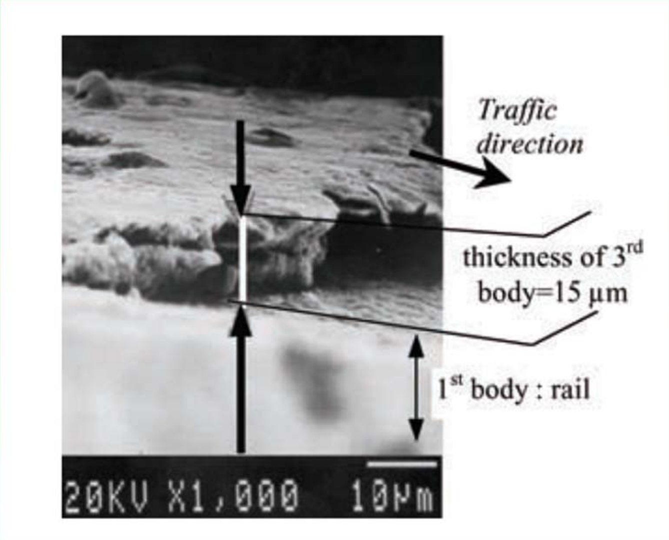
Traction/Creepage Curves



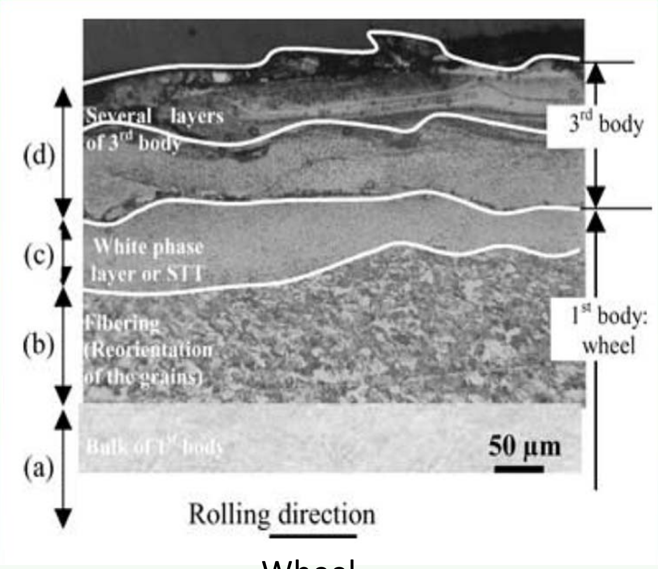


"Heuristic" expressions used for the saturation and physical meaning of the different parts.

Third Body Layer – Micron Scale



Rail



Wheel

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

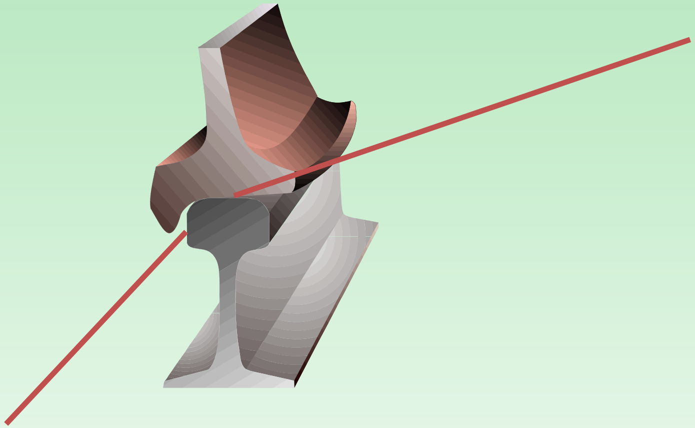
Key Points

- 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

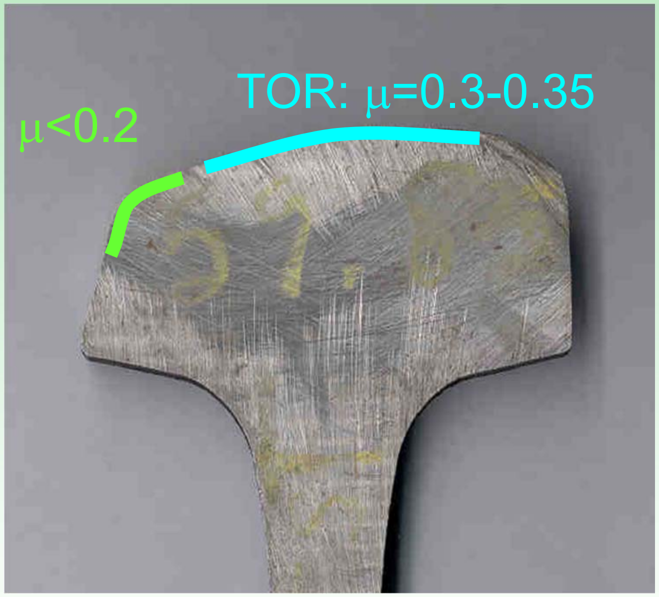


Top of Rail (TOR) Friction Impacts:
- Lateral Forces
- Rail / Wheel Wear (TOR, Tread)
- RCF Development
- Fuel Efficiency
- Squeal Noise
- Flange Noise (indirect)
- Corrugations
- Hunting
- Derailment Potential
  (L/V, rail rollover)

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

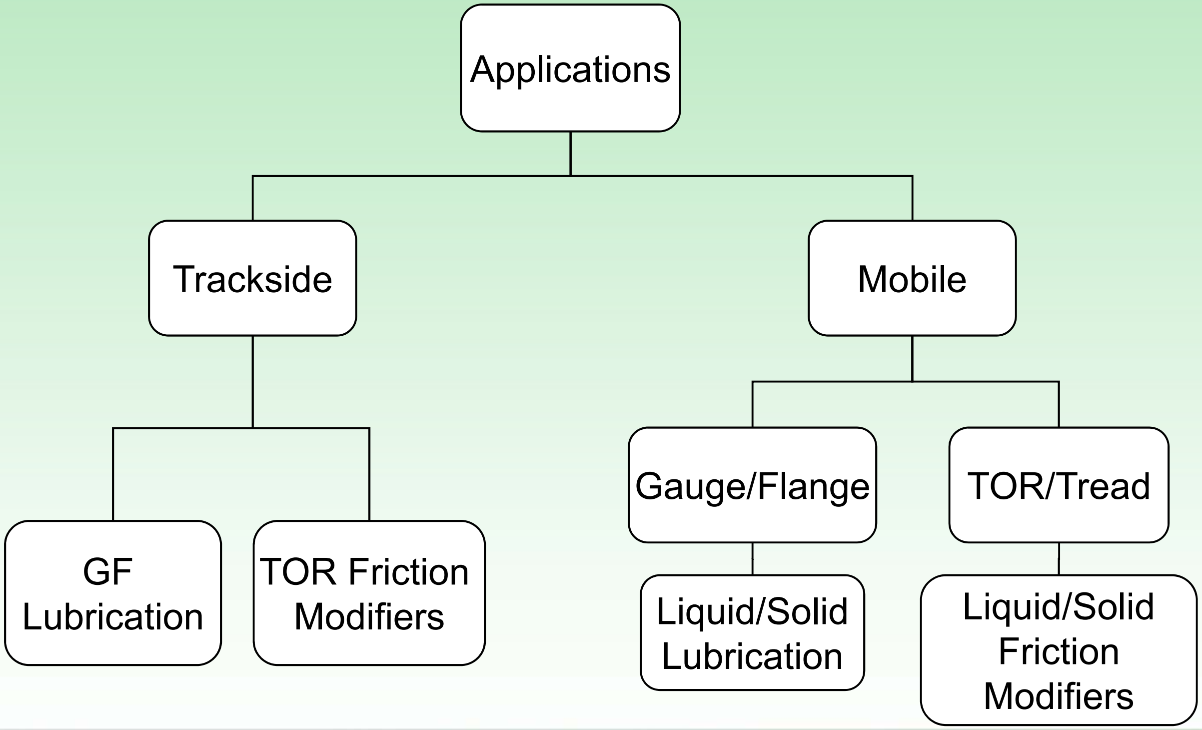
Ideal Targets

Low rail



High Rail

Friction Management Approaches



Applications

Trackside

Mobile

GF Lubrication

TOR Friction Modifiers

Gauge/Flange

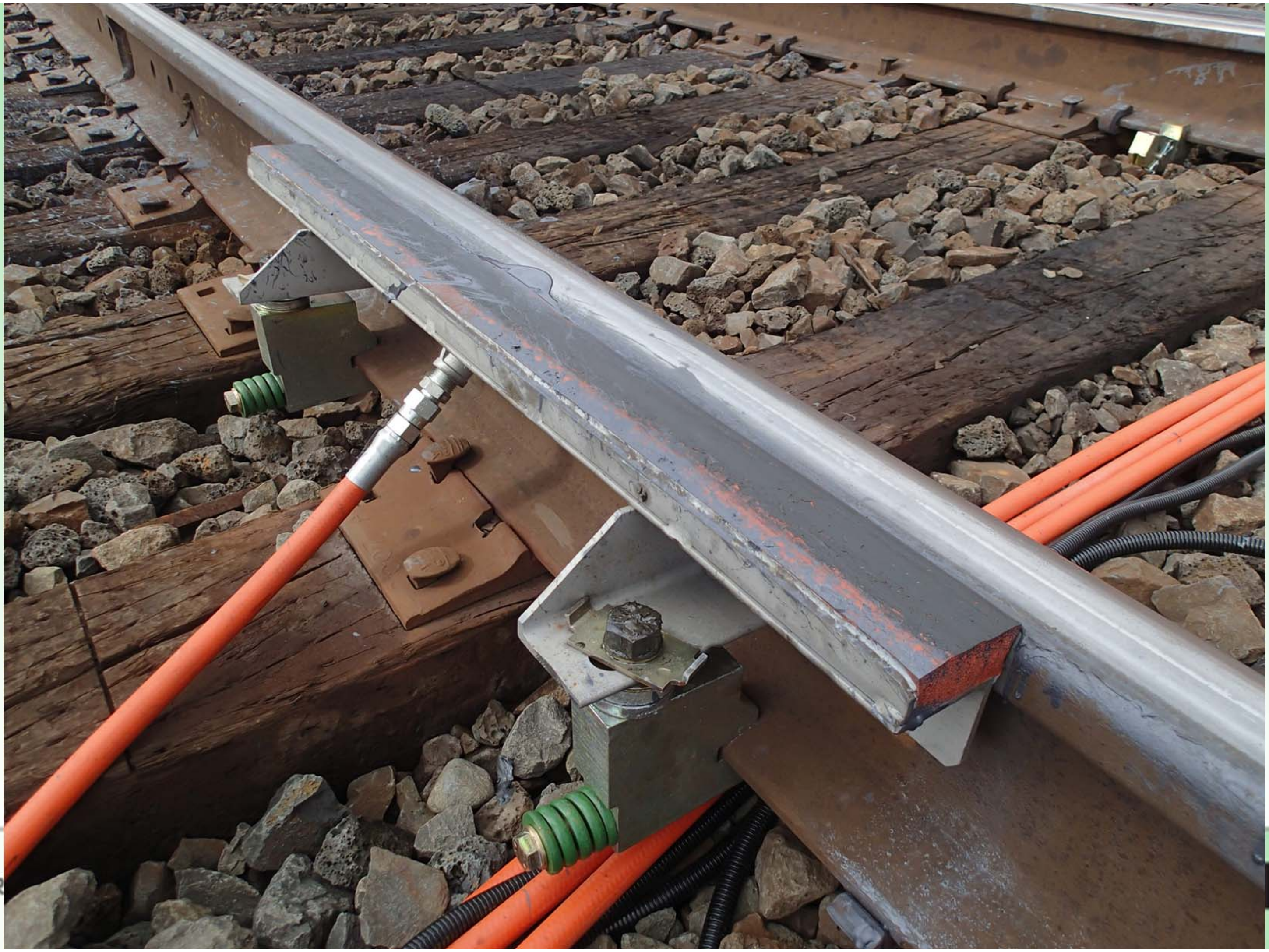
TOR/Tread

Liquid/Solid Lubrication

Liquid/Solid Friction Modifiers

Trackside Gage Face Lubrication

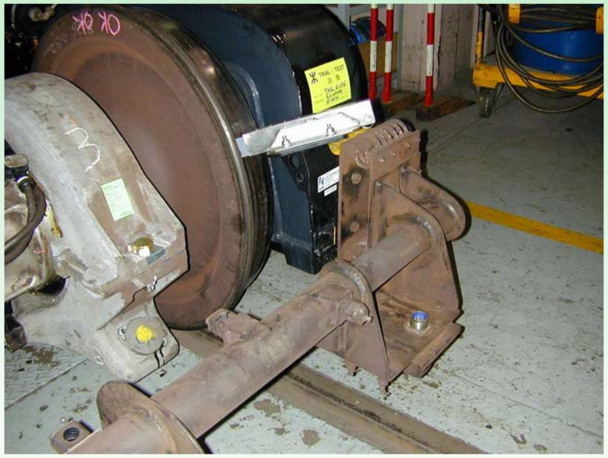
Trackside Top of Rail Friction Control



Solid stick application system

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

High speed train



Metro system

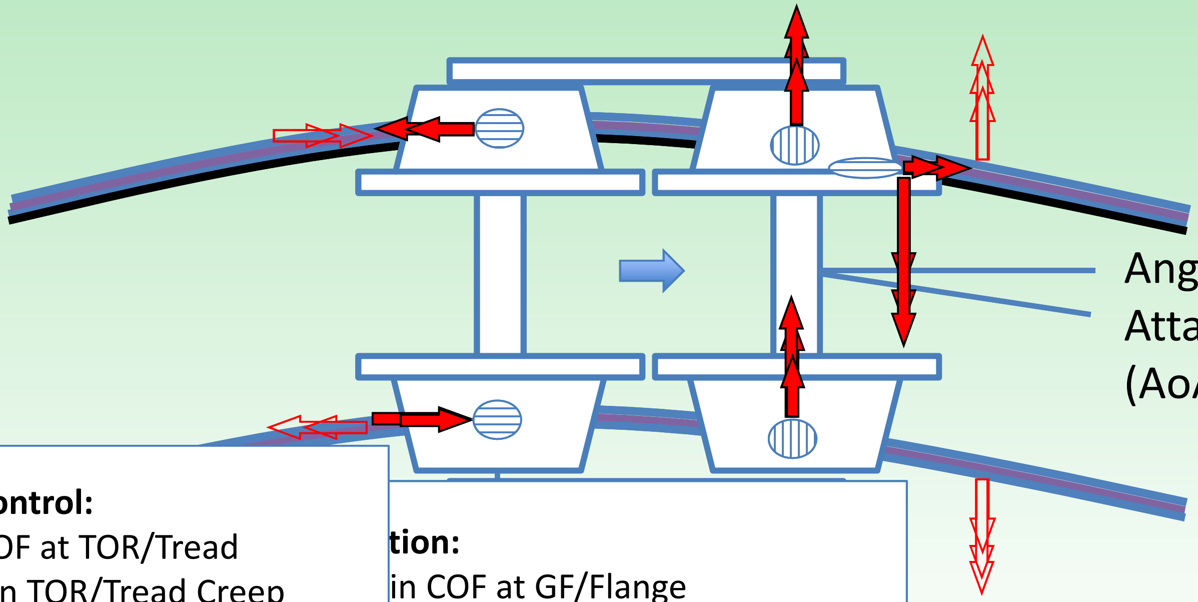
Mobile (Car Mounted) Top of Rail Friction Management

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

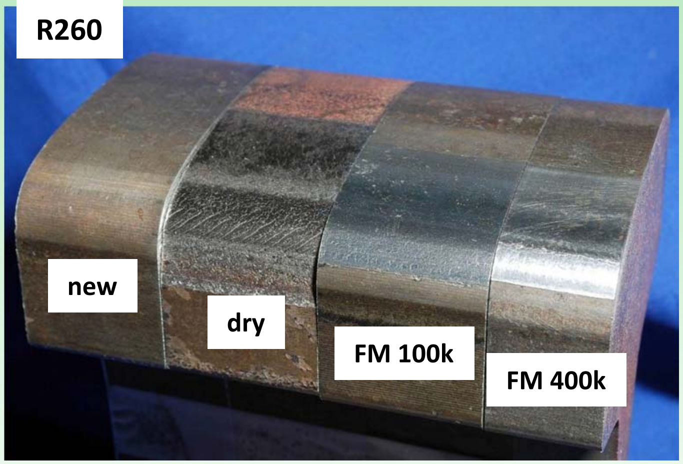
Example: Friction Management impacts on Curving Forces

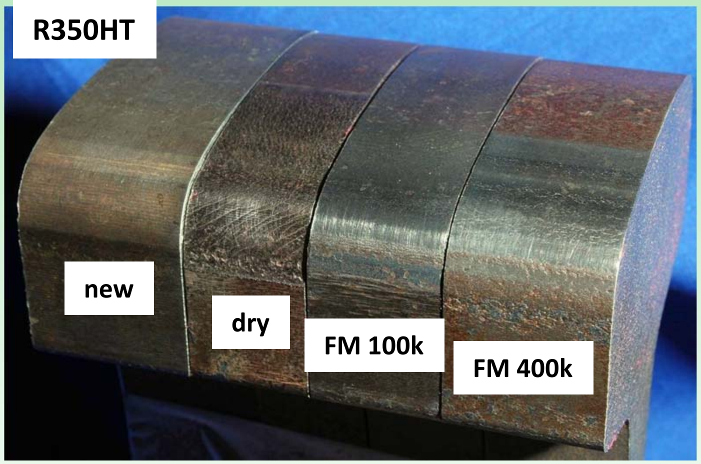


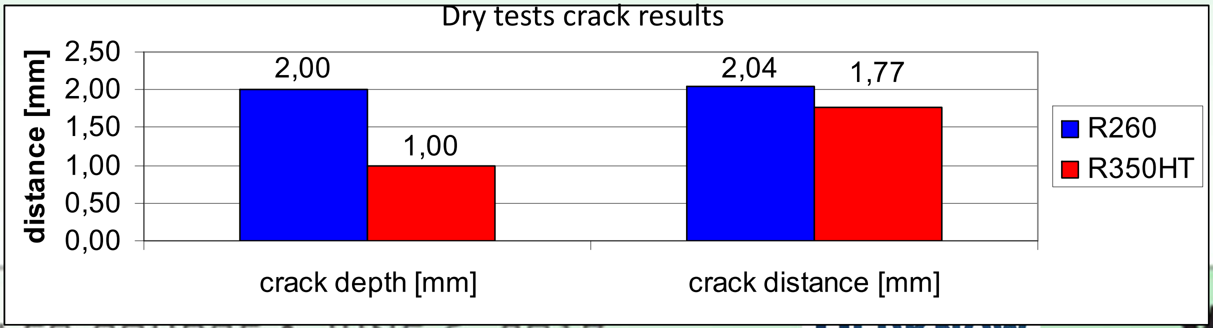
TOR Friction Control:
Reduction in COF at TOR/Tread
→ Reductions in TOR/Tread Creep Forces and *Negative* Steering Moments
→ Reductions in Lateral Forces, Wear, Energy, etc.

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






Dry tests crack results

Curving Noise

Spectral range for different noise types

Noise type	*Frequency range, Hz*
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

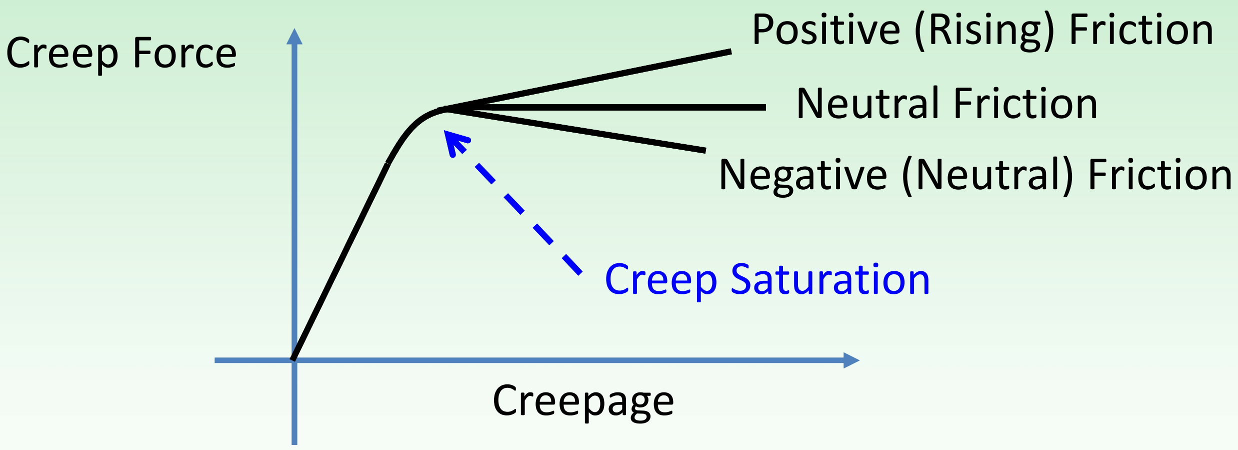
Top of rail wheel squeal noise

- **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



Creep Force

Positive (Rising) Friction

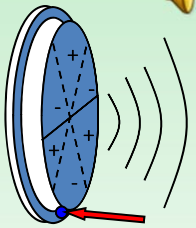
Neutral Friction

Negative (Neutral) Friction

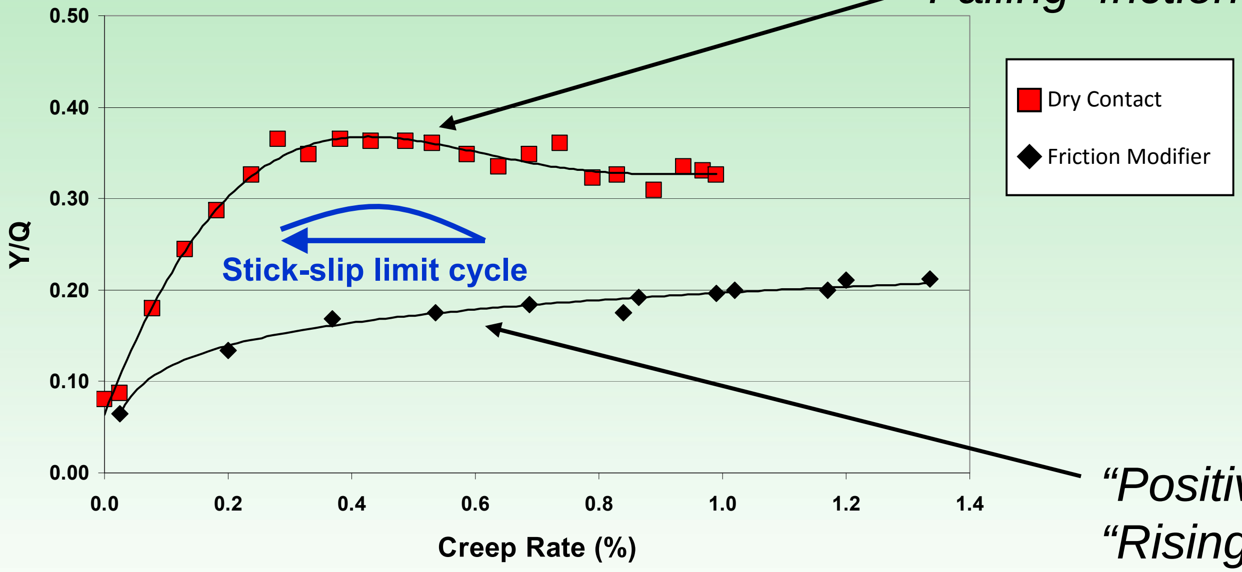
Creep Saturation

Creepage

Absolute Friction Levels and Positive/Negative Friction



Creepage / friction force

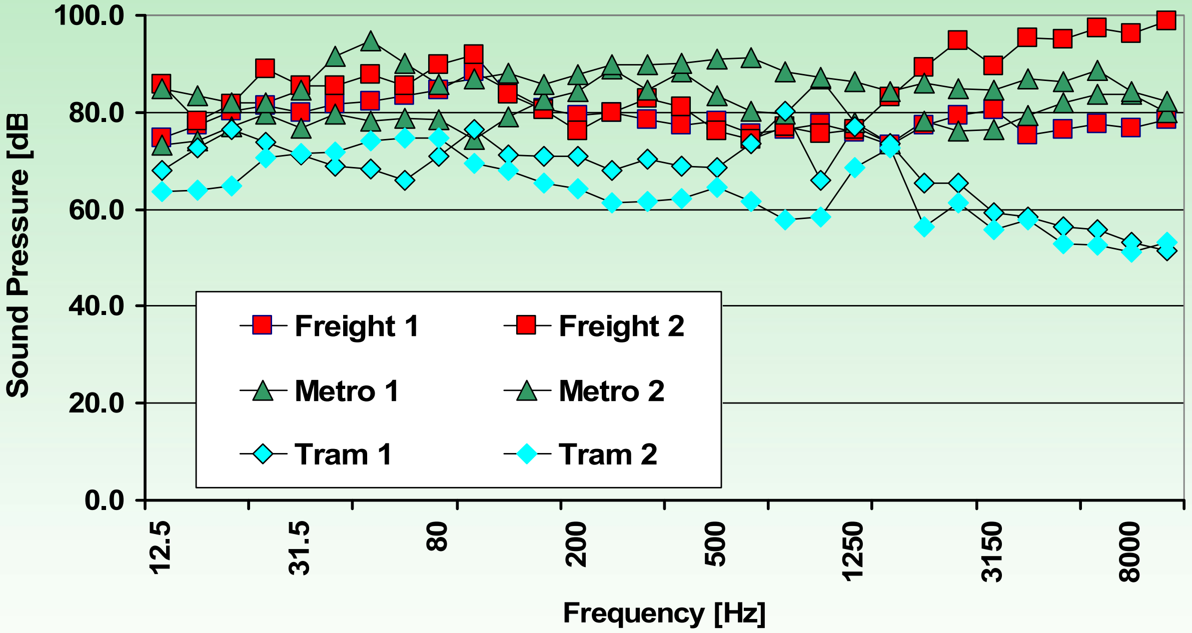


“Negative” or “Falling” friction

“Positive” or “Rising” friction

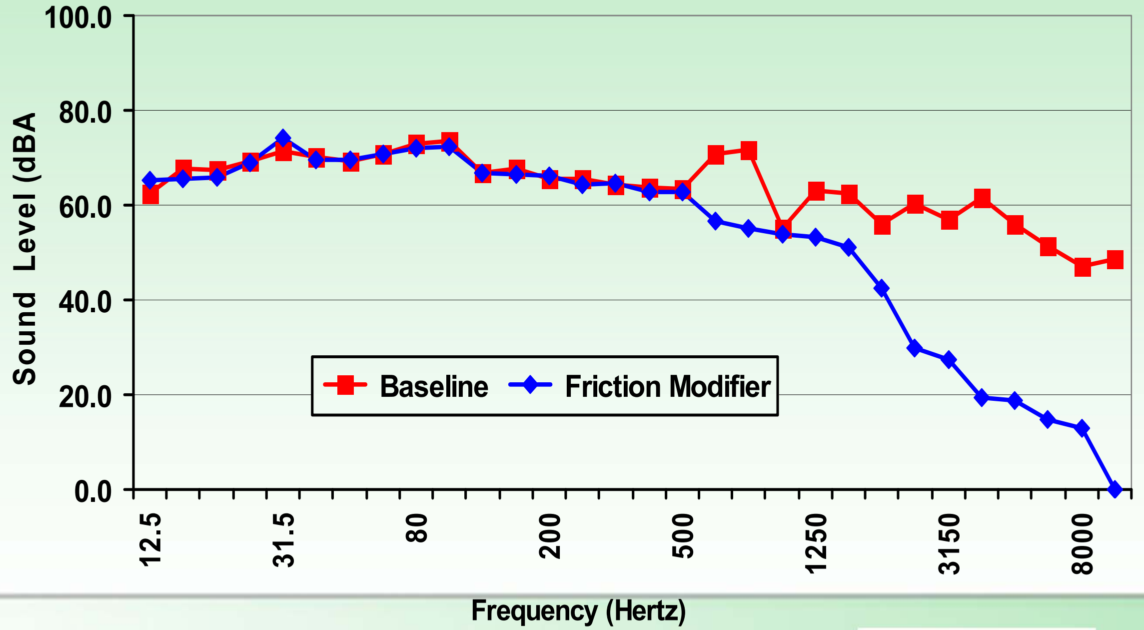
*** Replotted from: “Matsumoto a, Sato Y, Ono H, Wang Y, Yamamoto Y, Tanimoto M & Oka Y, Creep force characteristics between rail and wheel on scaled model, *Wear,* Vol 253, Issues 1-2, July 2002, pp 199-203**

Sound spectral distribution for different wheel / rail systems



Effect of friction characteristics on spectral sound distribution: Trams

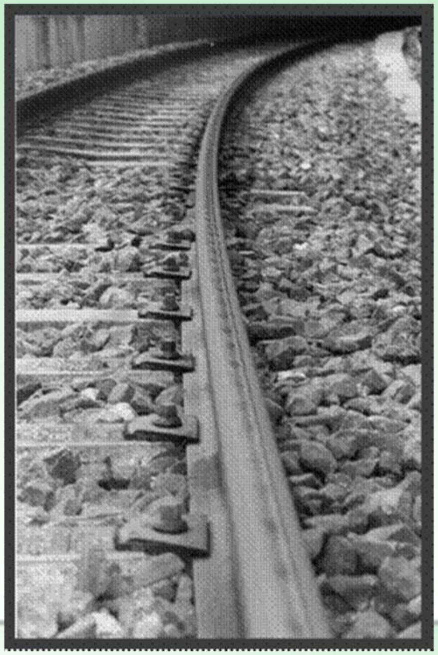

Effect of friction characteristics on spectral sound distribution: Trams



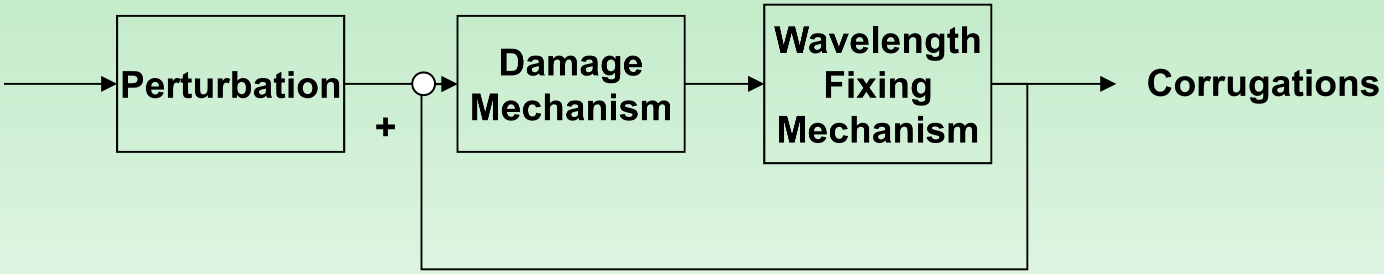
“Low Frequency” Stick-Slip / Noise

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

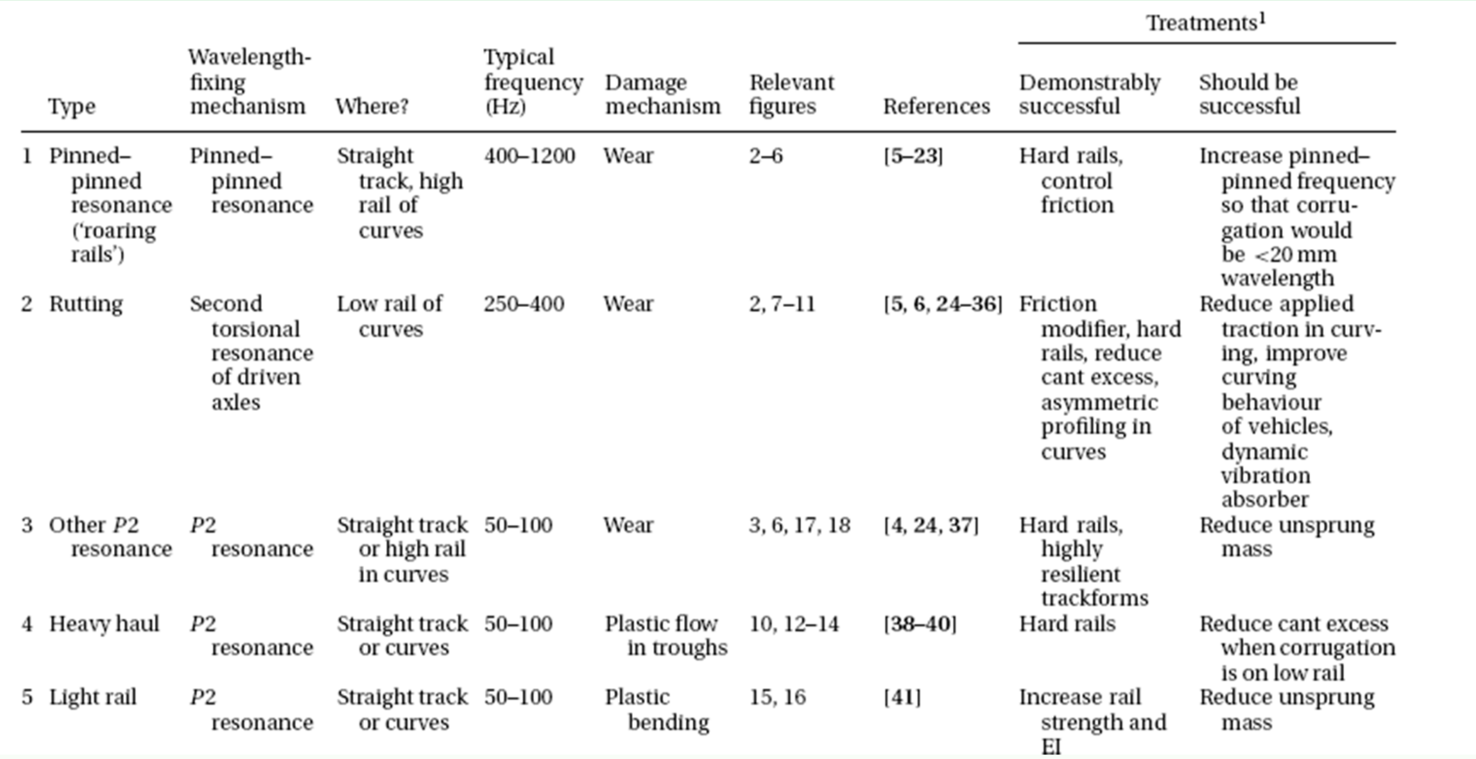
Corrugations (Short Pitch)



Corrugation formation: common threads



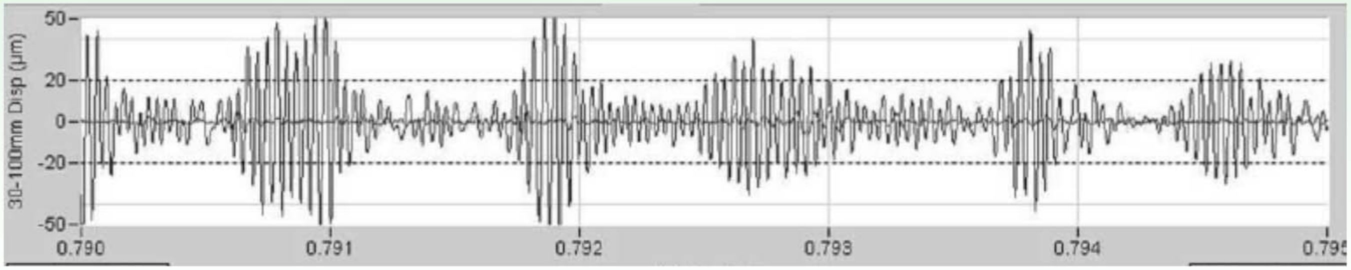
$$\boxed{\lambda = v/f}$$



								Treatments[1]	
	Type	Wavelength-fixing mechanism	Where?	Typical frequency (Hz)	Damage mechanism	Relevant figures	References	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 *P*2 resonance	*P*2 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	*P*2 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	*P*2 resonance	Straight track or curves	50–100	Plastic bending	15, 16	[41]	Increase rail strength and EI	Reduce unsprung mass

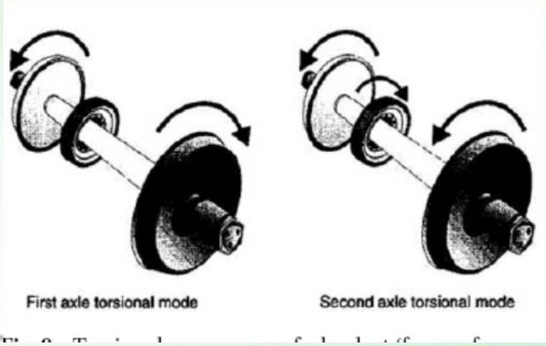
Pinned-Pinned corrugation ("roaring rail")

- 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



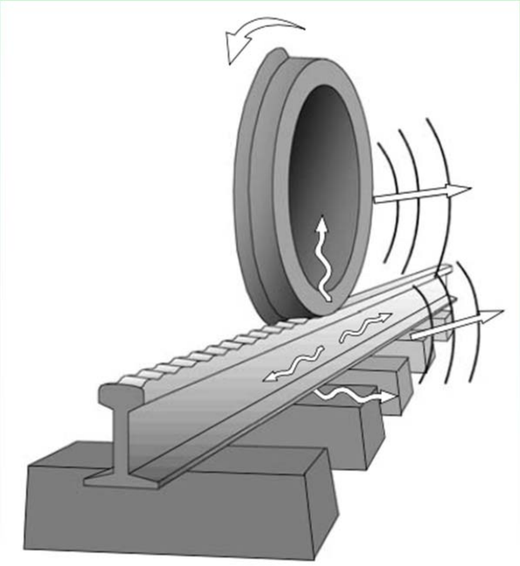
Rutting

- 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