Wheel-Rail Interaction Fundamentals

Kevin Oldknow, Ph.D., P.Eng.

Principal Engineer, Wheel/Rail Interface

L.B. Foster Rail Technologies

Introduction and Objectives

- This two-part 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)
  - Curving Noise
  - 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 and passenger rail systems.

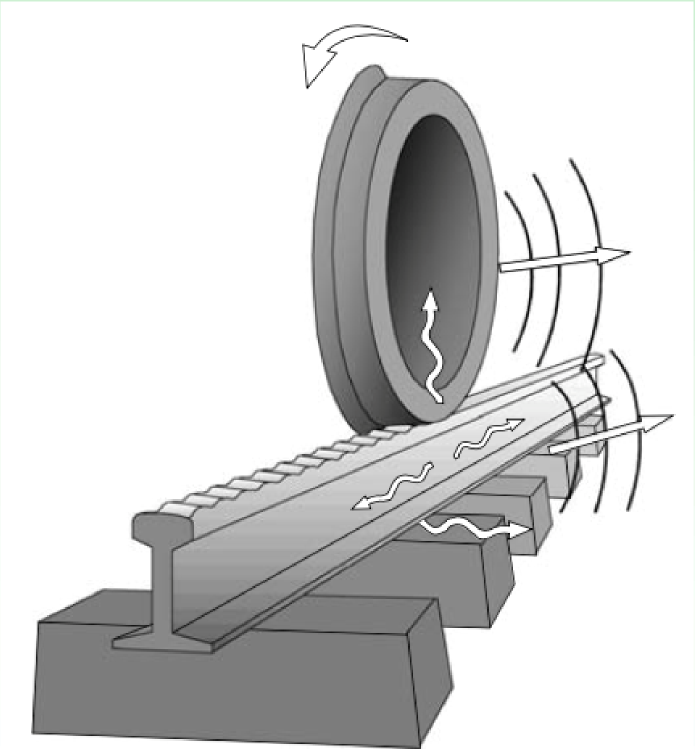
Three questions that we will aim to answer….

Question #1: How can we estimate the lateral forces (and L/V ratios) that a vehicle is exerting on the track?

Question #2: How can we determine if there is a risk of rolling contact fatigue (RCF) developing under a given set of vehicle/track conditions?

Question #3: How is the noise captured in these two sound files generated at the wheel/rail interface?

- File #1:
- File #2:

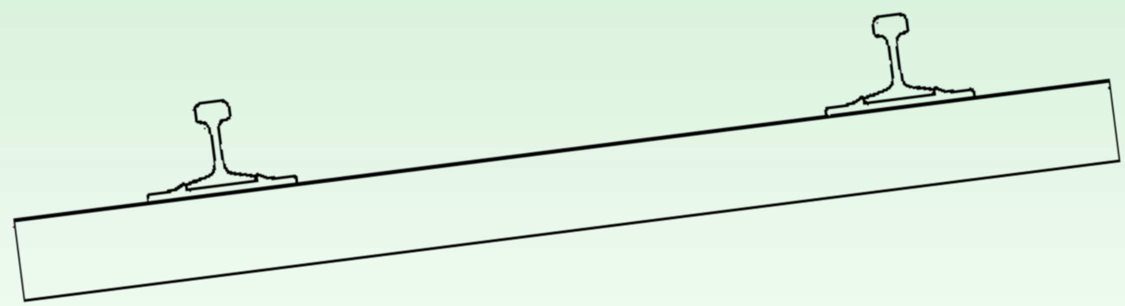


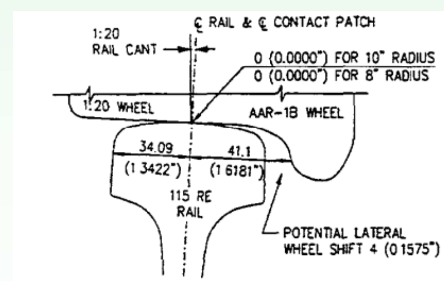
Overview: Part I

- 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

Back to basics…

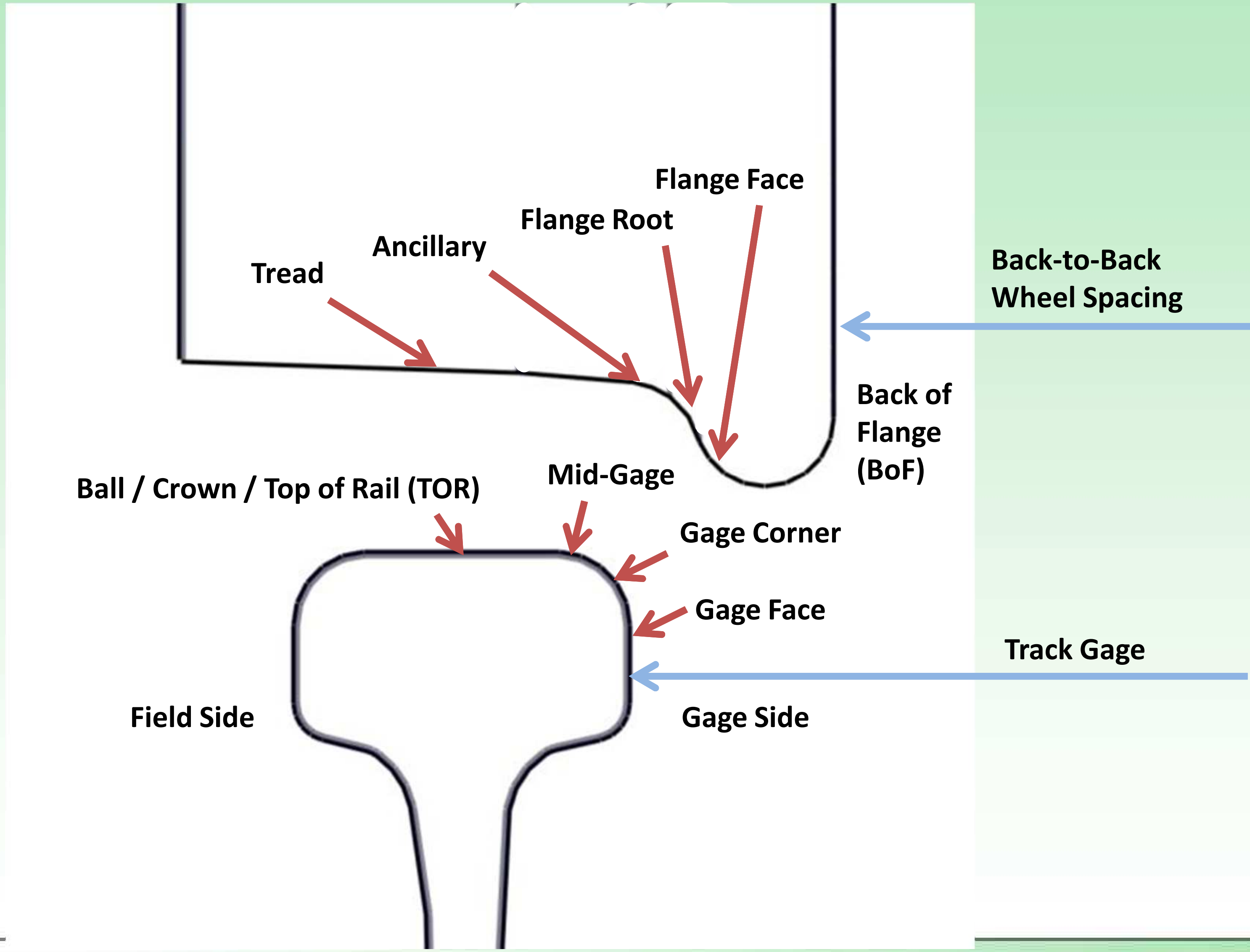
- Tangent
- Curve
- Spiral
- High Rail
- Low Rail
- Superelevation (aka Cant)
- Rail Cant



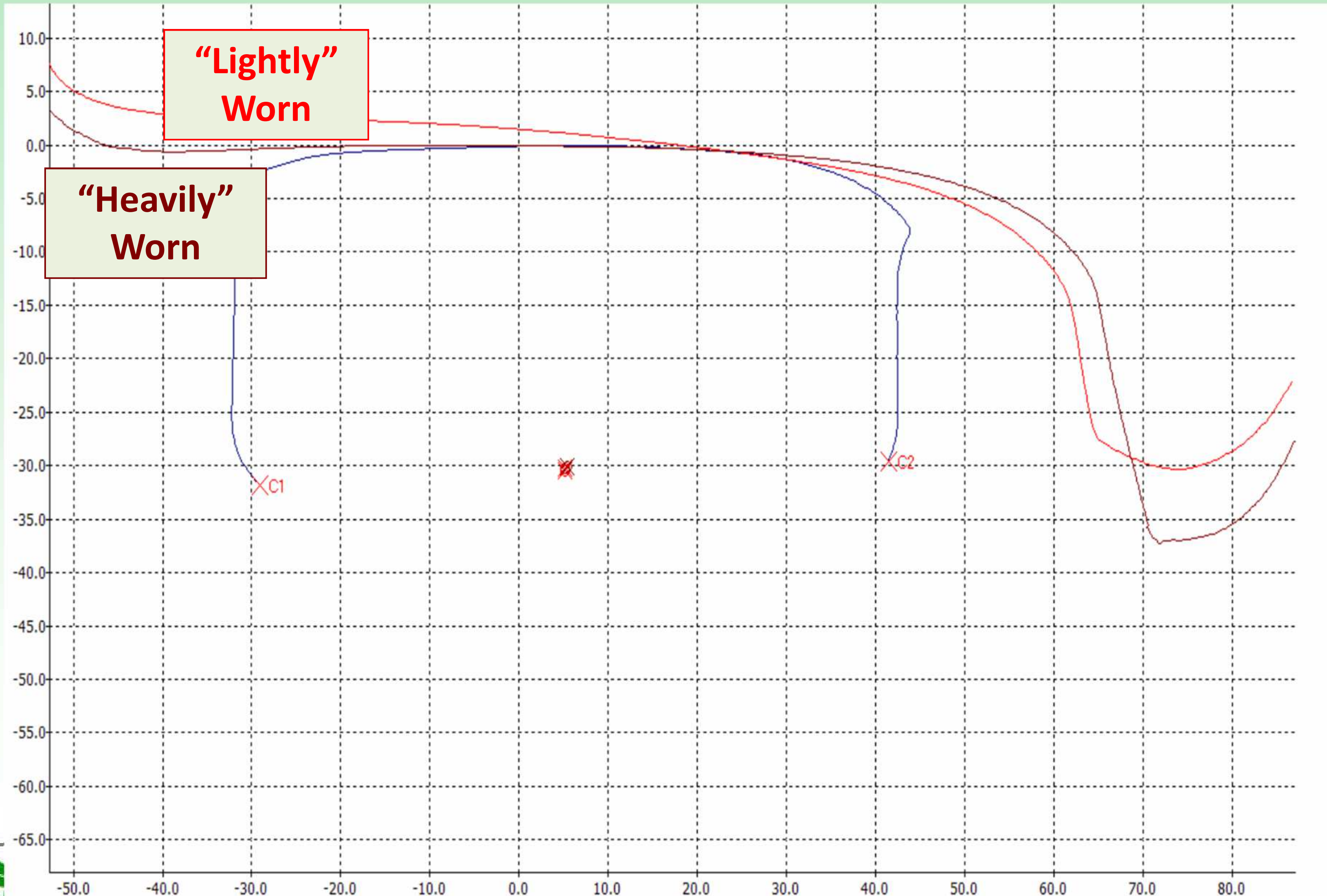


1:20 CANT

The Wheel / Rail Interface and Key Terminology



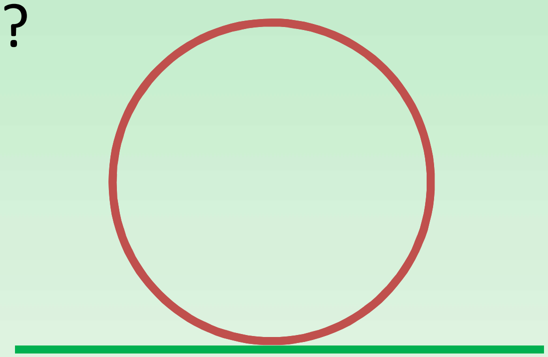
The Wheel / Rail Interface and Key Terminology (e.g. Low Rail Contact)



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

The Contact Patch and Contact Pressures

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

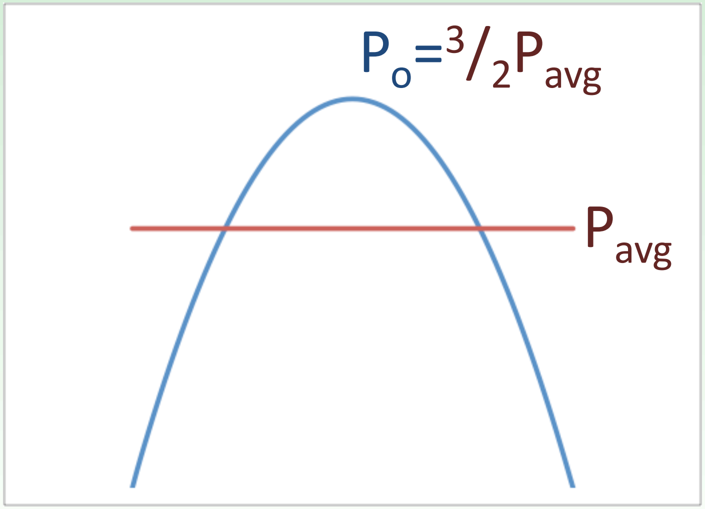


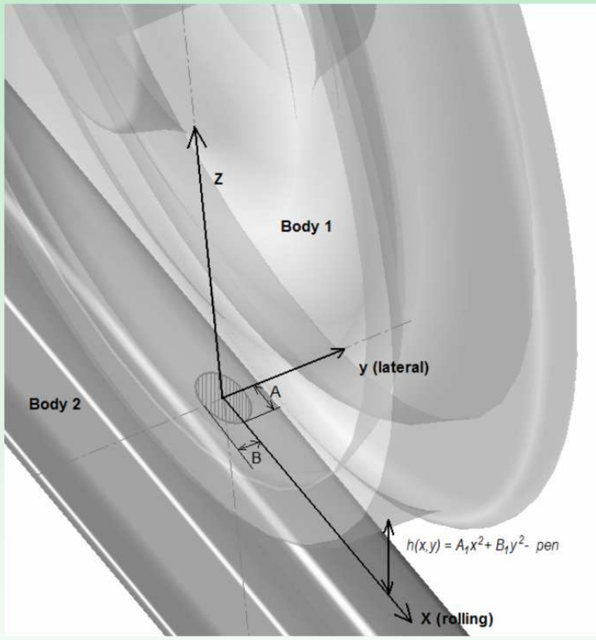
- Question #2: Given Force and Area, how do we calculate pressure?

- 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





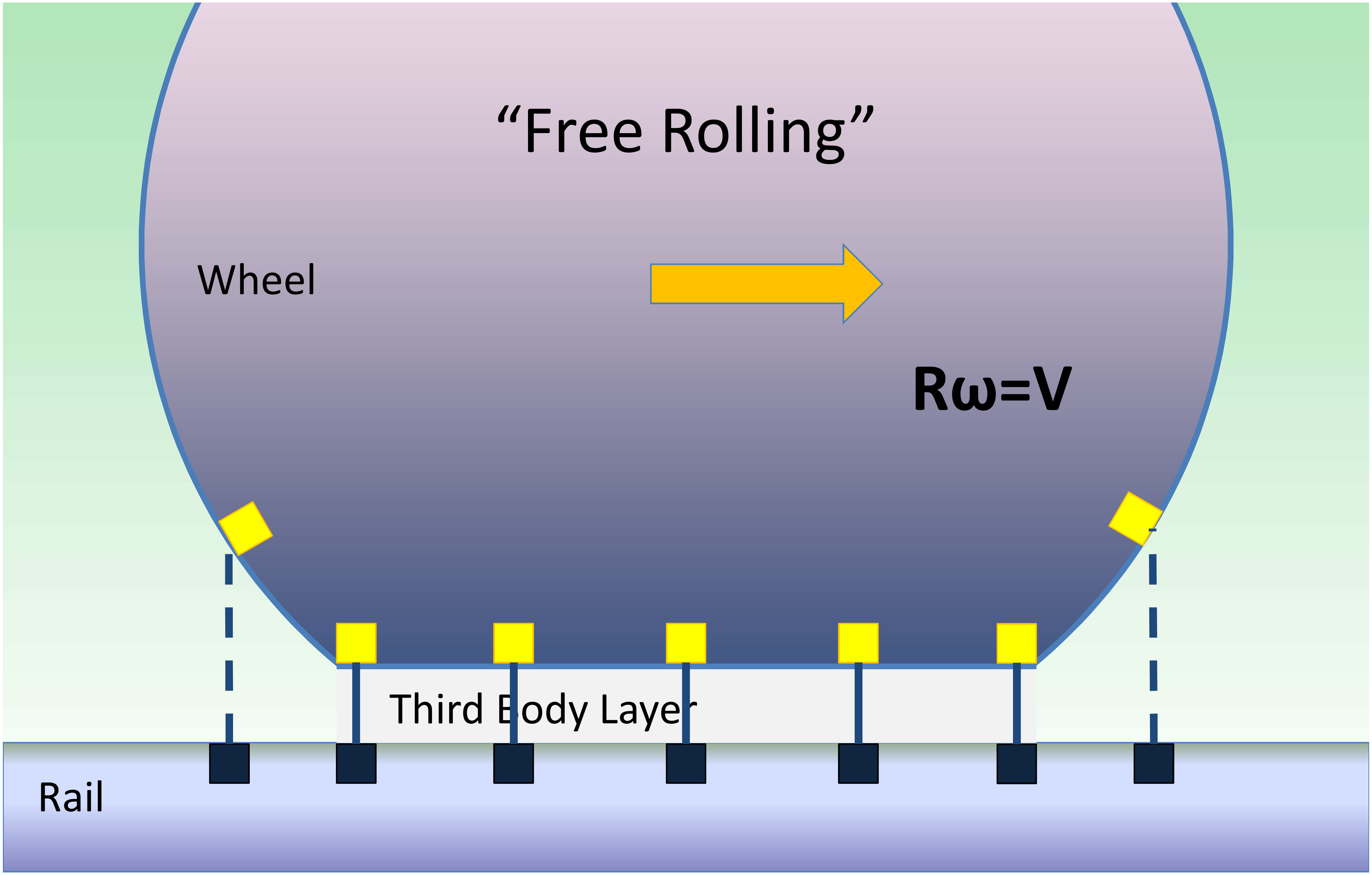
- Contact theory was subsequently broadened to apply to rolling contact (Carter and Fromm) with non-elliptical contact and arbitrary creepage (Kalker; *more on this later…*)

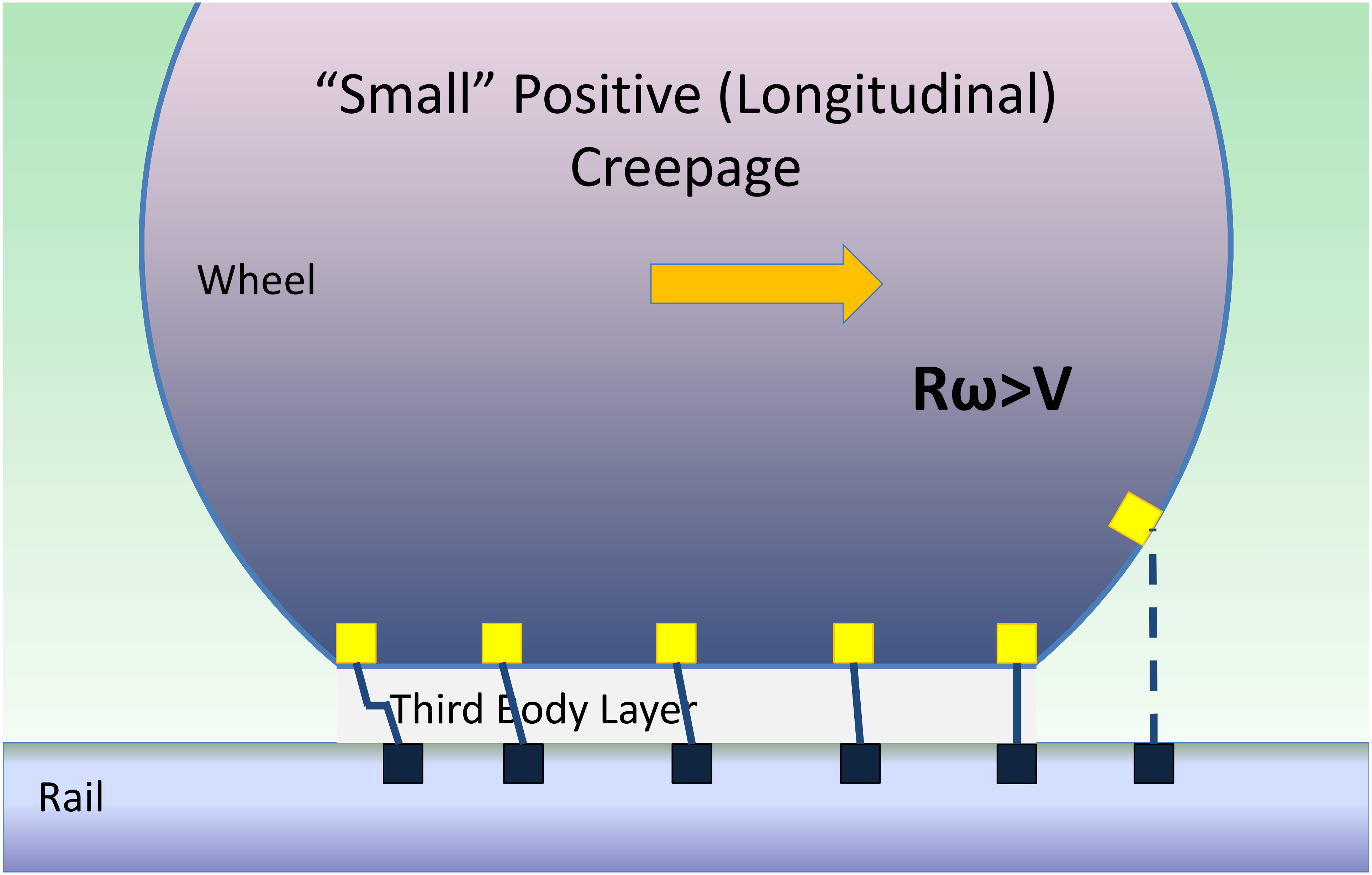
Creepage, Friction and Traction Forces

- Longitudinal Creepage
- The Traction-Creepage Curve
- Lateral Creepage
- Spin Creepage
- Friction at the Wheel-Rail Interface

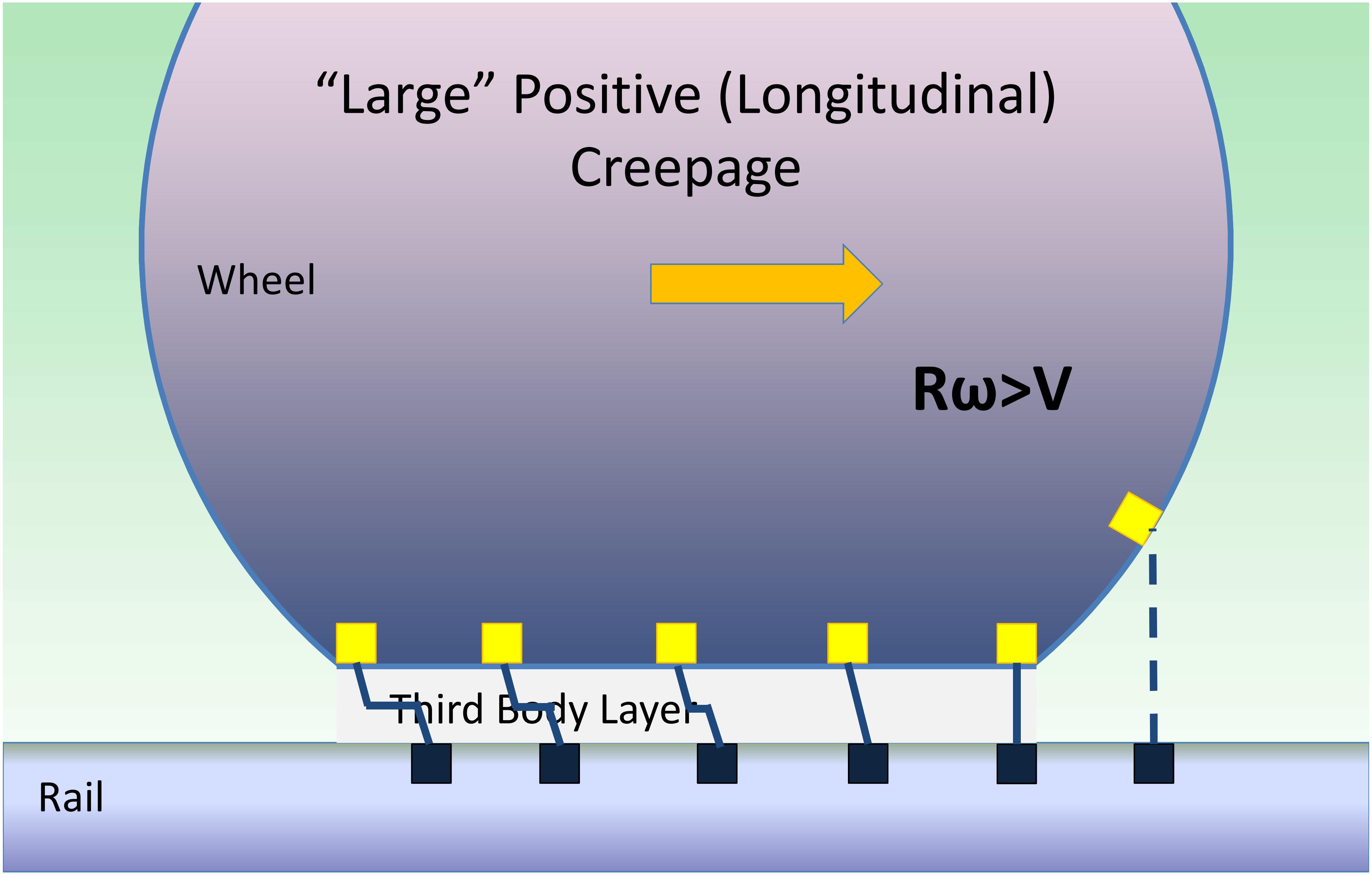
What does Longitudinal Creepage *mean*?...

- The frictional contact problem (Carter and Fromm, 1926) relates frictional forces to velocity differences between bodies in rolling contact.
- Longitudinal Creepage can be calculated as: $$\frac{R\omega - V}{V}$$
- In adhesion, 1% longitudinal creepage means that a wheel would **turn 101 times while traveling a distance of 100 circumferences**.
- In braking, -1% longitudinal creepage means that a wheel would **turn 99 times while traveling a distance of 100 circumferences.**

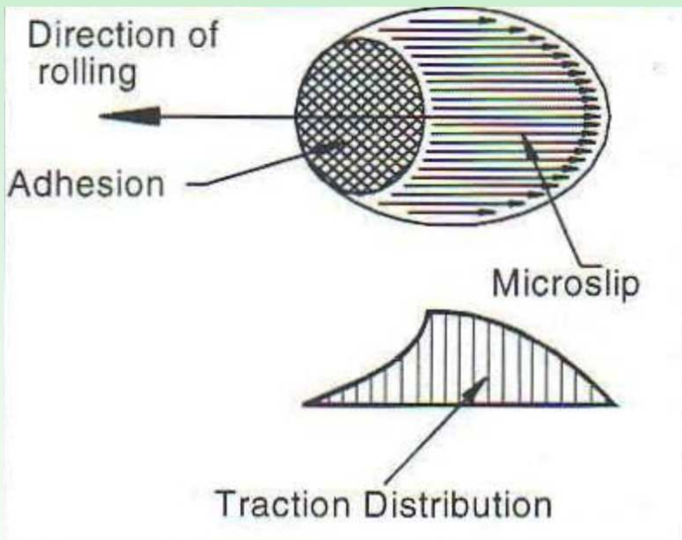

"Free Rolling"
Wheel
Rω=V
Third Body Layer
Rail

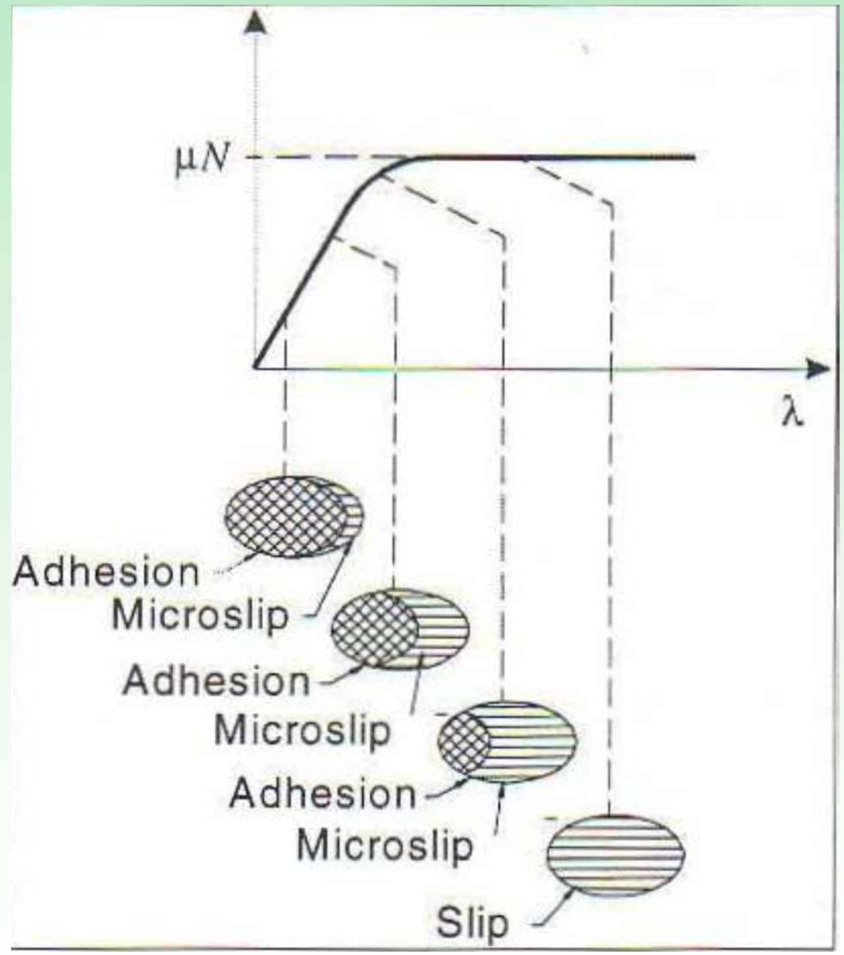

"Small" Positive (Longitudinal)
Creepage
Wheel
Rω>V
Third Body Layer
Rail

"Large" Positive (Longitudinal) Creepage



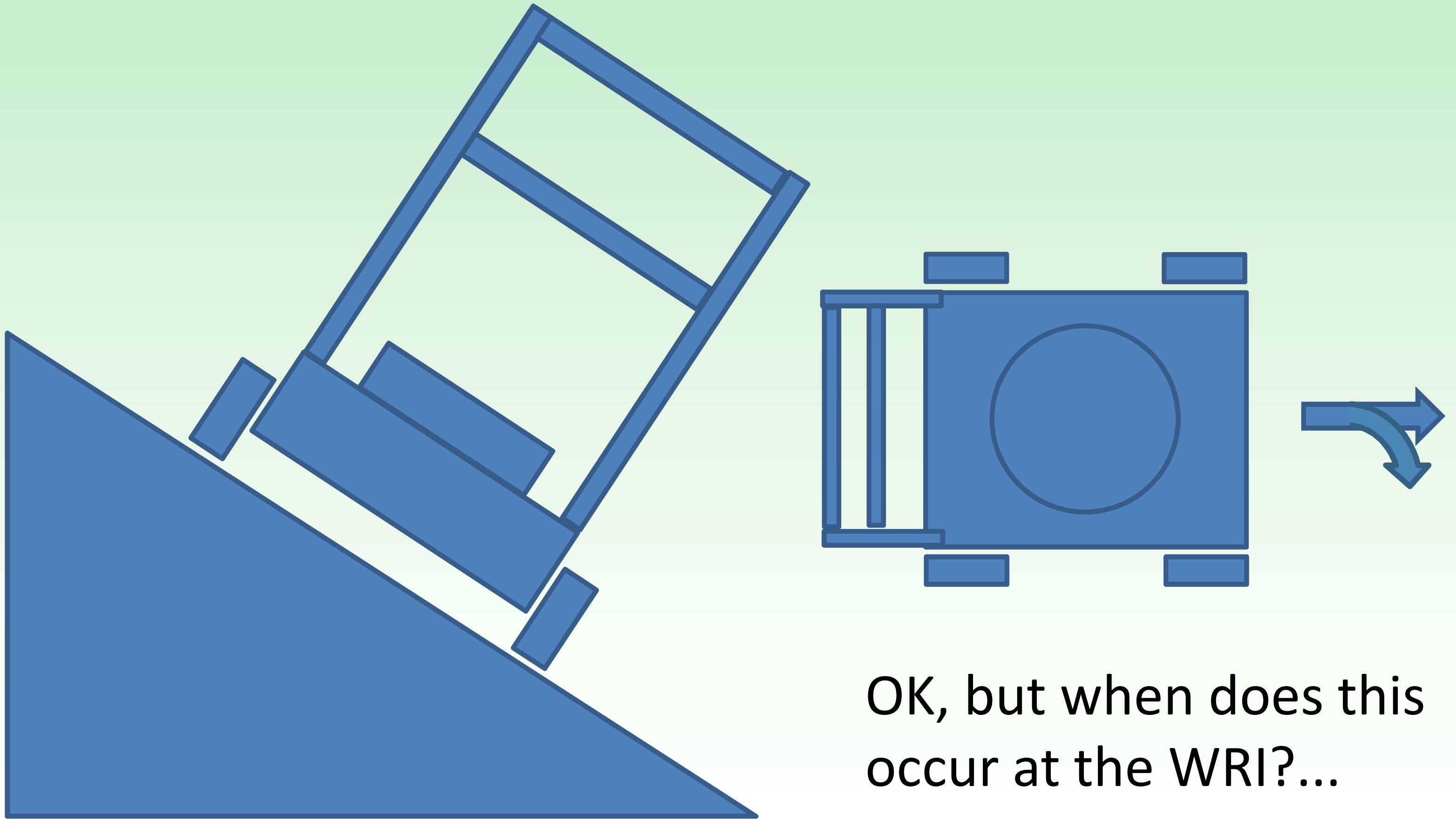
The Traction-Creepage Curve





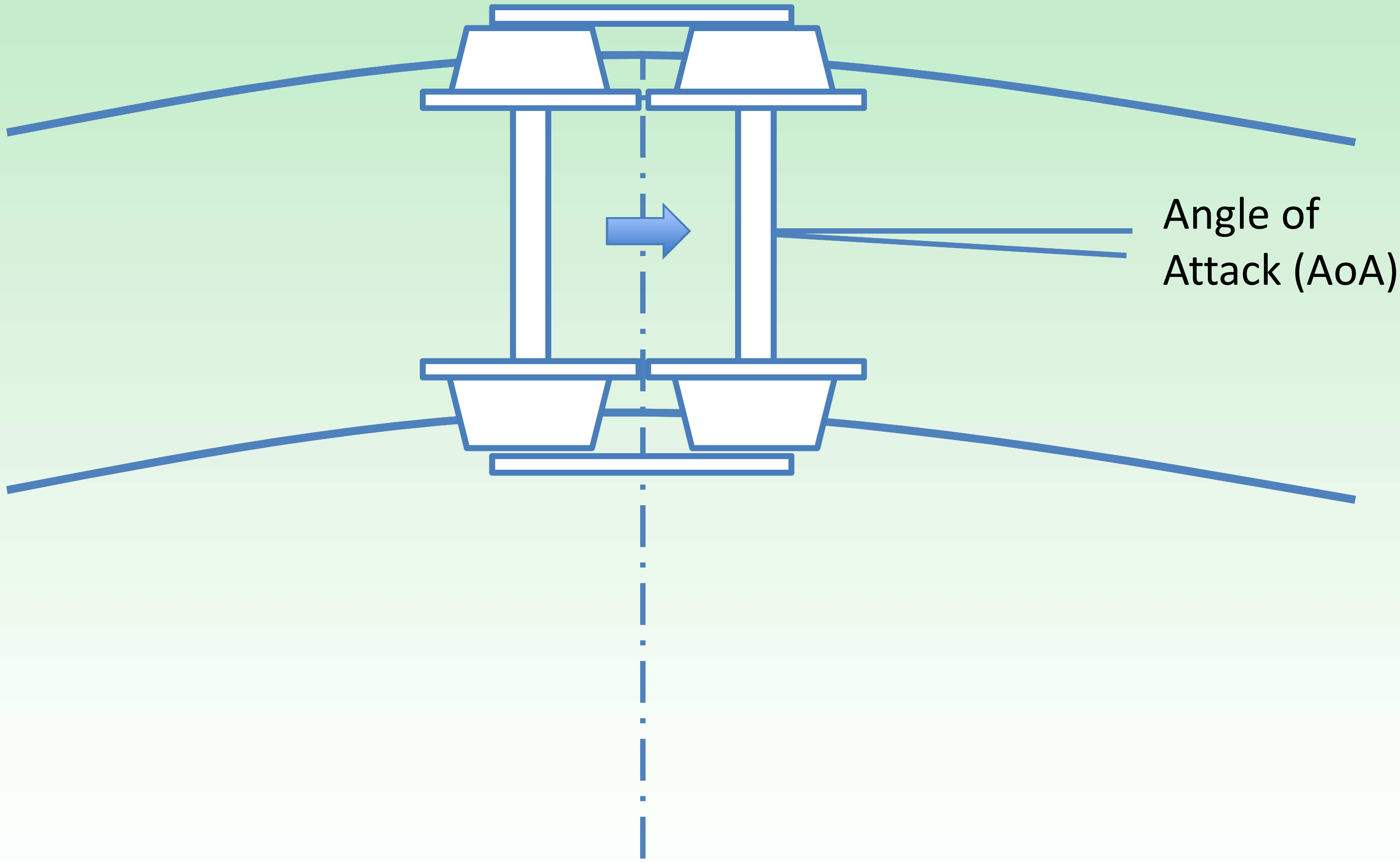
Lateral creepage

Imagine pushing a lawnmower across a steep slope…

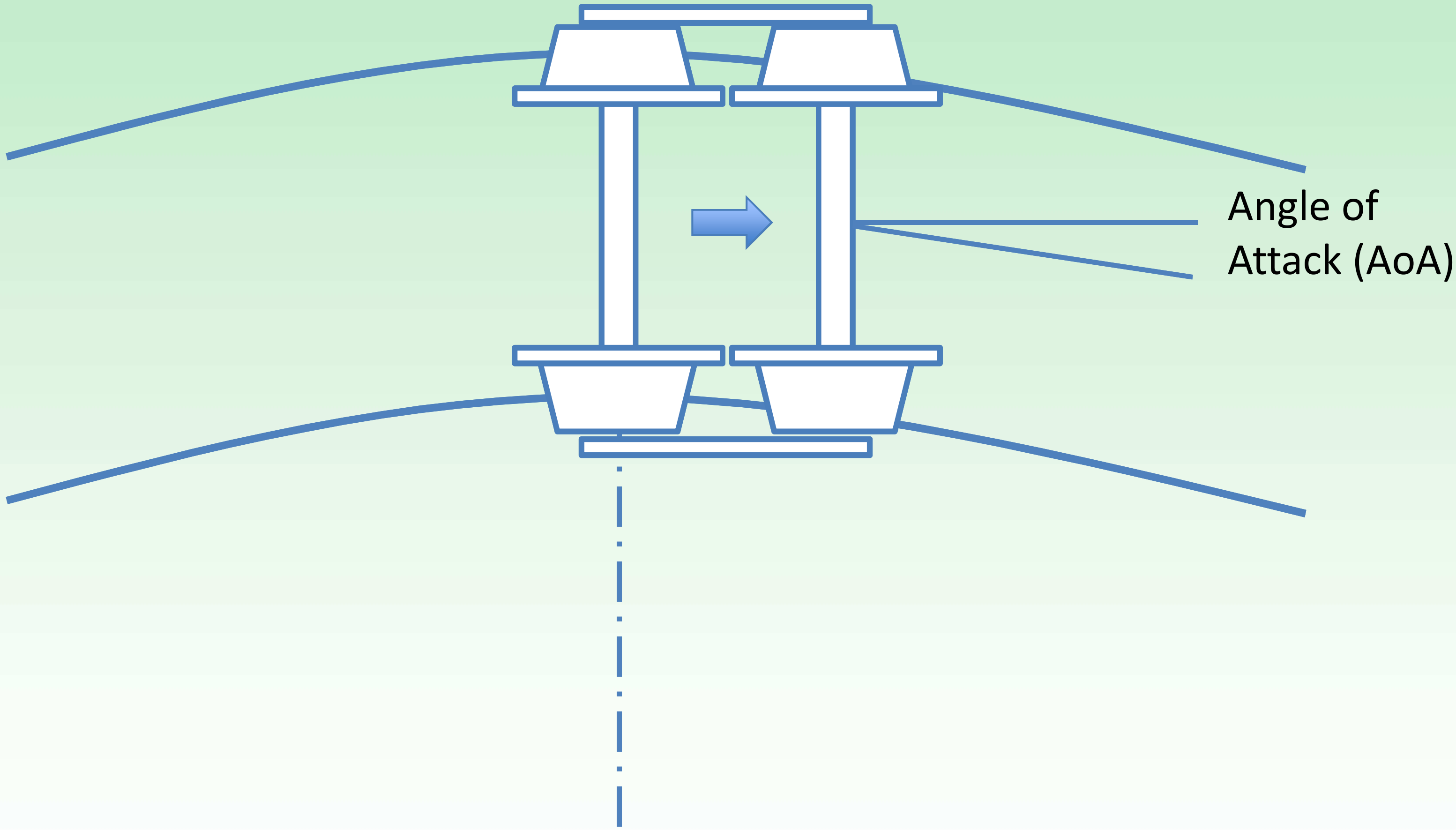


OK, but when does this occur at the WRI?...

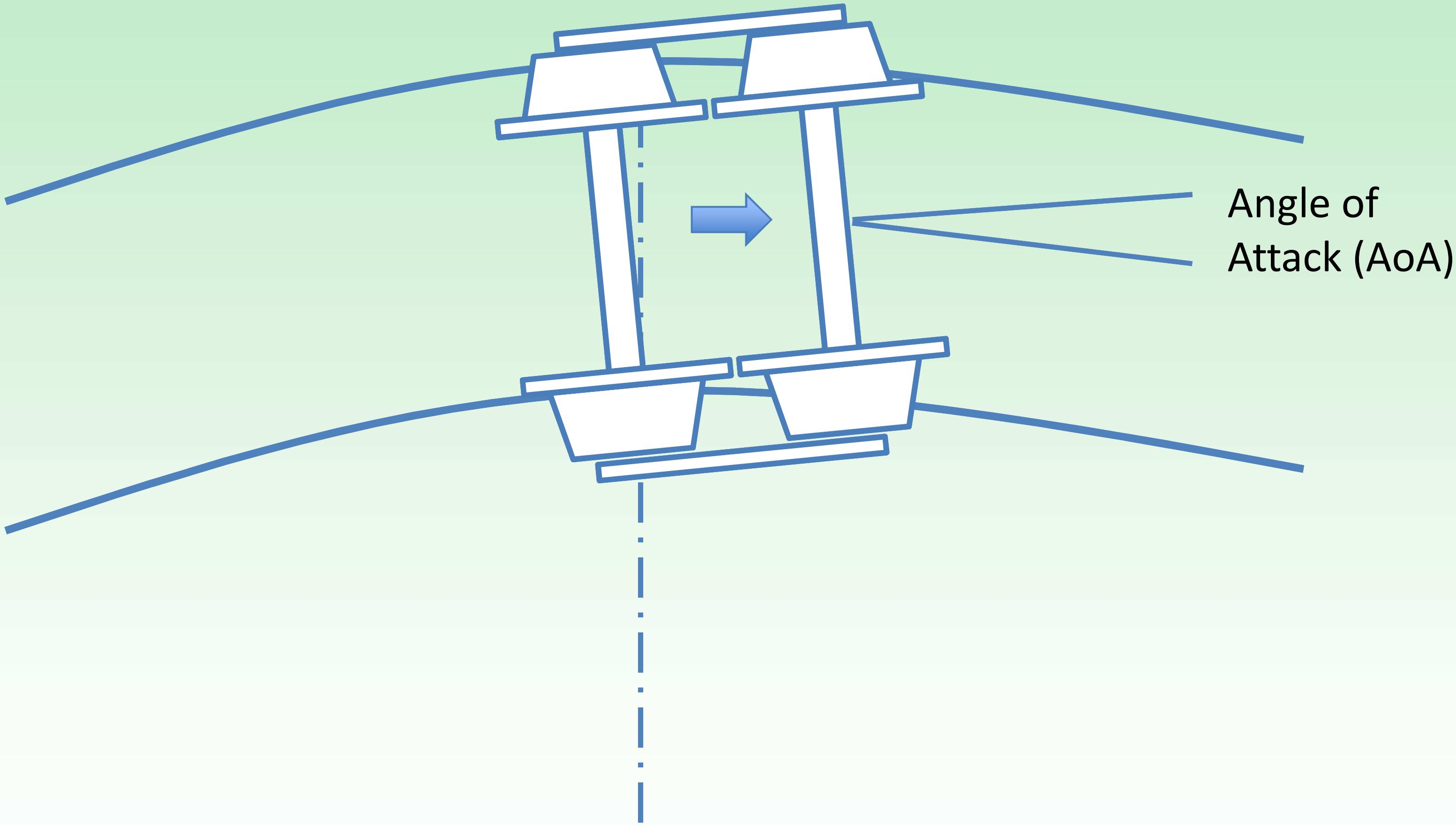
Steering in "Steady State" Curving ("Mild" Curves)



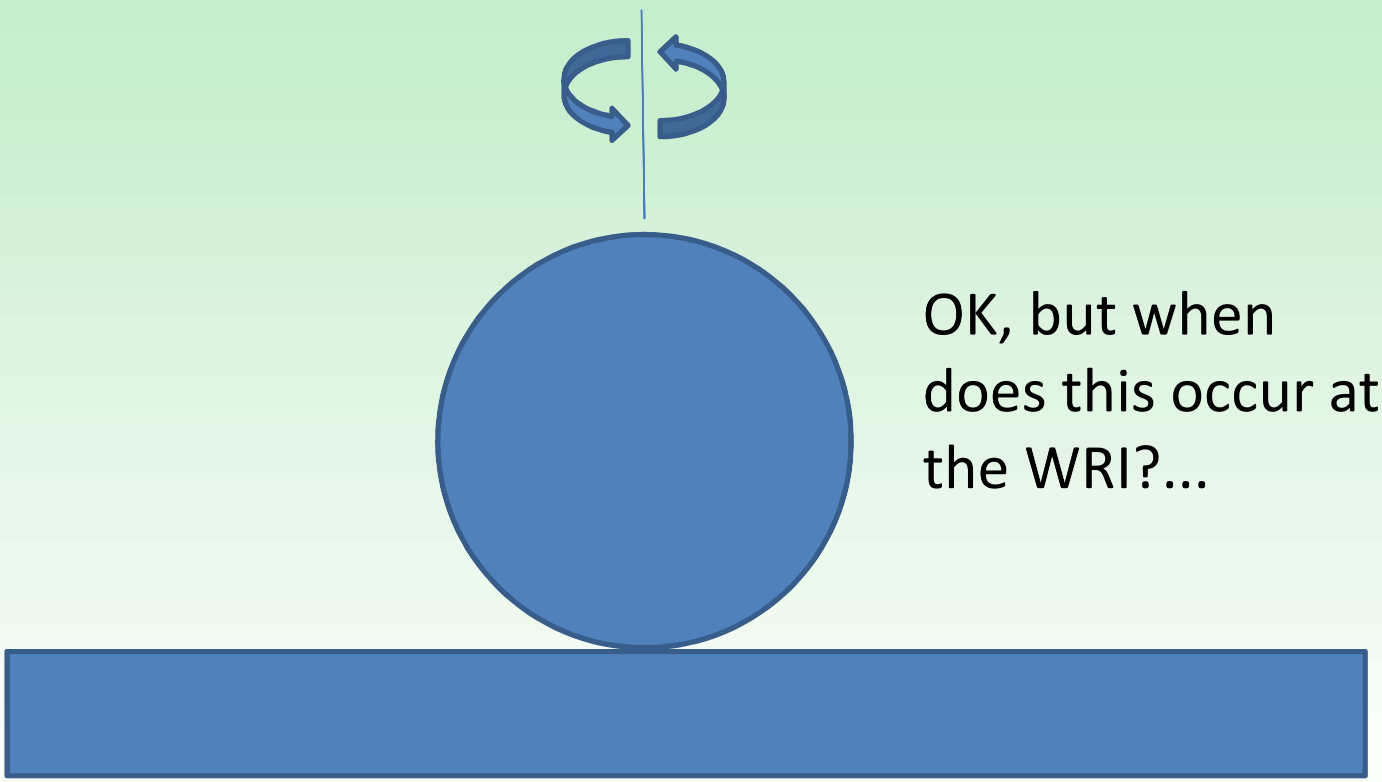
Steering in "Steady State" Curving ("Sharp" Curves)



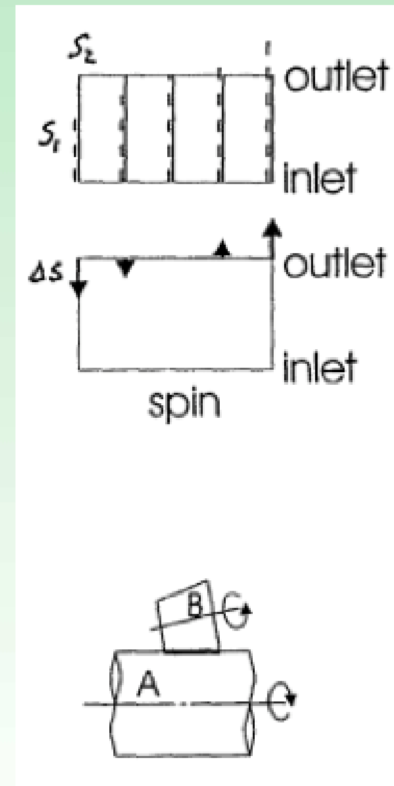
Steering in “Steady State” Curving (“Very Sharp” Curves)

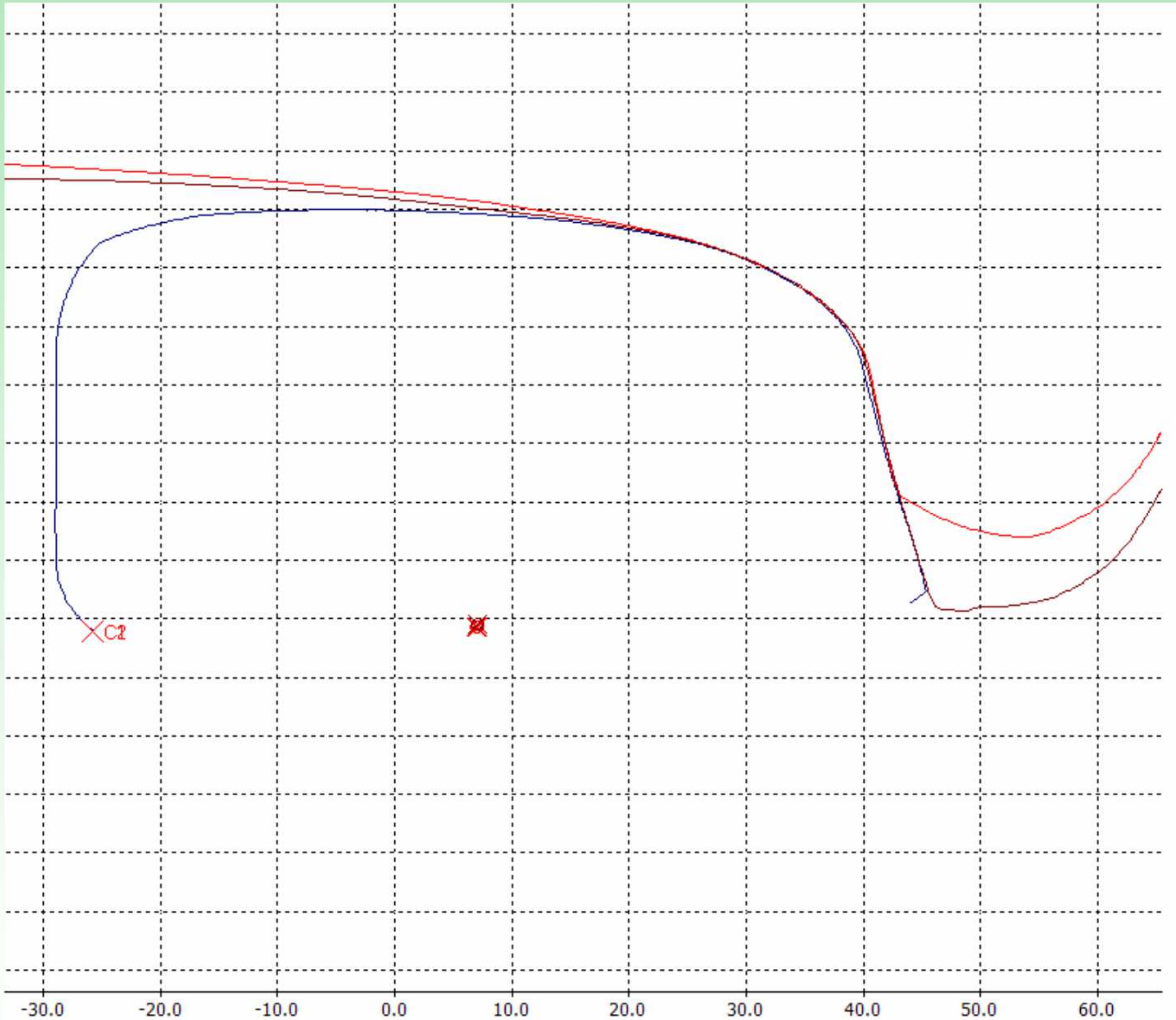


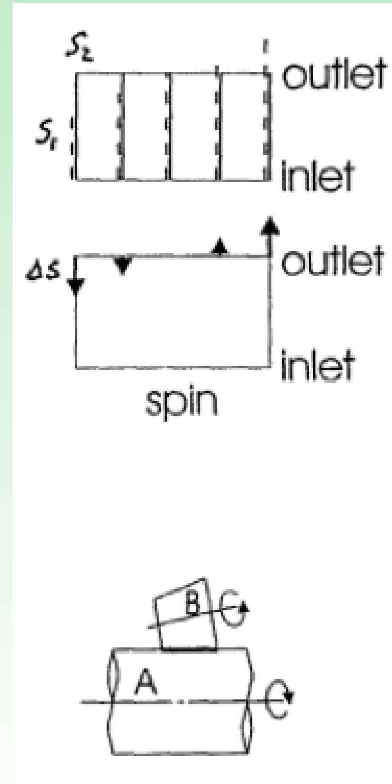
Spin Creepage
Think of spinning a coin on a tabletop….



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




C2
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0


S_2
outlet
S_1
inlet
Δs
outlet
inlet
spin
B
A

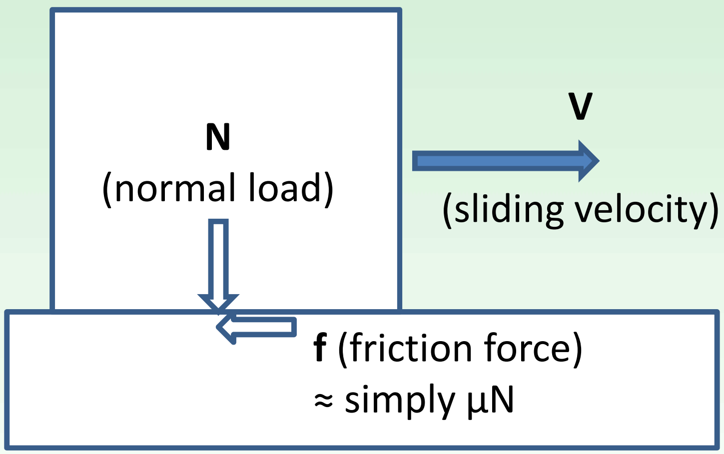
Rolling vs. Sliding Friction

They are not the same!

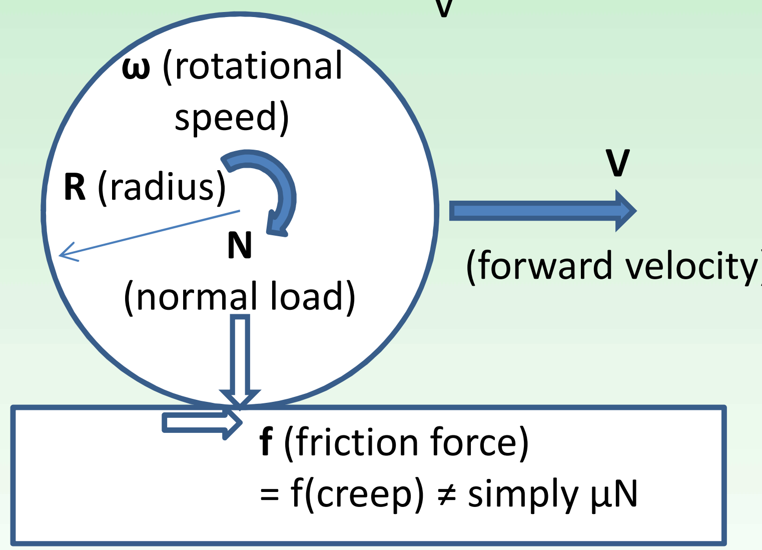
μ: coefficient of (sliding) friction

creep:

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

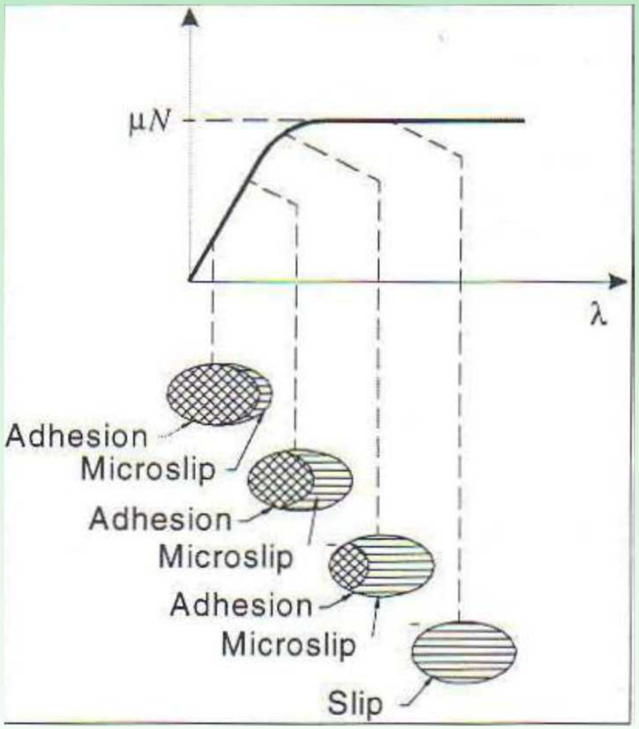


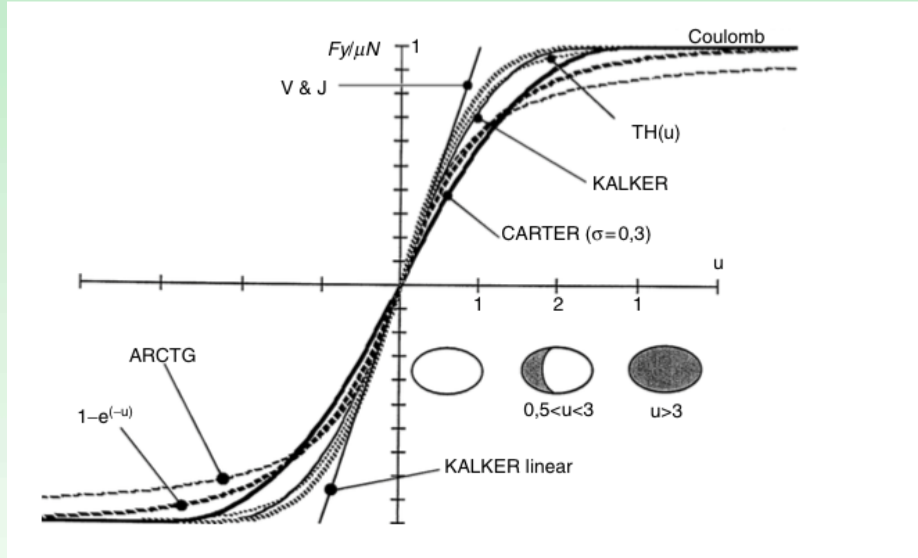
friction force shown as acting on block for positive sliding velocity



friction force shown as acting on wheel for positive creep

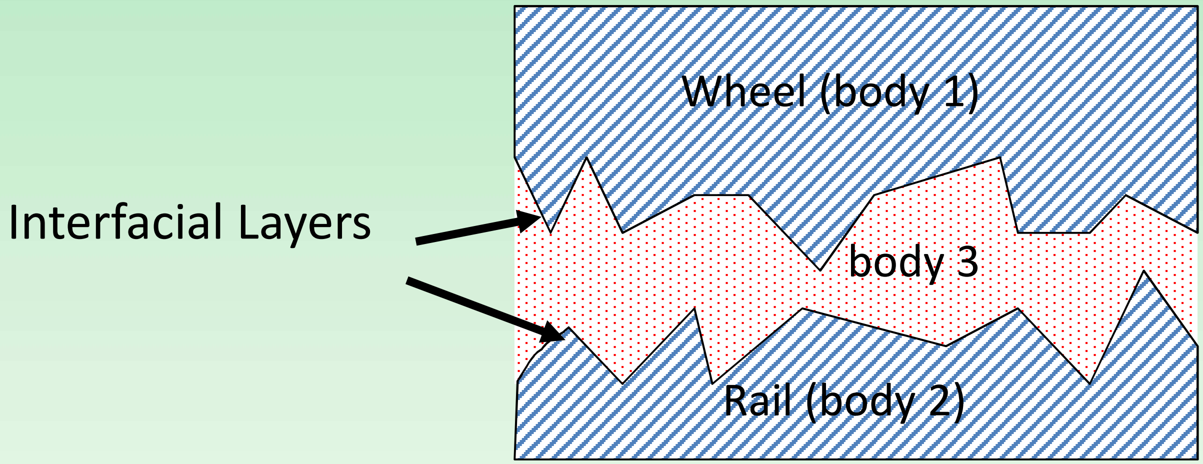
Traction/Creepage Curves





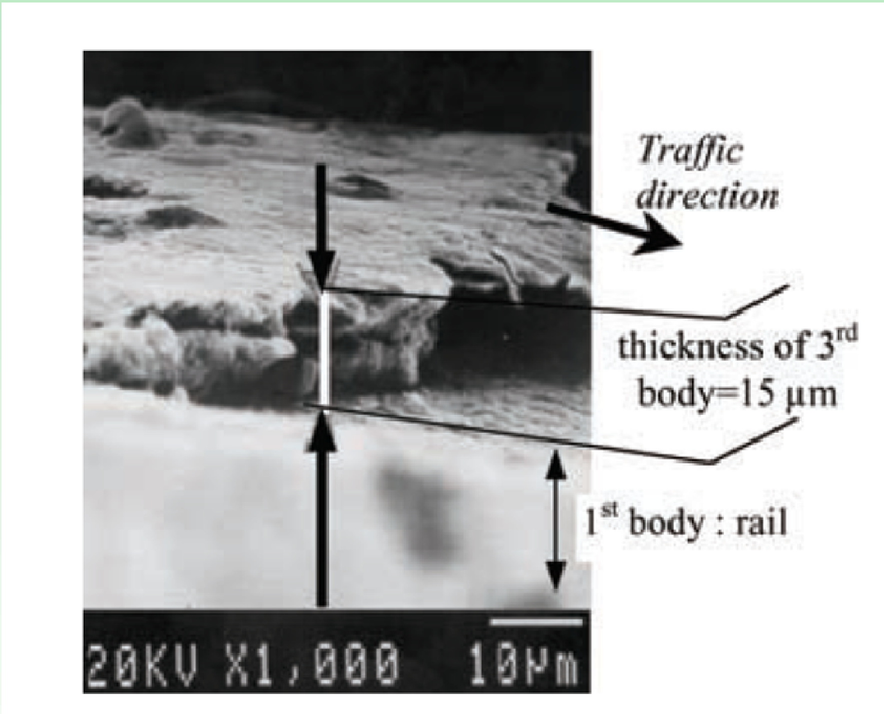
"Heuristic" expressions used for the saturation and physical meaning of the different parts.

Third Body at Wheel/Rail Contact

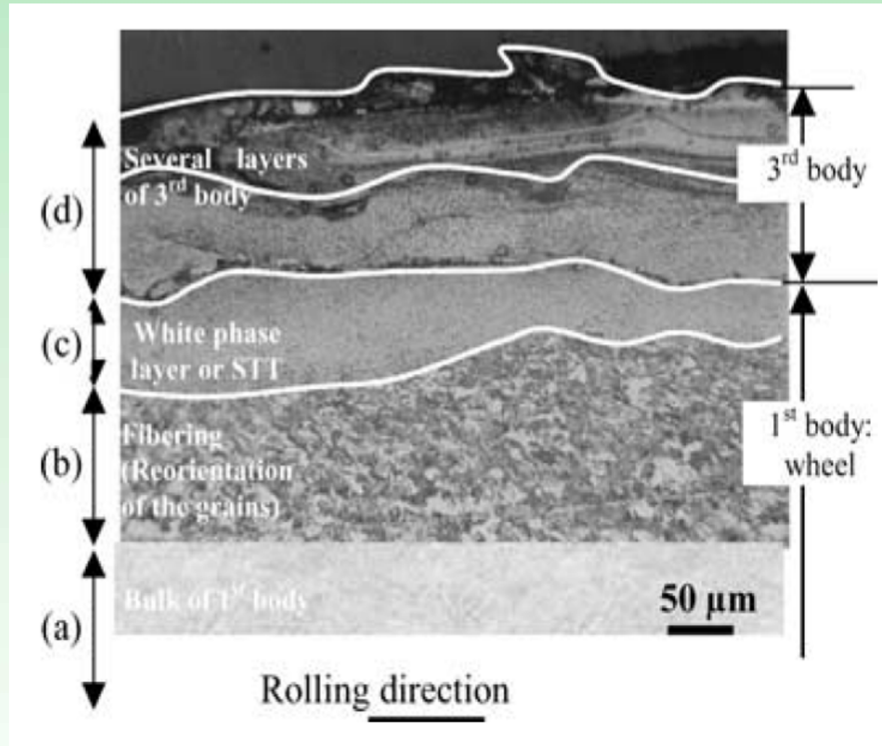


- Third Body is made up of iron oxides, sands, wet paste, leaves etc….
- Third Body separates wheel and rail surface, accommodates velocity differences and determines wheel/rail friction.
- Wheel/Rail friction depends on the shear properties / composition of the third body layer.

Third Body Layer – Micron Scale



Rail

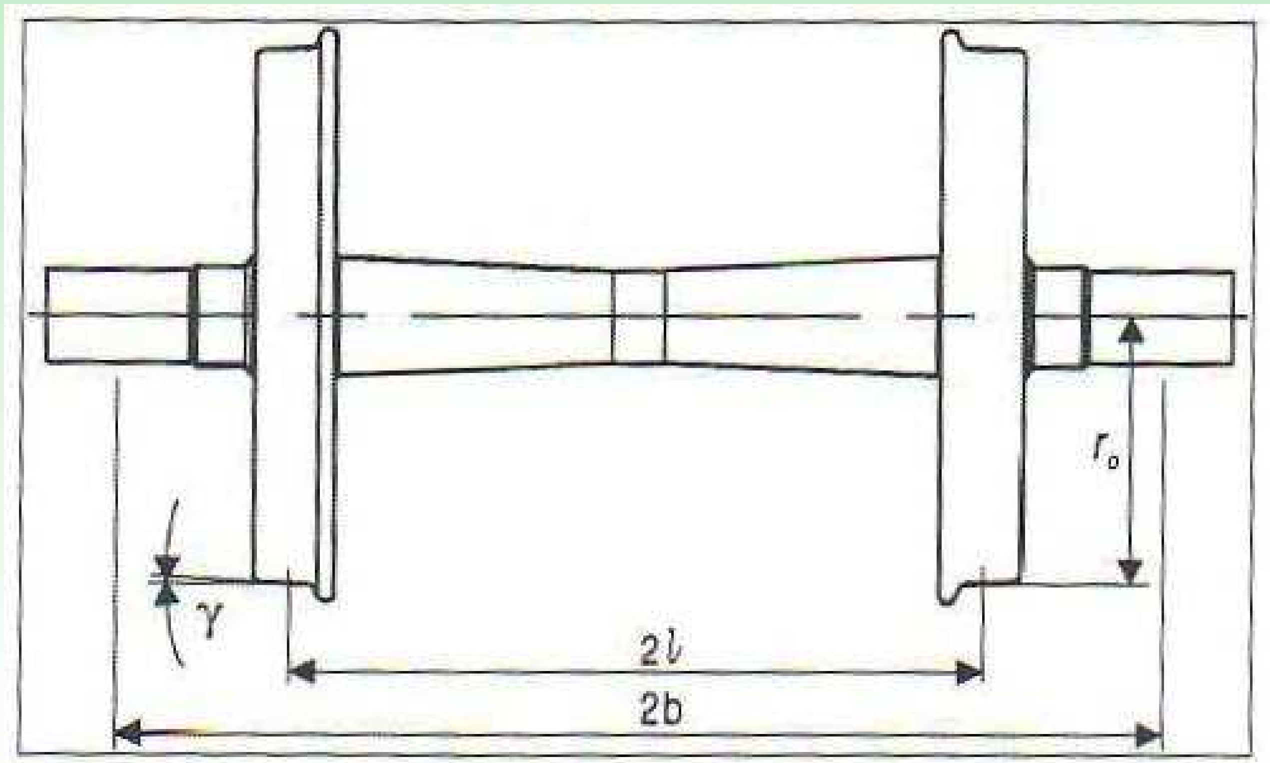


Wheel

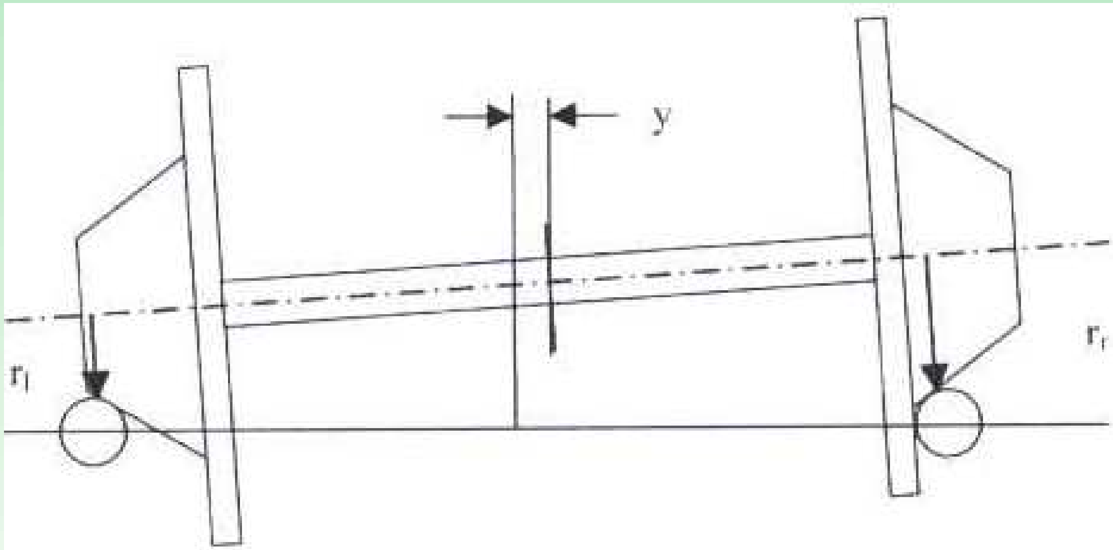
Y.Berthier, S. Decartes, M.Busquet et al. (2004). The Role and Effects of the third body in the wheel rail interaction. *Fatigue Fract. Eng. Mater Struct. 27, 423-436*

Vehicle Steering and Curving Forces

- The wheel set



Displaced wheel set



λ = effective conicity

r_0 = wheel radius of undisplaced wheelset

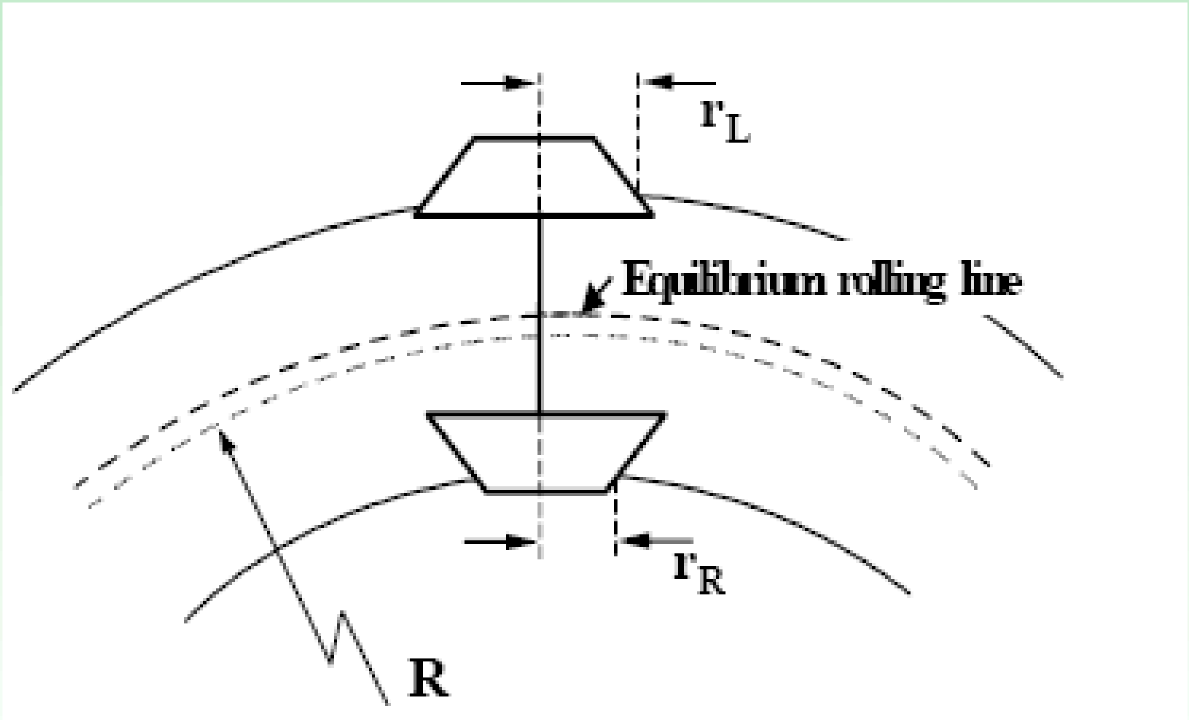
R = curve radius

L_0 = half gauge

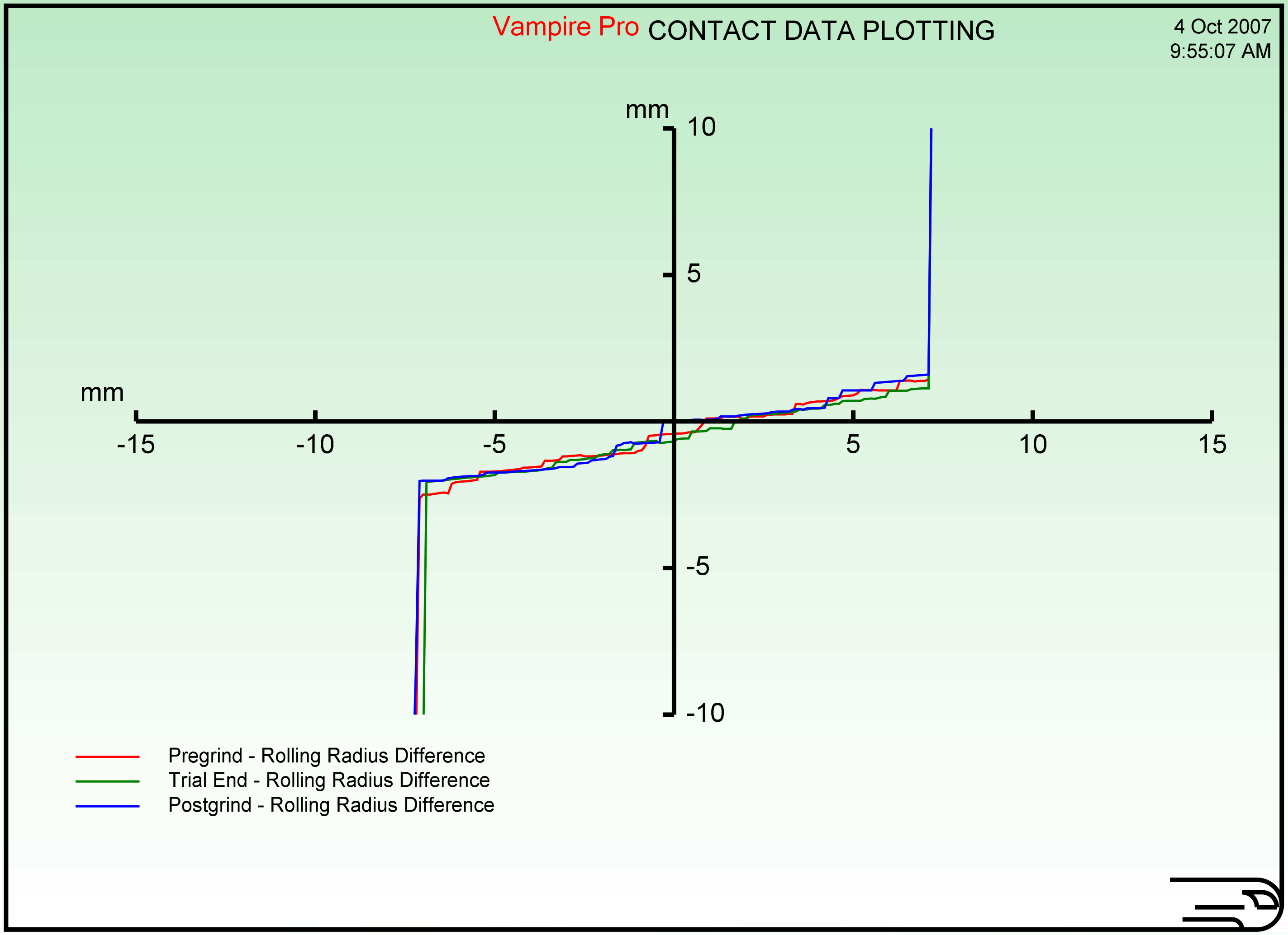
$$\boxed{\frac{r_0 - \lambda y}{r_0 + \lambda y} = \frac{R - l_0}{R + l_0},}$$

$$\boxed{y = \frac{r_0 l_0}{R\lambda}.}$$

Theoretical Equilibrium

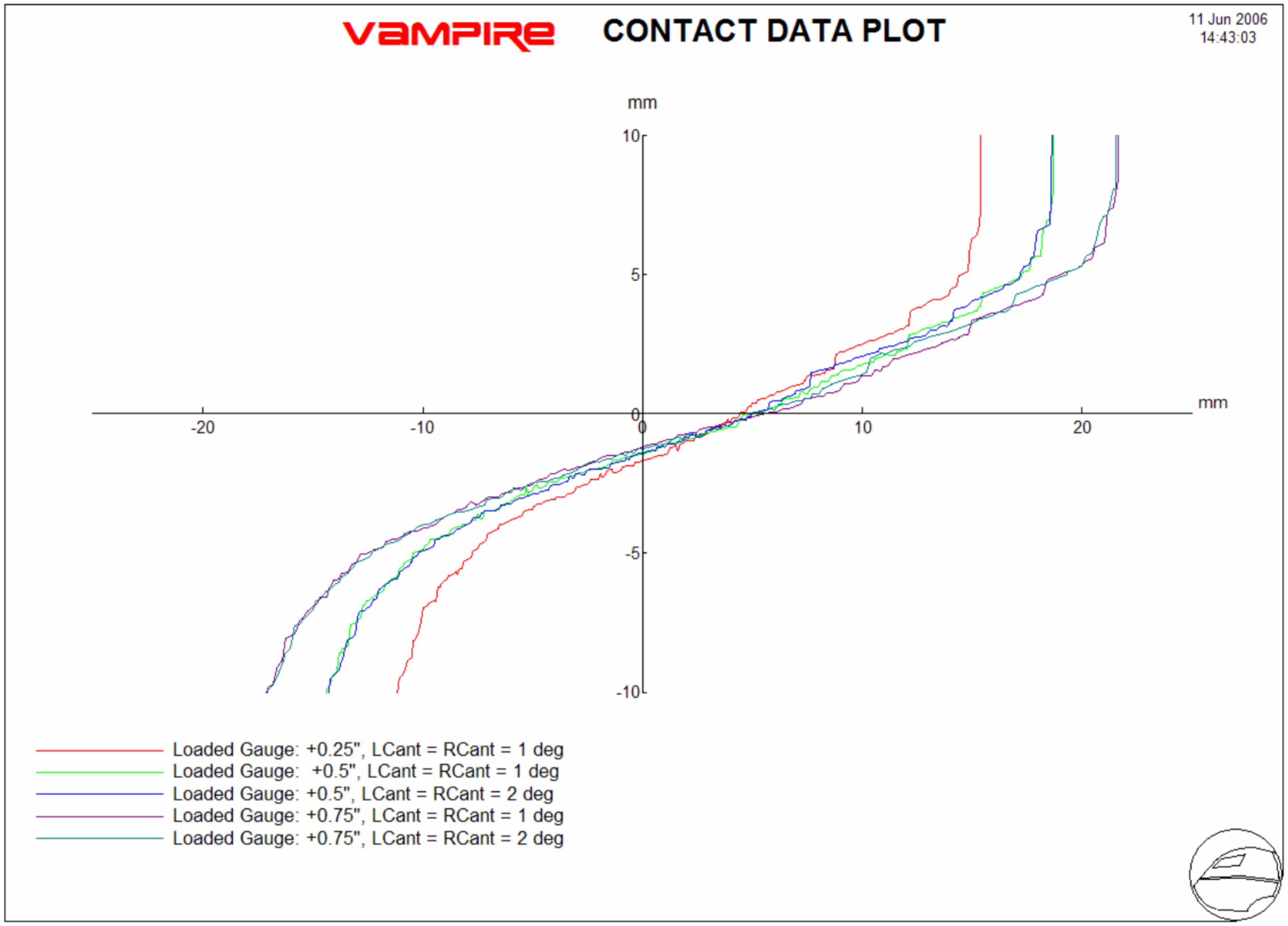


Effective Conicity



Rolling Radius Difference

Effective Conicity (Worn Wheels)



VAMPIRE Plot

Important Concept:

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

Effect of rolling radius difference on steering moment

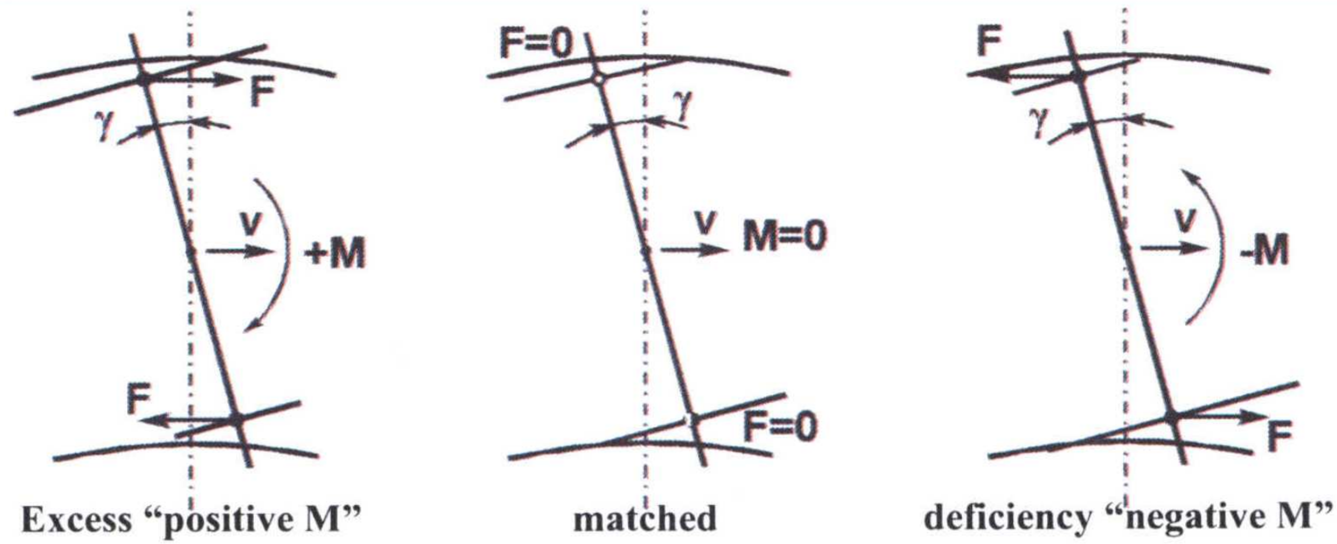
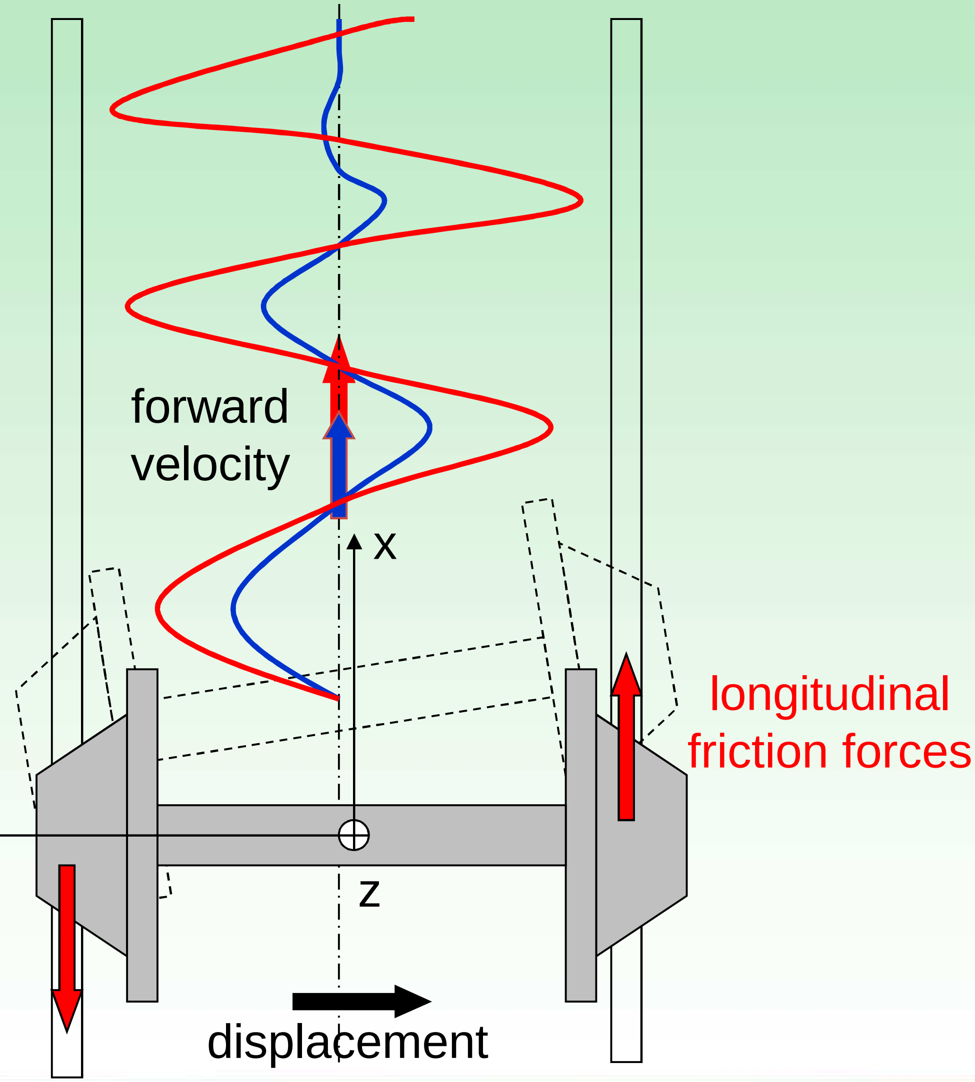


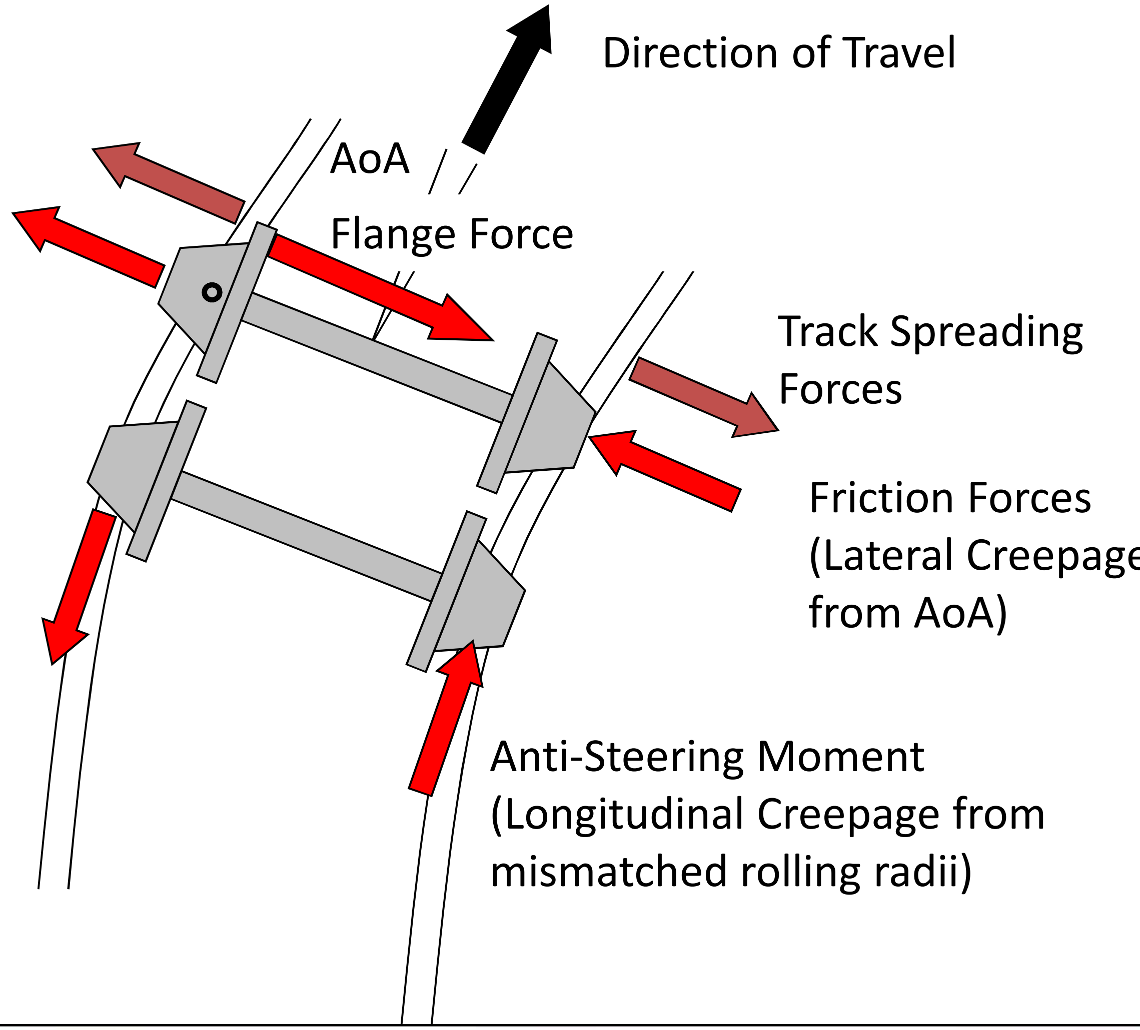
Figure 2: effect of rolling radius difference on longitudinal component of creepage force

Tangent Running and Stability

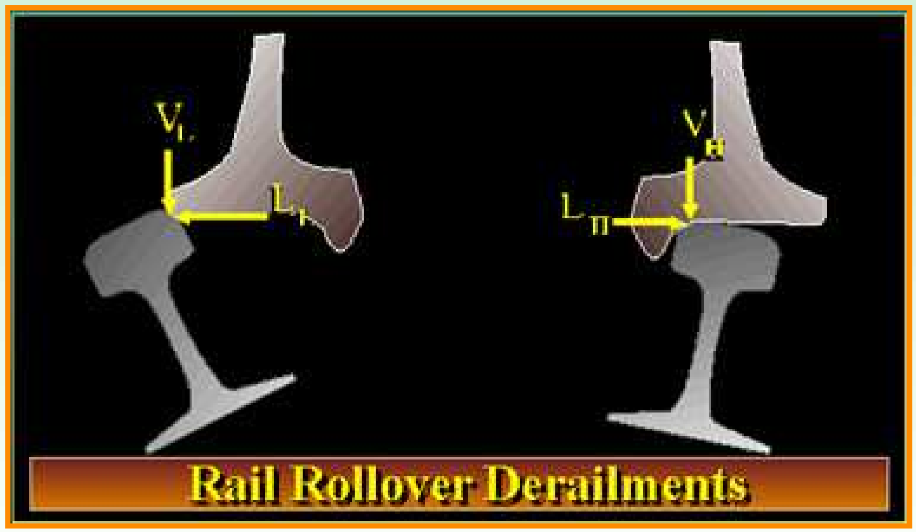
- Lateral displacement
  → ΔR mismatch
  → friction forces
  → steering moment
- Wheelset passes through central position with lateral velocity.
- At low speeds, oscillations decay.
- Above critical hunting speed, oscillations persist.



Curving Forces (101)

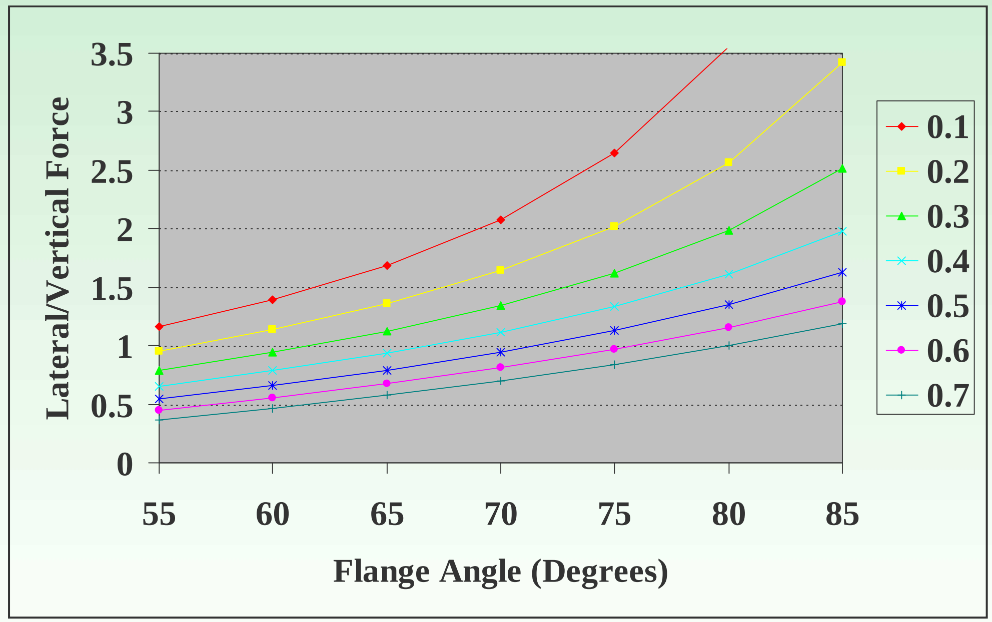


Impacts of High Lateral Loads: Rail Rollover / Track Spread Derailments

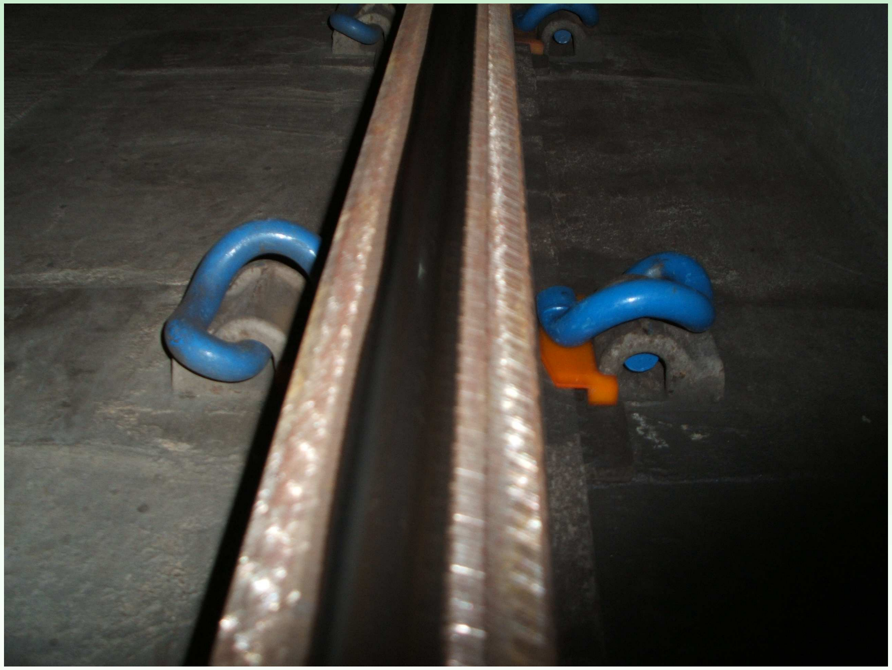


Impacts of High Lateral Loads: Plate Cutting, Gauge Widening

Impacts of High Lateral Loads: Wheel Climb Derailments

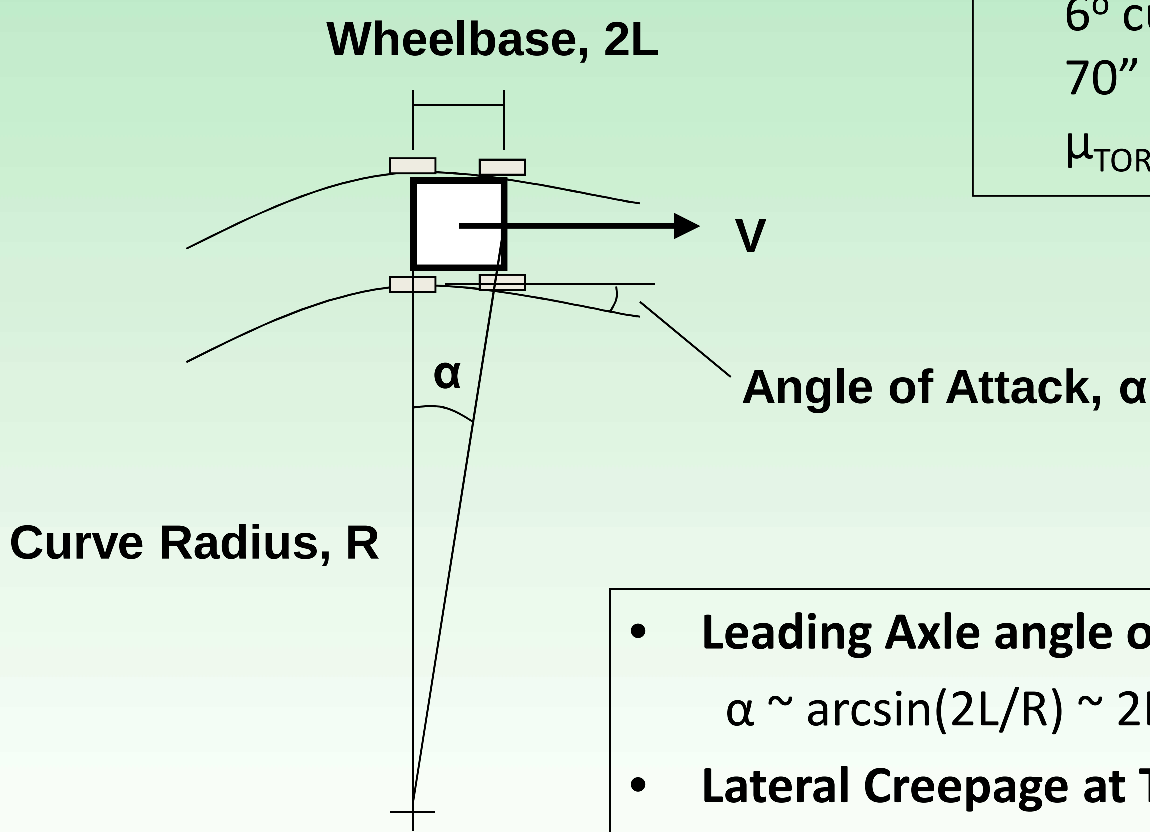


Impacts of High Lateral Loads: Fastener Fatigue / Clip Breakage



Returning to Question #1: How can we estimate the lateral forces (and L/V ratios) that a vehicle is exerting on the track?

Estimating AoA and Lateral Creepage in a “Sharp” Curve

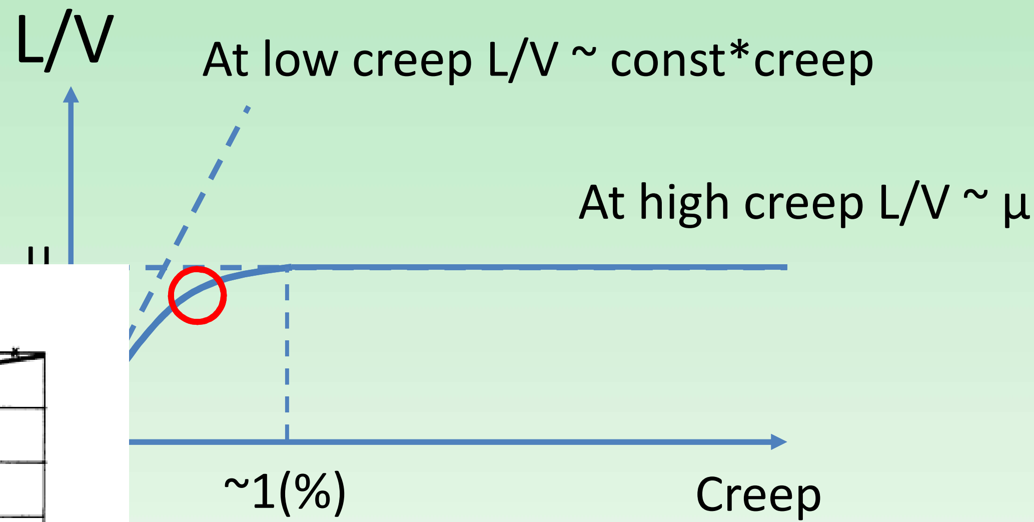


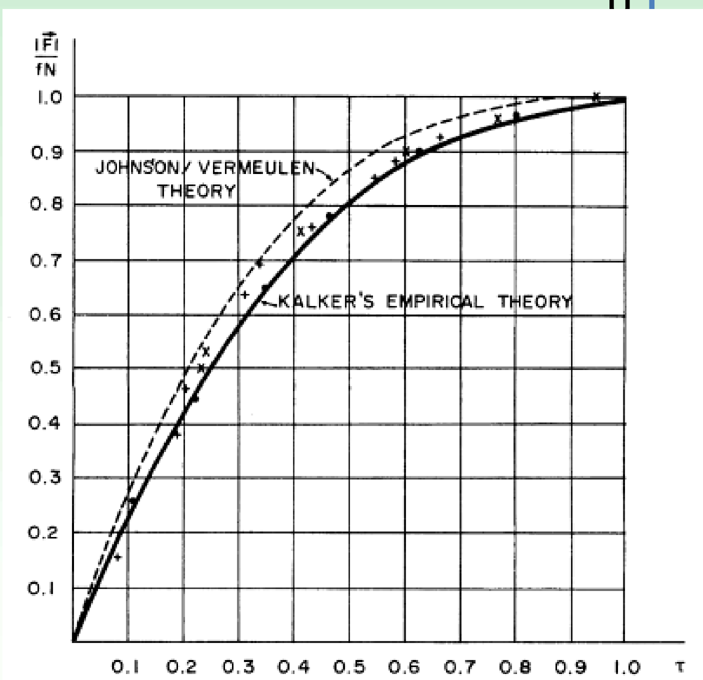
- Example:
  6^o curve (R = 955’)
  70” wheelbase (2L = 5.83’)
  μ_{TOR} = 0.5 (dry)

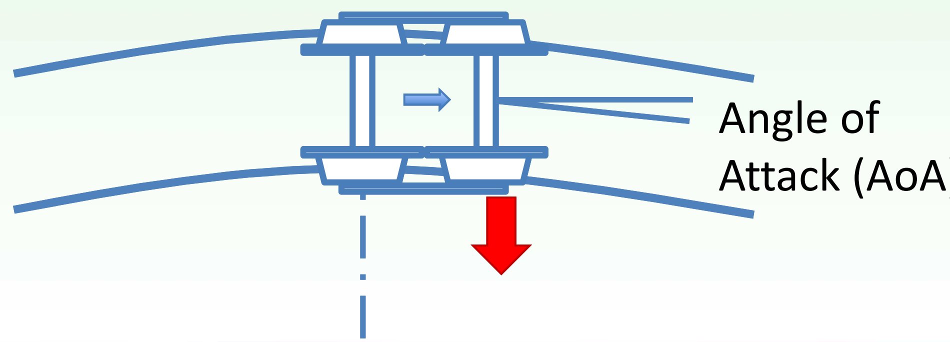
- **Leading Axle angle of attack:**
  $\alpha \sim \arcsin(2L/R) \sim 2L/R = 0.0061$ Rad (6.1 mRad)
- **Lateral Creepage at TOR contact:**
  $V_{lat}/V \sim 2L/R \sim \alpha = 0.61\%$

Estimating Low Rail L/V and Lateral Force

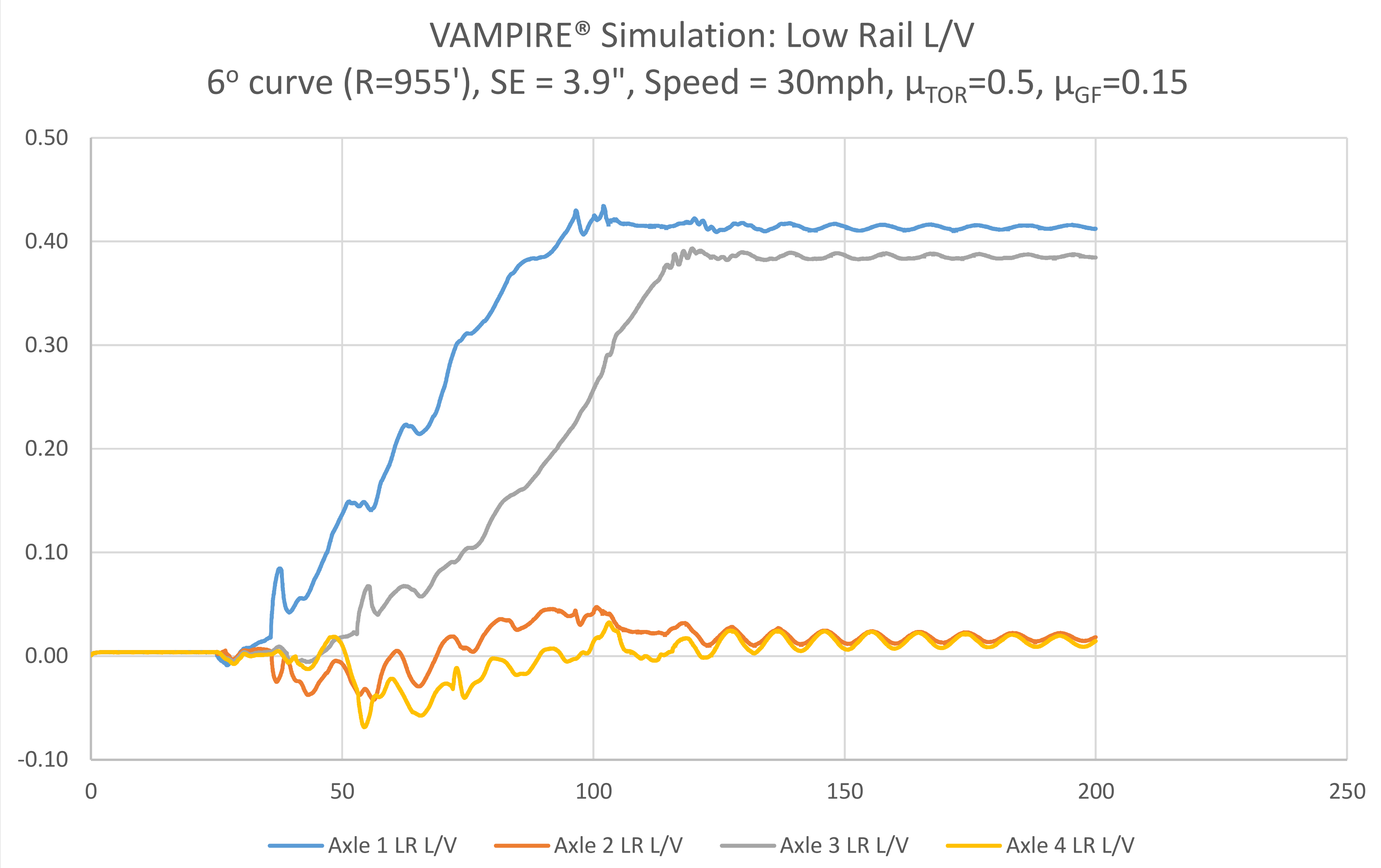
- At 0.61% creep: L/V = _______ μ







How does this compare with simulation results?



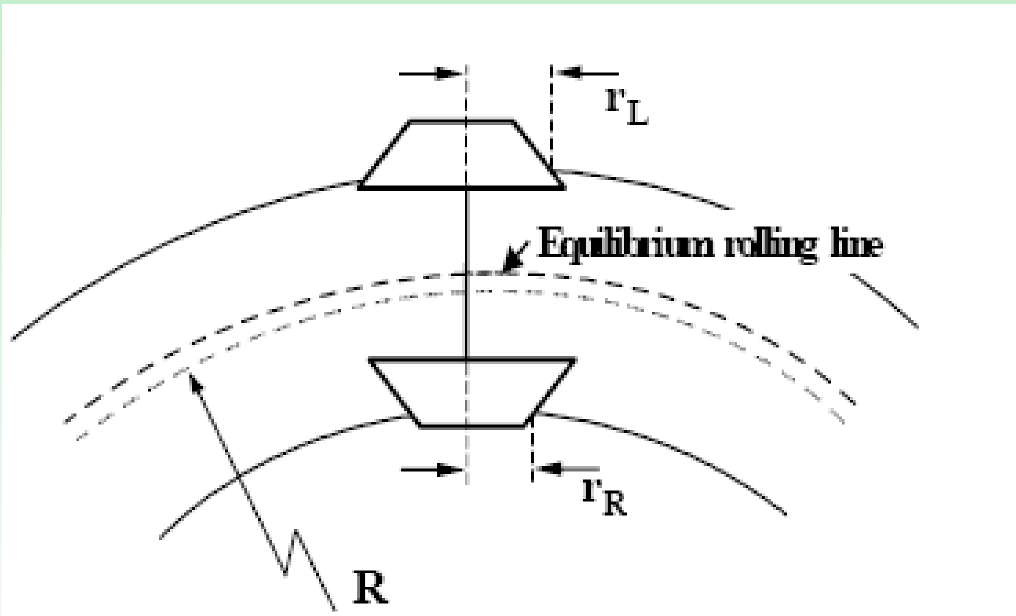
Questions & Discussion

Overview: Part II

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

Curving Forces (201)

- Remember this?

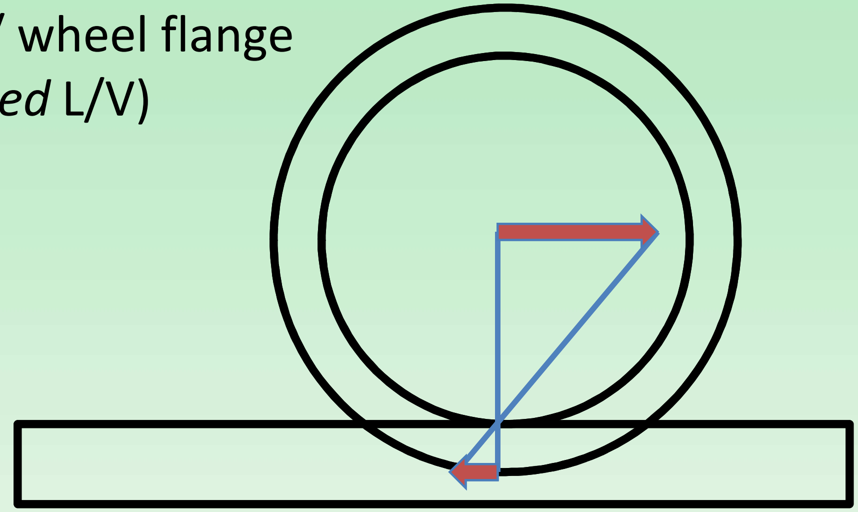


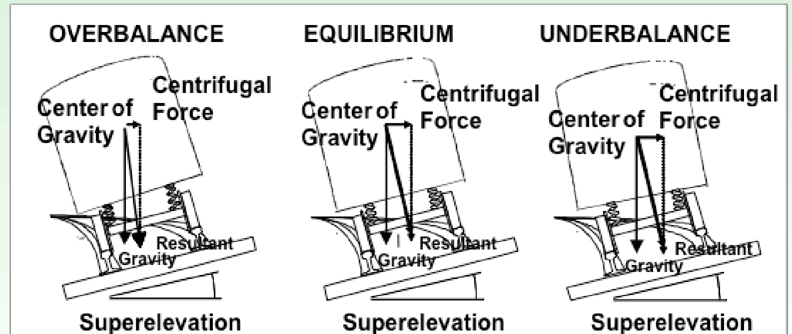
How often to we see a single (isolated) wheel set in operation?

Hopefully not very often!

Factors Affecting Curving Forces

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





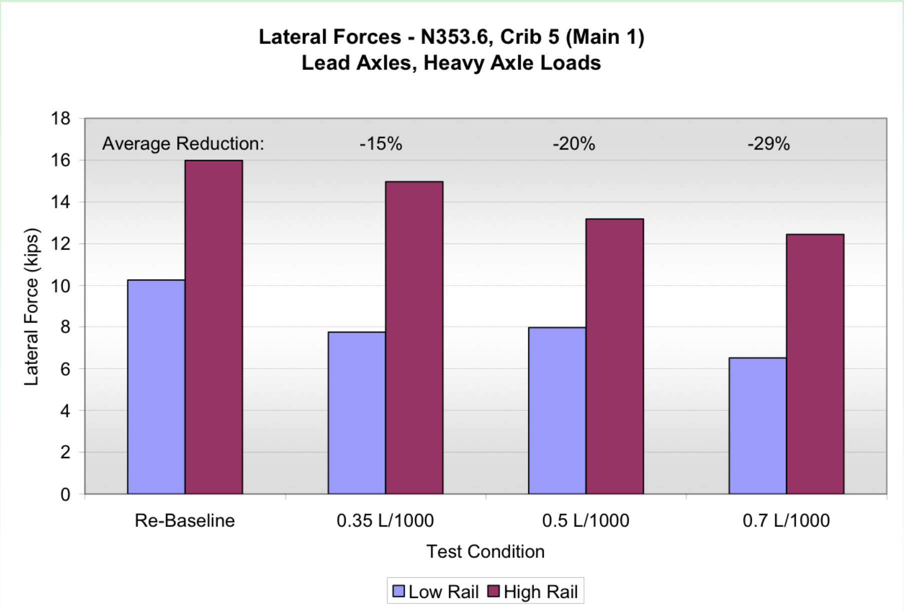
$$V_{max} = \sqrt{\frac{E_a + 3}{0.0007D}}$$

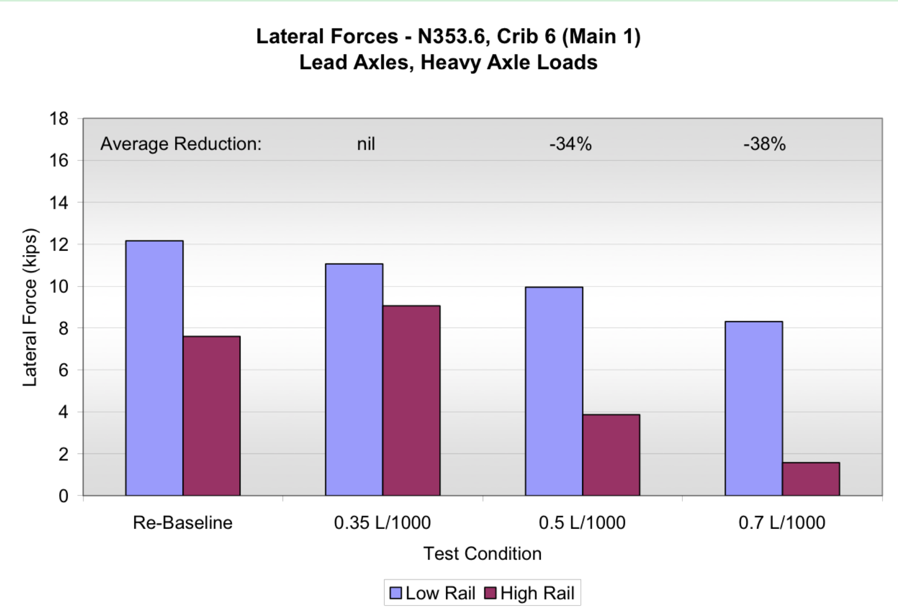
Amount of Underbalance

V_{max} = Maximum allowable operating speed (mph).
E_a = Average elevation of the outside rail (inches).
D = Degree of curvature (degrees).

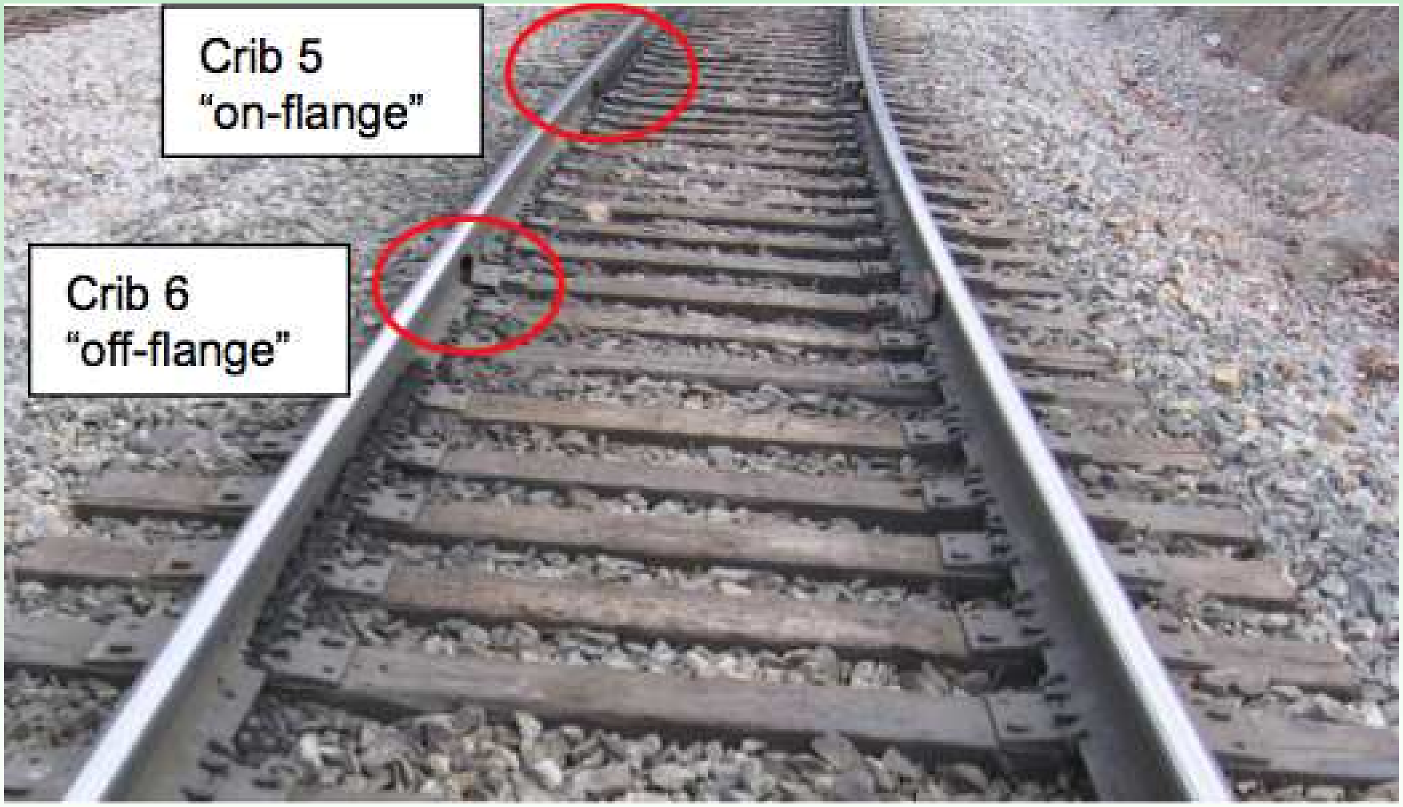
An example…

- Why are the lateral forces measured a few cribs apart so different?





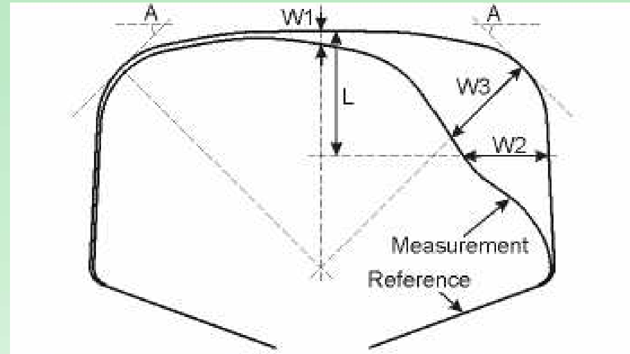
Mystery solved…



Rail and Wheel Wear

Rail and Wheel Wear

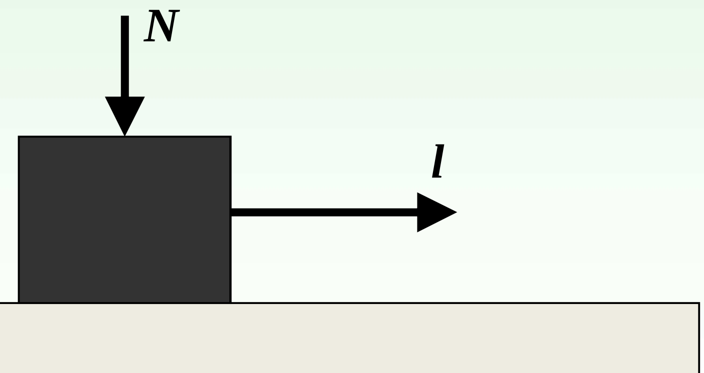
- Wear Types:
  - Adhesion
  - Surface Fatigue
  - Abrasion
  - Corrosion
  - Rolling Contact Fatigue
  - Plastic Flow



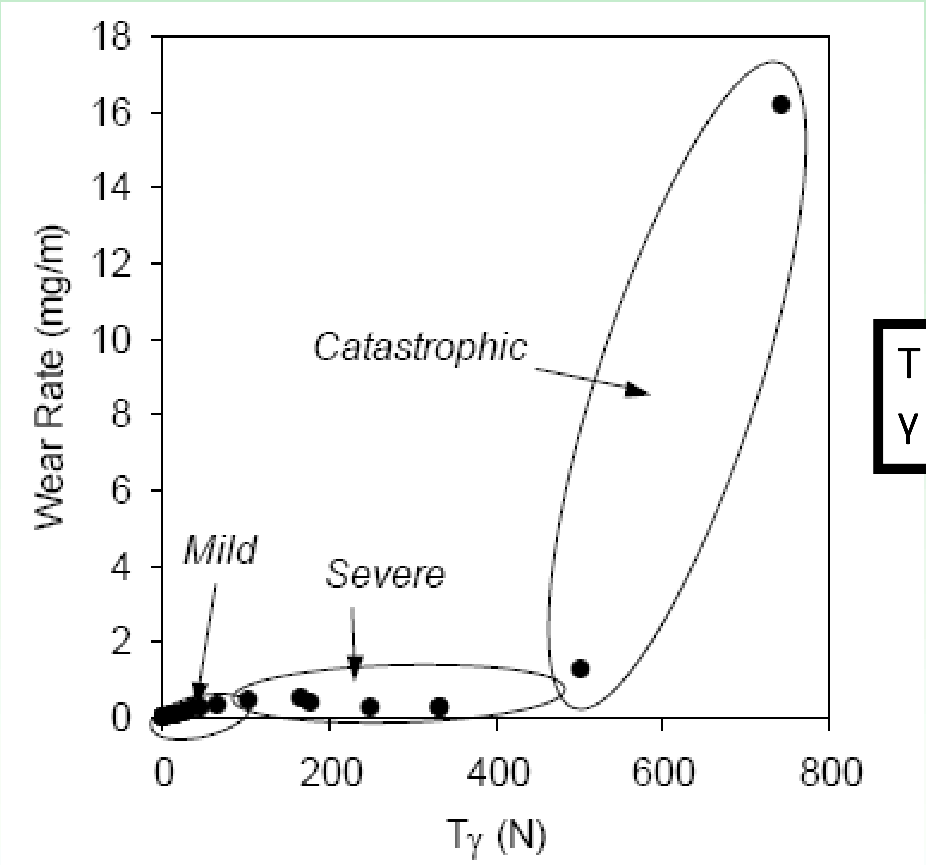
- "Archard" Wear Law: $$V = c\frac{Nl}{H}$$

c proportional to COF

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



Wear regimes

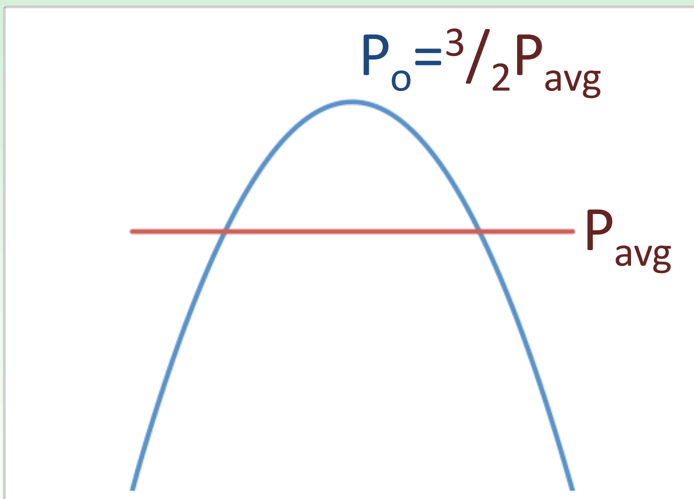


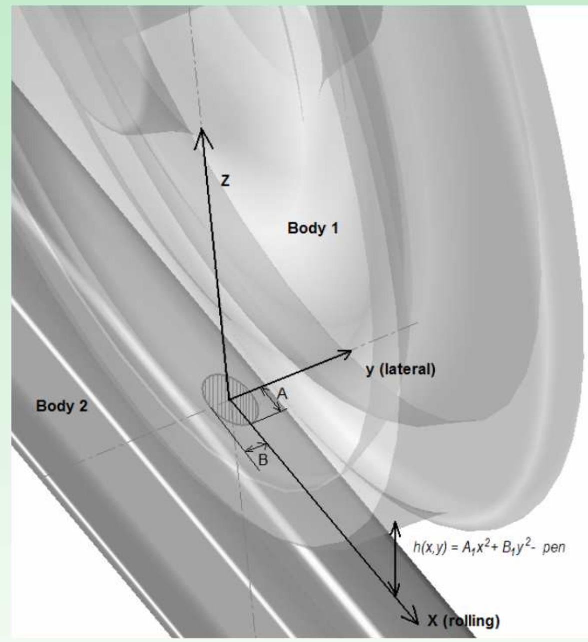
T = Tractive force
γ = Slip

Shakedown and Rolling Contact Fatigue (RCF)

Recall: Hertzian Contact

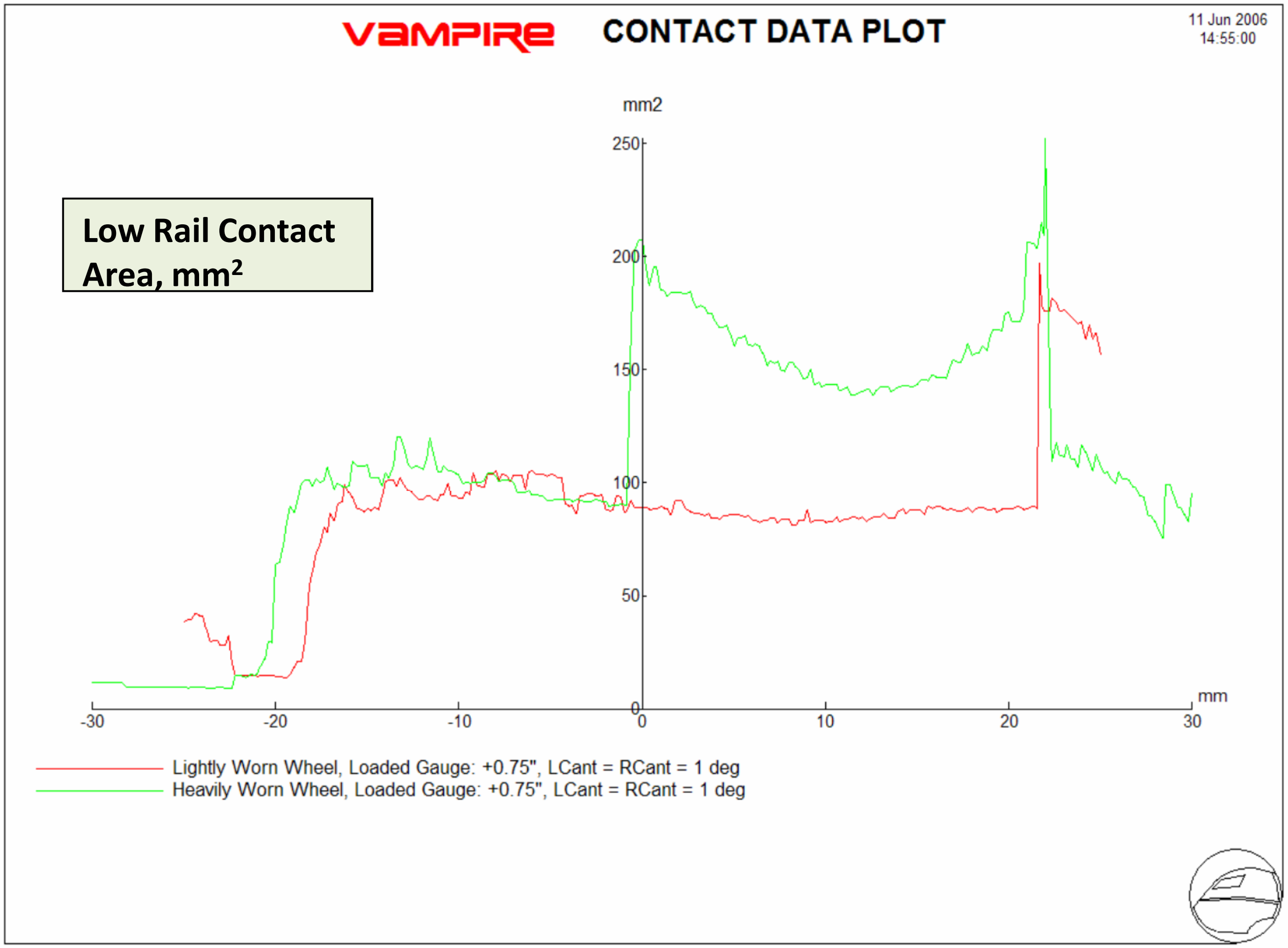
- "Contact Patches" tend to be **elliptical**
- This yields **parabolic** contact pressures





The Contact Patch and Contact Pressures

The Contact Patch and Contact Pressures



VAMPIRE Plot

Example calculation: Average and Peak Pressure

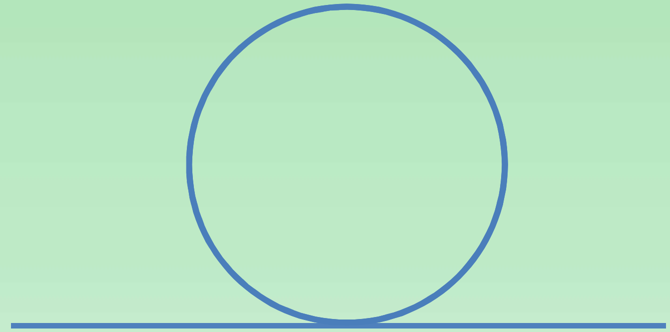
- Let's assume a circular contact patch, with a radius of **0.28" (7 mm)**
- The contact area is then: **0.24 in^2 (154 mm^2)**
- Assuming a HAL vehicle weight (gross) of 286,000 lbs, we have a nominal wheel load of 35,750 lbs, i.e. **35.75 kips (159 kN)**
- The resulting average contact pressure (Pavg)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

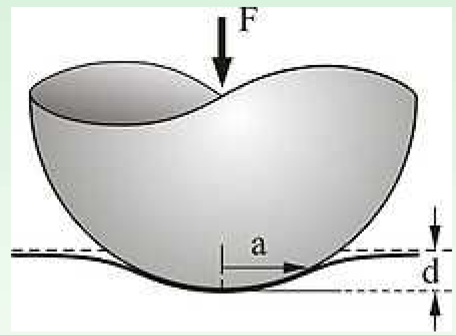
Steel	Hardness (Brinnell)	K	
		ksi	MPa
"Standard"	260-280	65-70	448-483
"Intermediate"	320-340	80-85	552-587
"Premium"	340-380	85-95	587-656
"HE Premium"	380-400	95-100	656-691

**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)

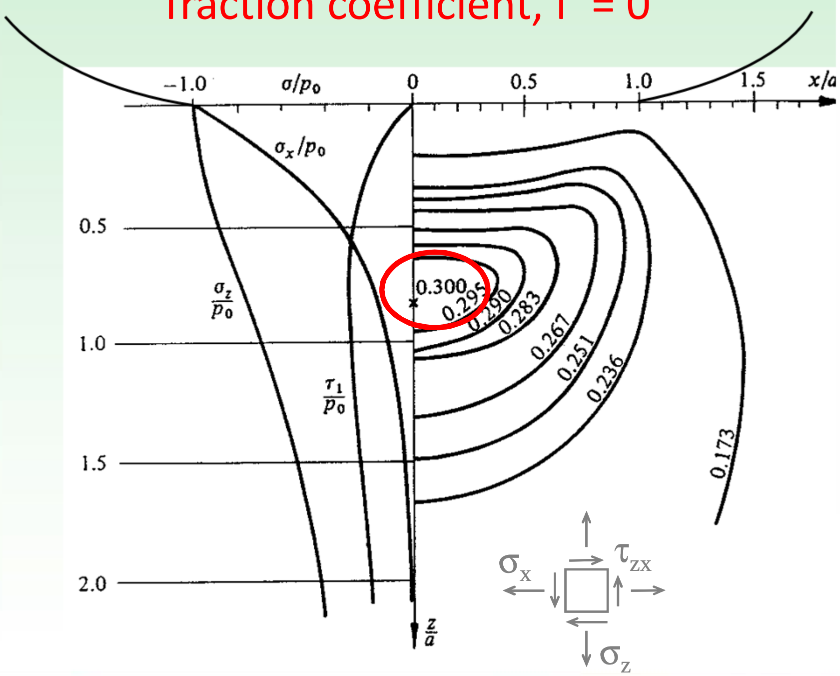


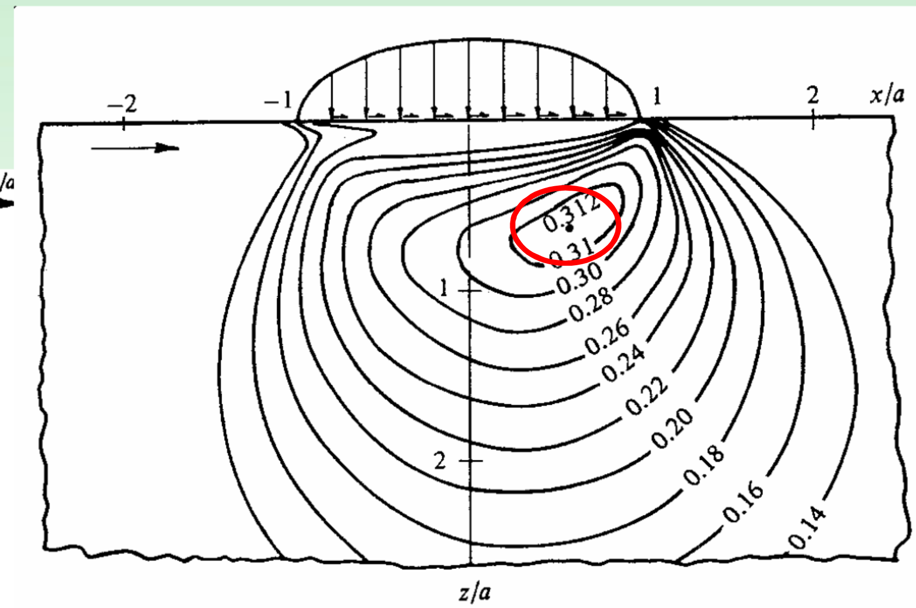
Spherical Contact with Elastic Half-Space (3-D loading)

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



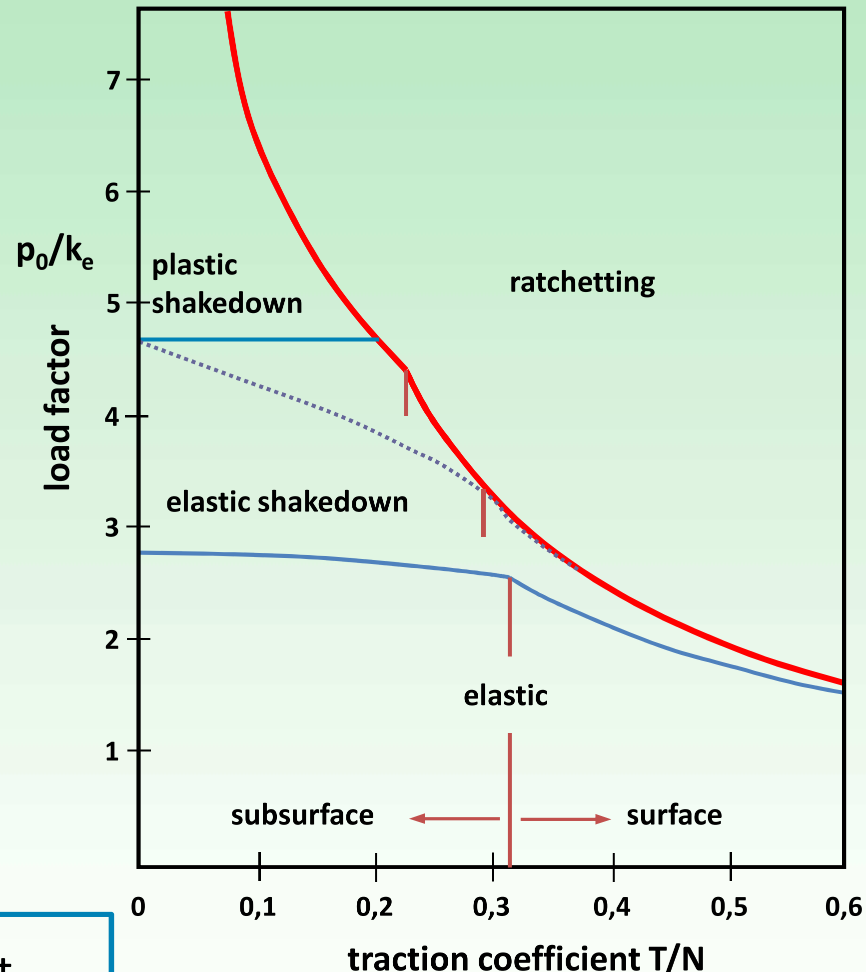


Traction coefficient, f = 0.2

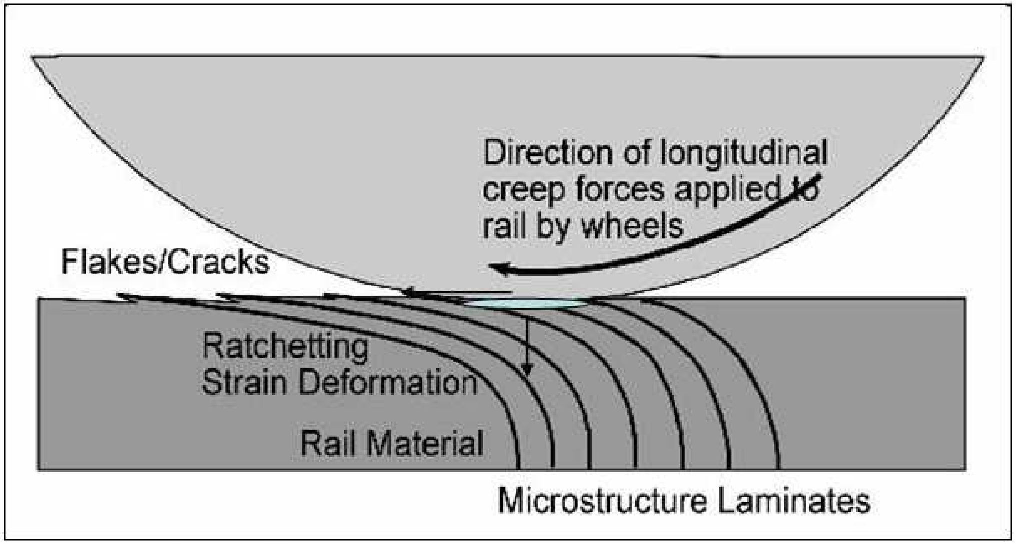
RCF Development: Shakedown

Increased Mat'l Strength

Reduced Stress
(e.g. wheel/rail profiles)

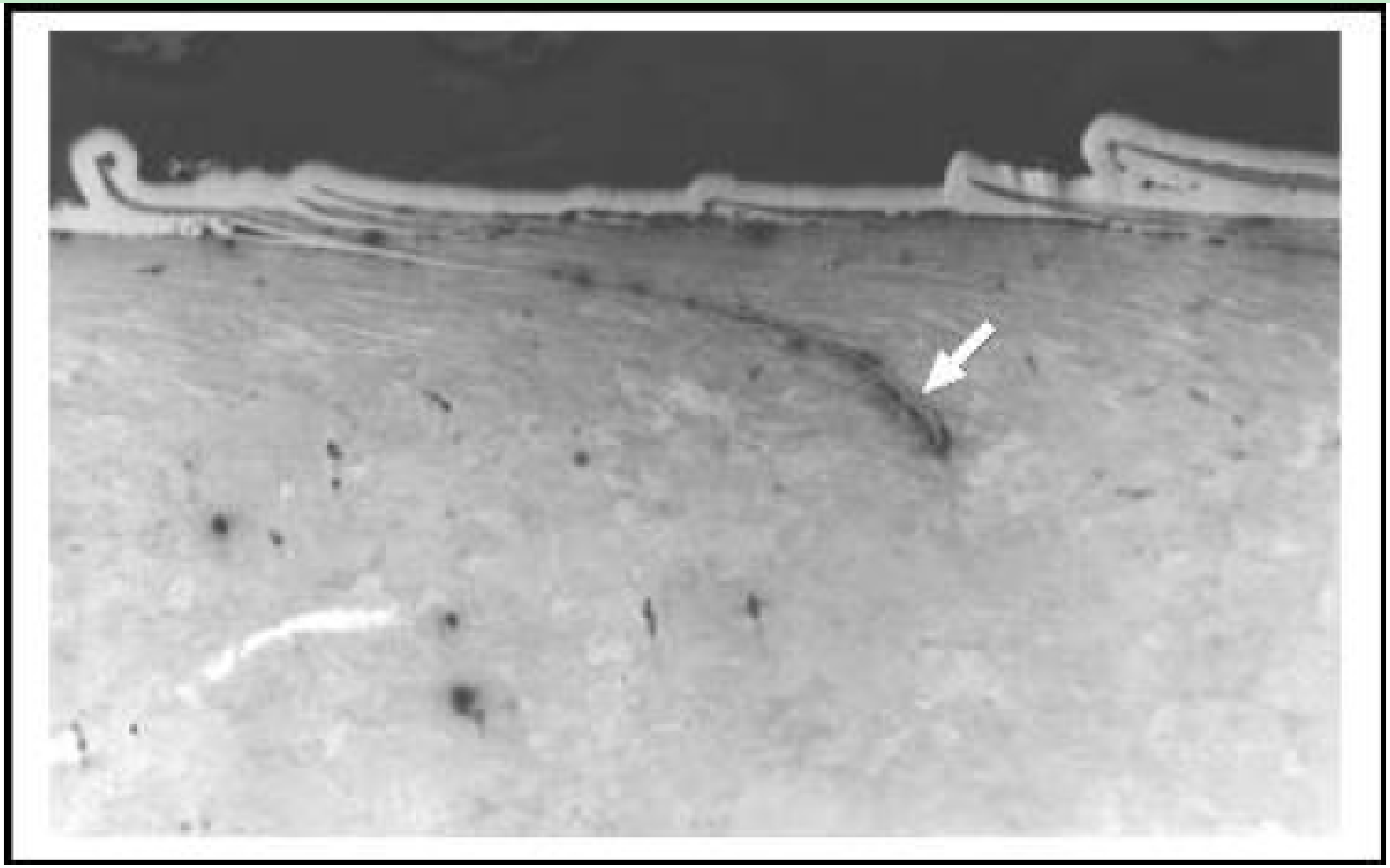


Reduced Traction Coefficient
(e.g. reduced friction)


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

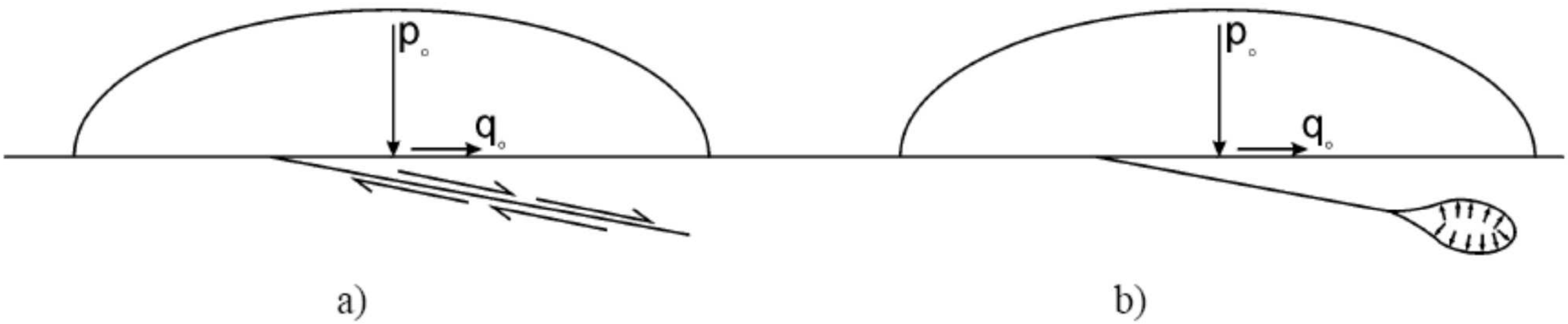
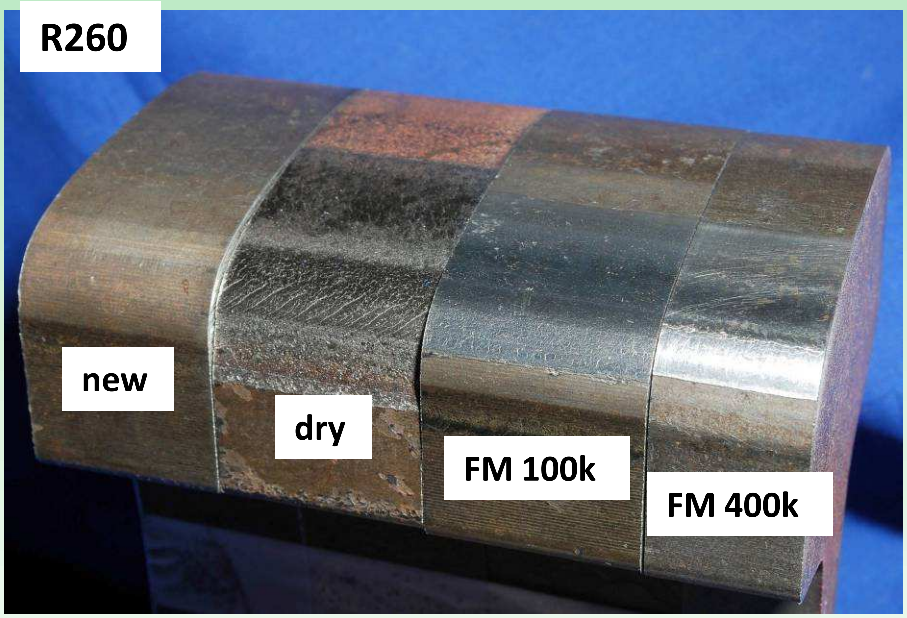
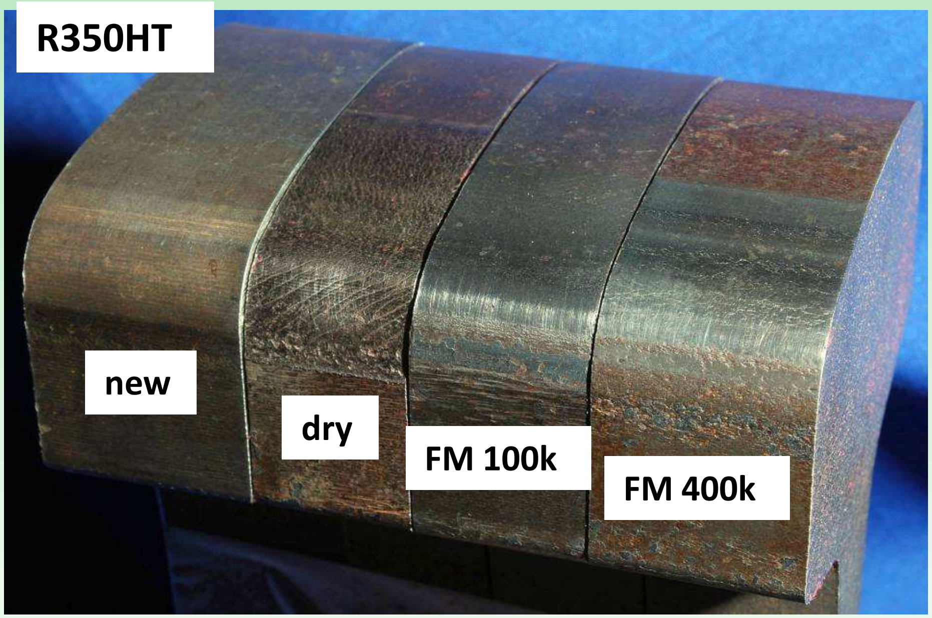
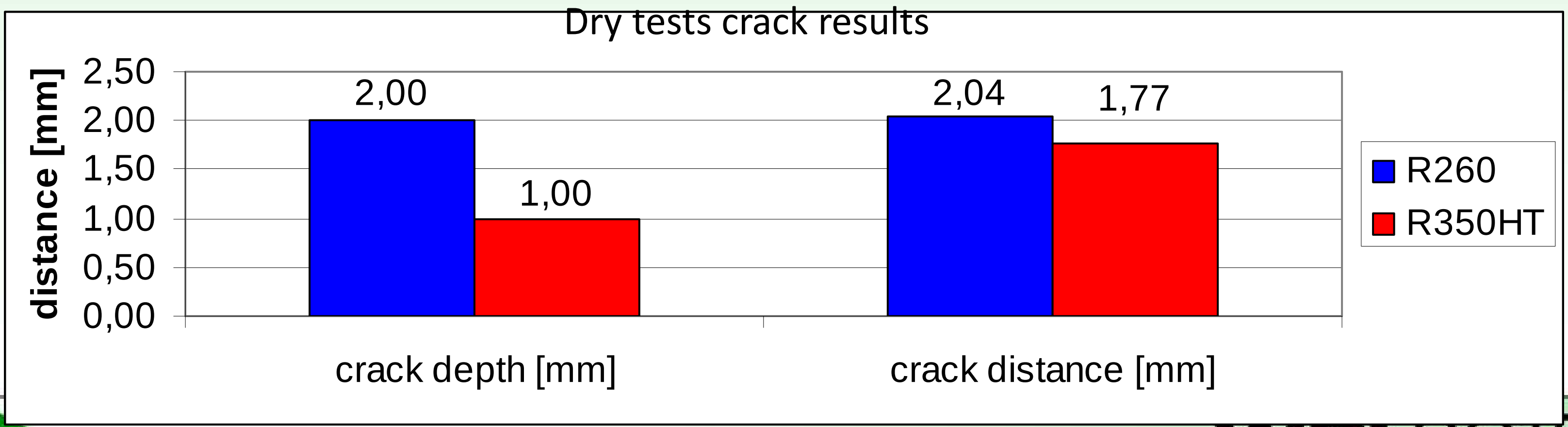


Figure 8: Influence of grease and water on crack propagation through a) control of crack-face friction, and b) hydraulic pressurization of the crack tip.

Wear and RCF
wheel/rail rig test results







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 **μ = 0.6**

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

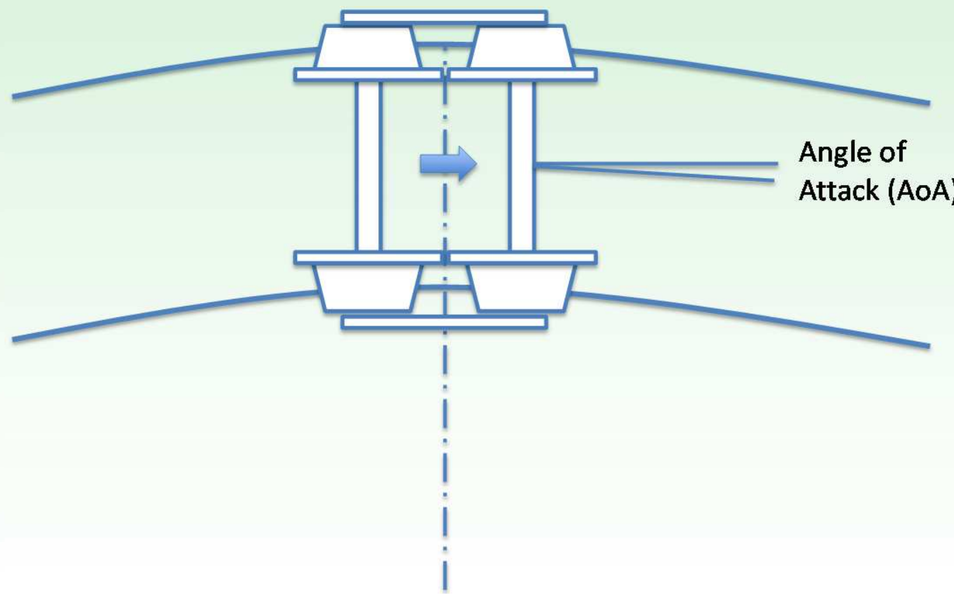
Estimating lateral creepage, traction ratio & contact pressure:

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

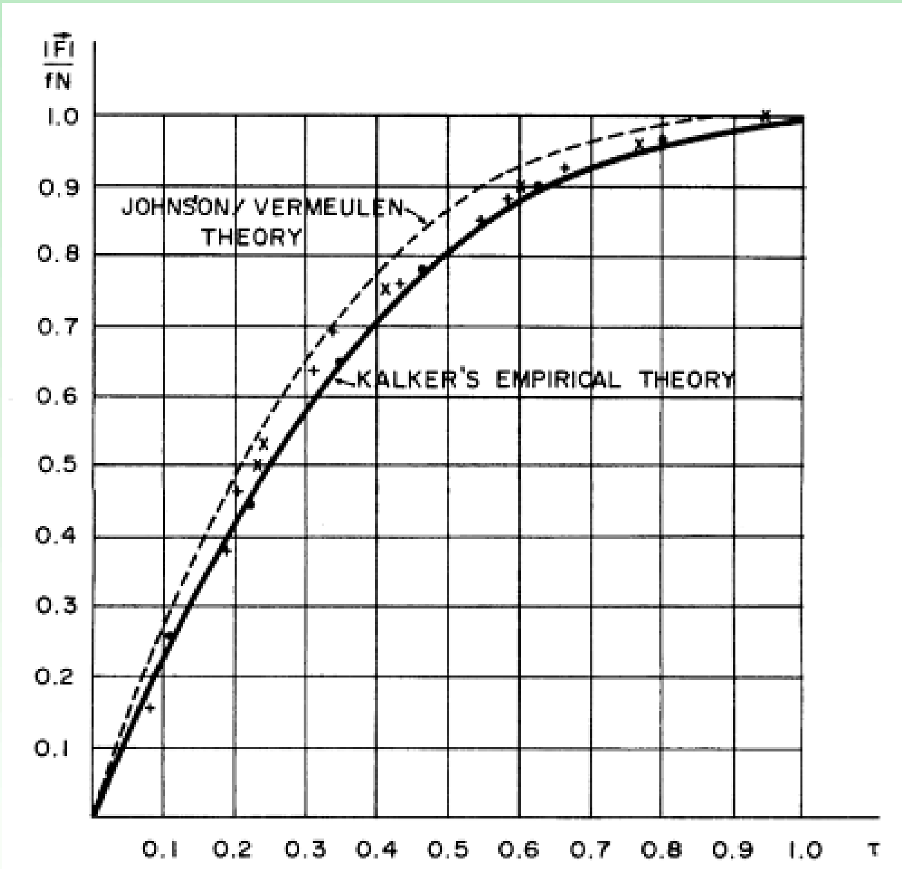
  α ~ arcsin(L/R) ~ L/R = 0.0030 Rad (3.0 mRad)

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

  V_{lat}/V ~ 2L/R ~ α = 0.3%



Estimating the traction ratio (L/V)

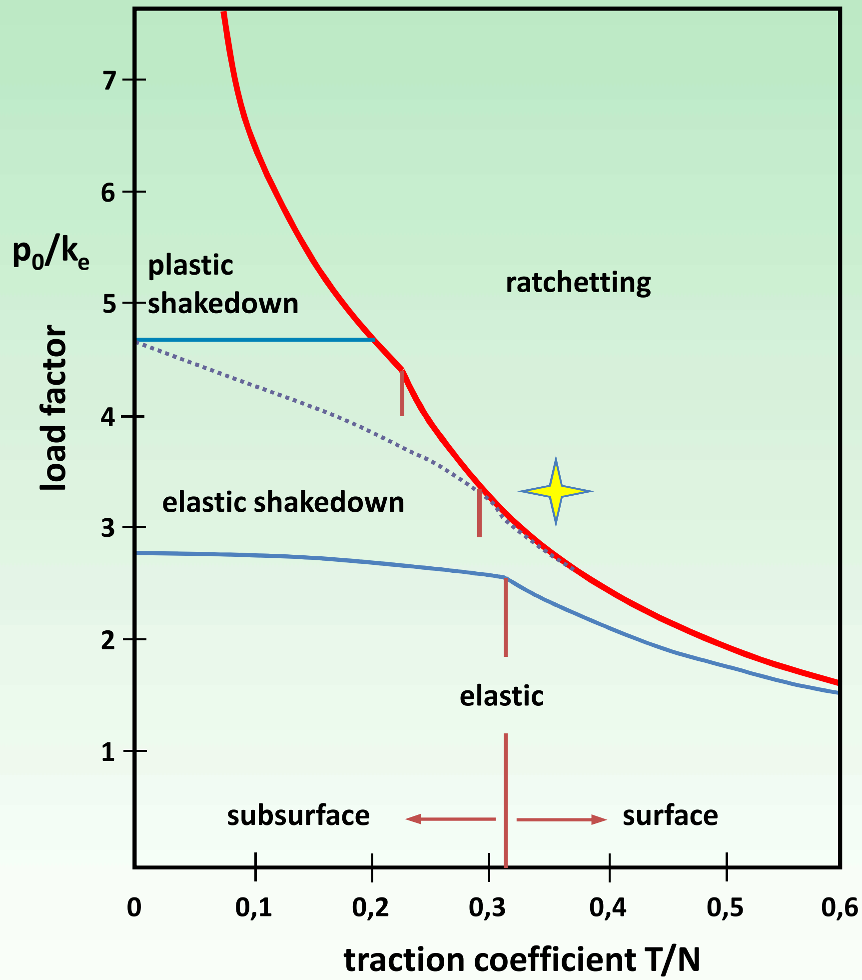


- At 0.3% creep:
  T/N ~ 0.6 μ
- With μ = 0.6
  Traction Ratio (T/N) ~ 0.36

**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



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

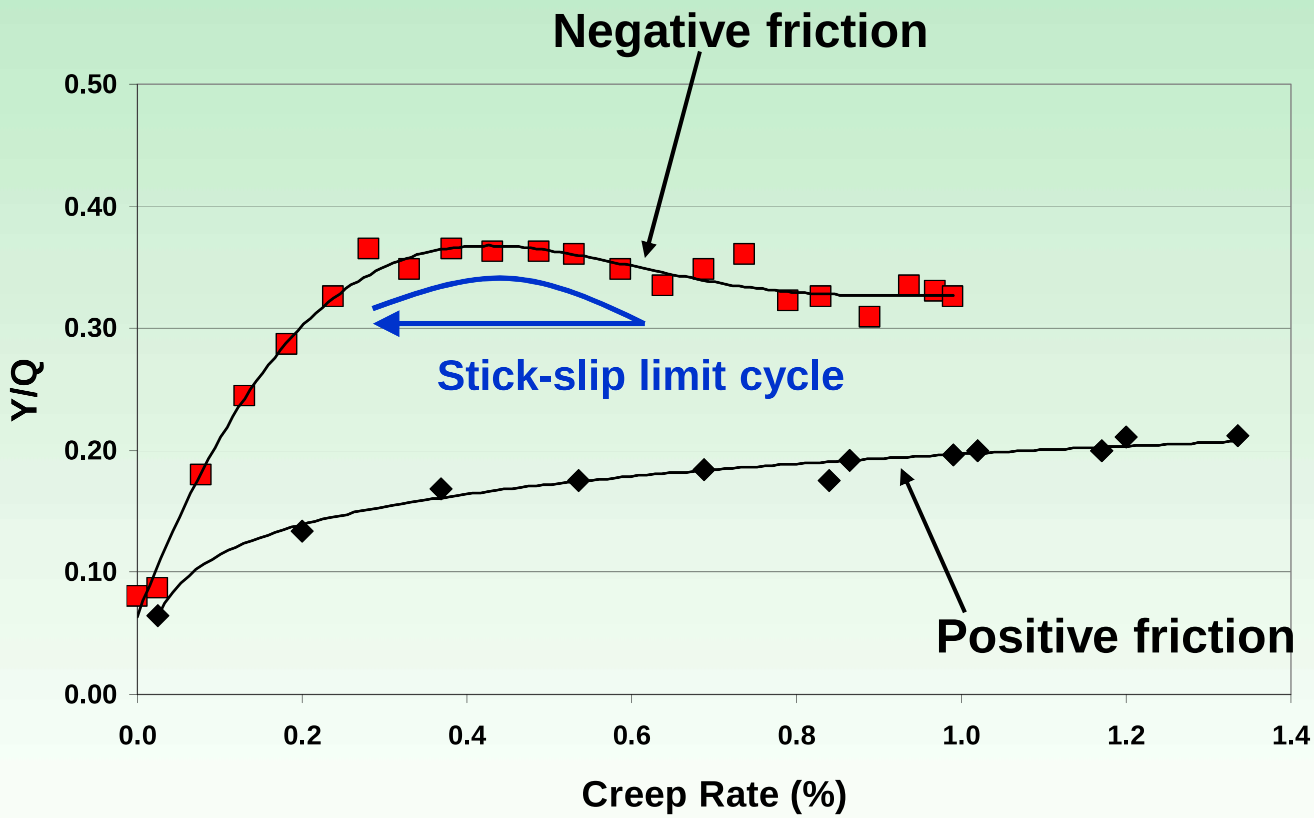
Top of rail wheel squeal noise

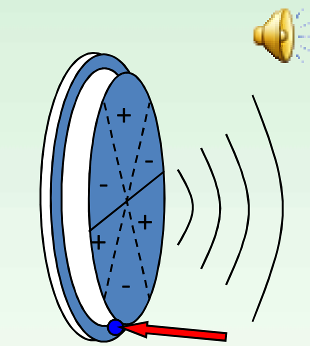
- **High pitched, tonal squeal (predominantly 1000 – 5000 Hz)**
- **Prevalent noise mechanism in “problem” curves, usually < 300m radius**
- **Related to both negative friction characteristics of Third Body at tread / top of rail interface and absolute friction level**
  - **Stick-slip oscillations**

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**

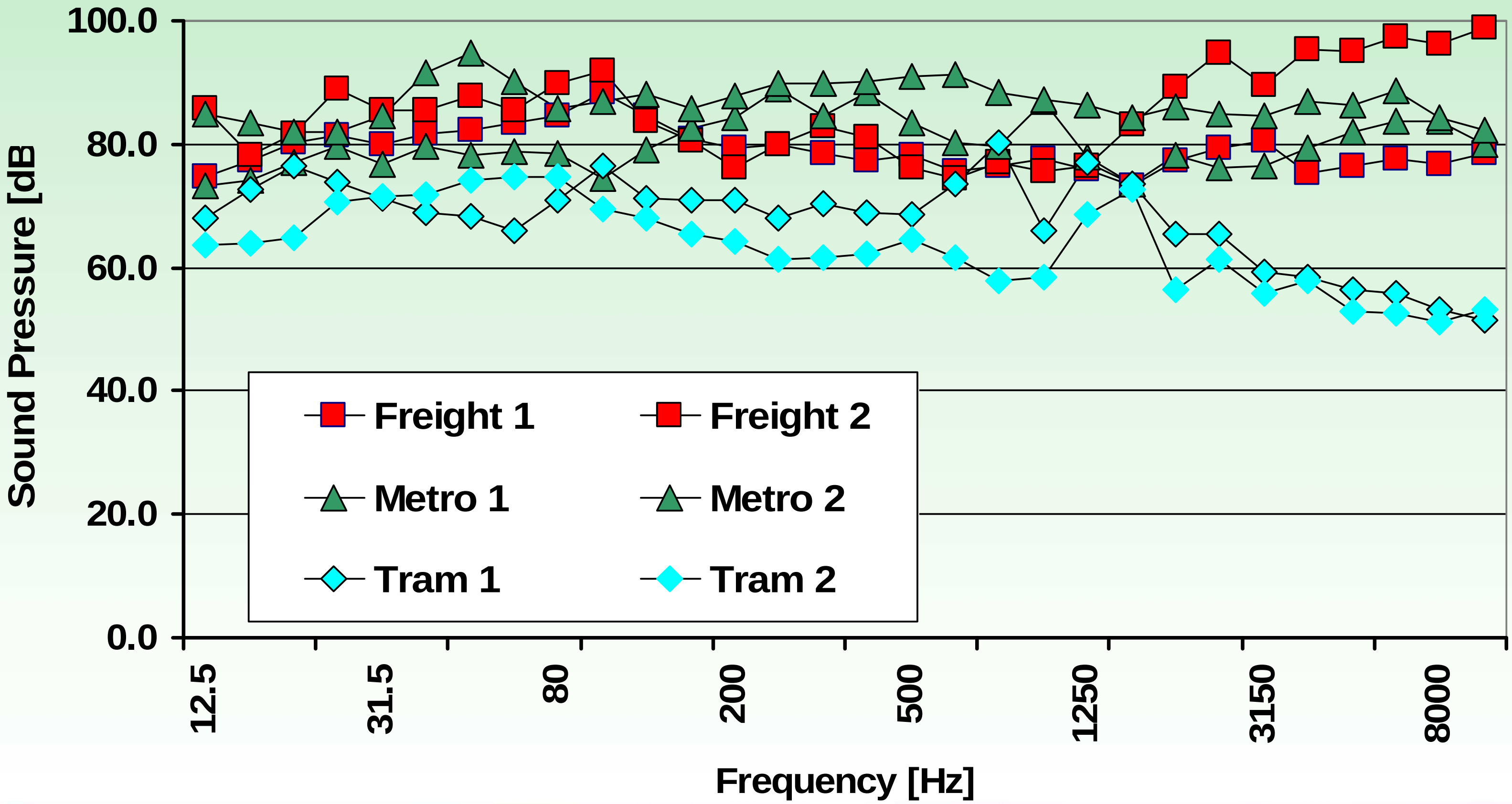
Absolute Friction Levels and Positive/Negative Friction





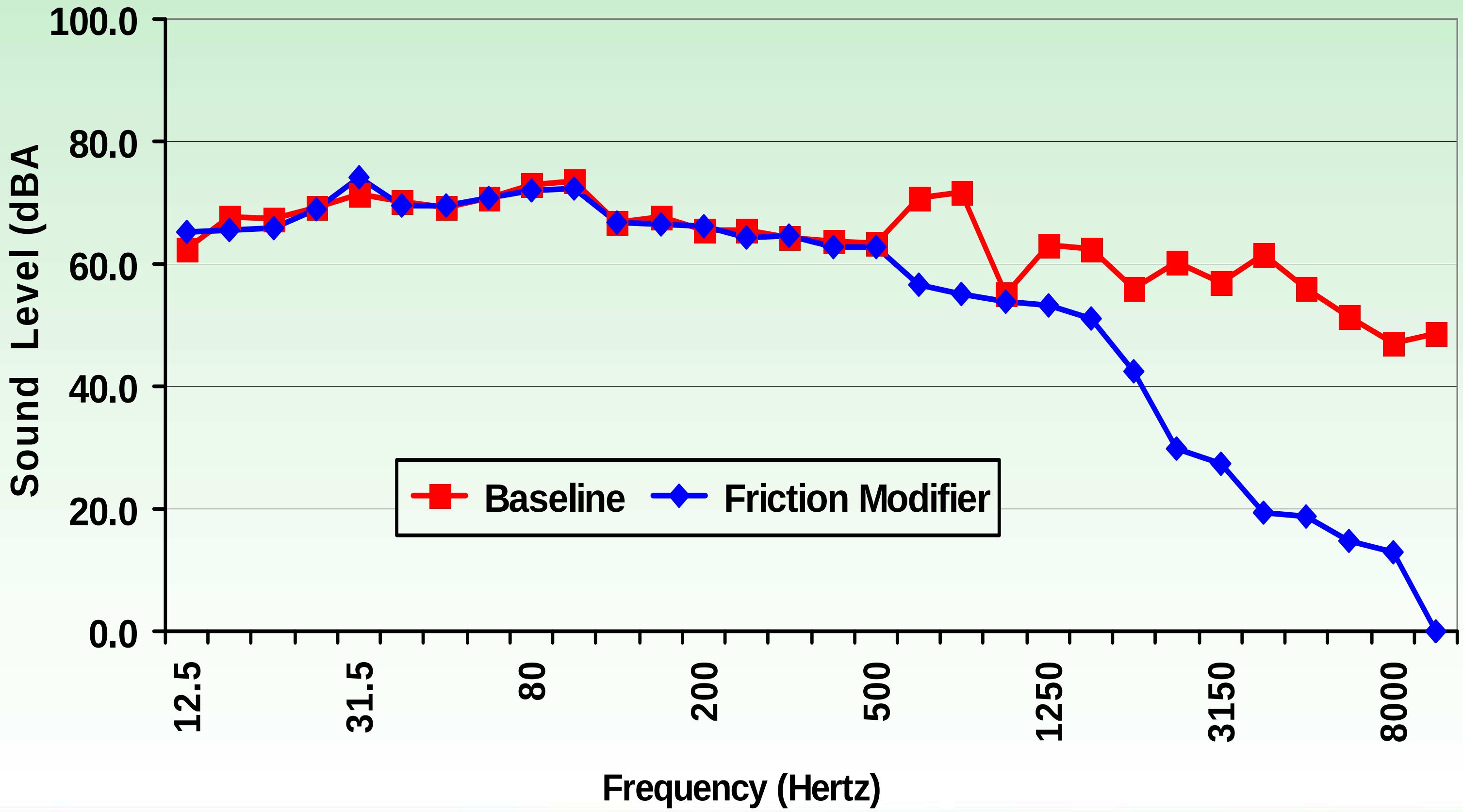
* Replotted from: "Matsumoto a, Sato Y, Ono H, Wang Y, Yamamoto Y, Tanimoto M & Oka Y, Creep force characteristics between rail and wheel on scaled model, *Wear,* Vol 253, Issues 1-2, July 2002, pp 199-203.

Sound spectral distribution for different wheel / rail systems

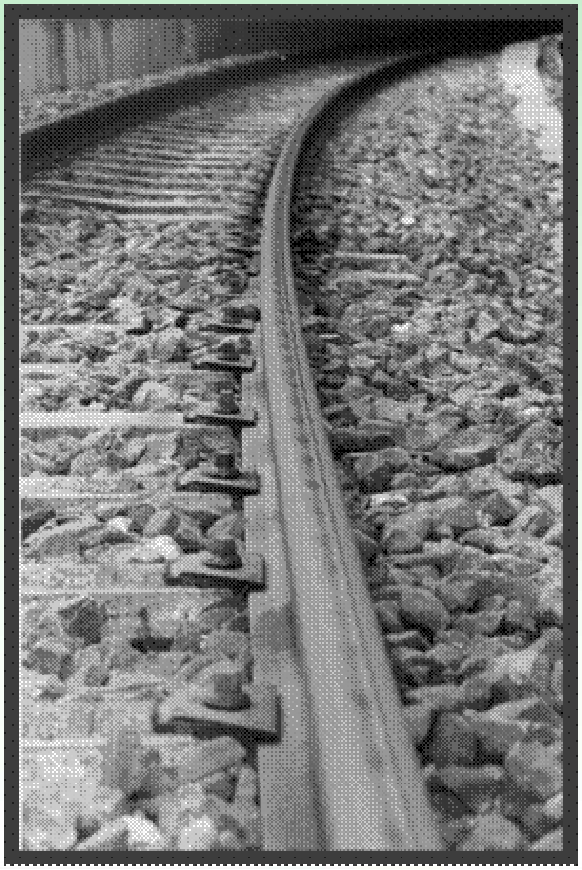


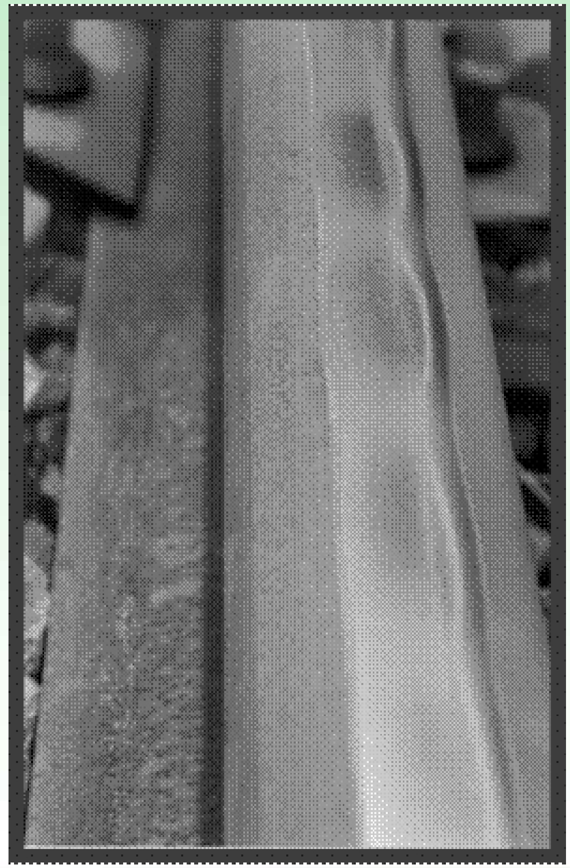
Effect of friction characteristics on spectral sound distribution: Trams

Effect of friction characteristics on spectral sound distribution: Trams

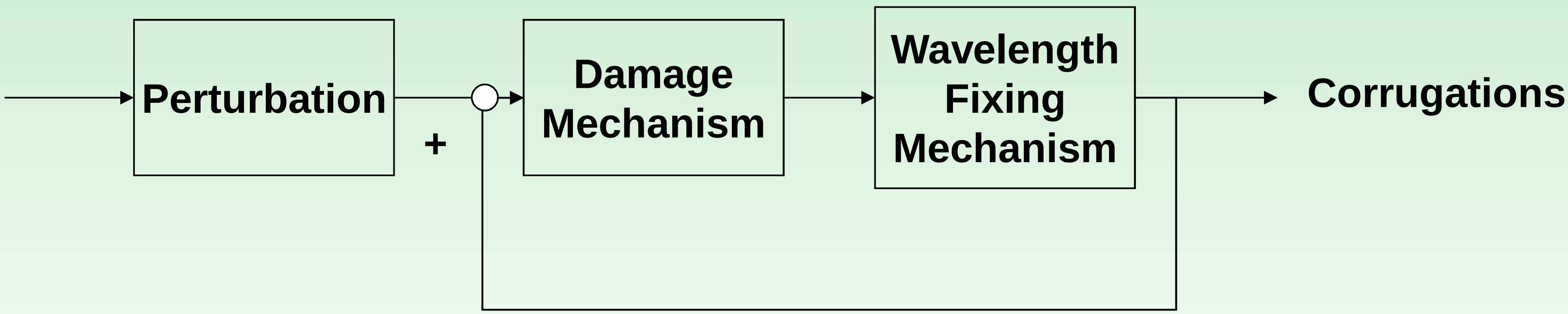


Corrugations (Short Pitch)





Corrugation formation: common threads

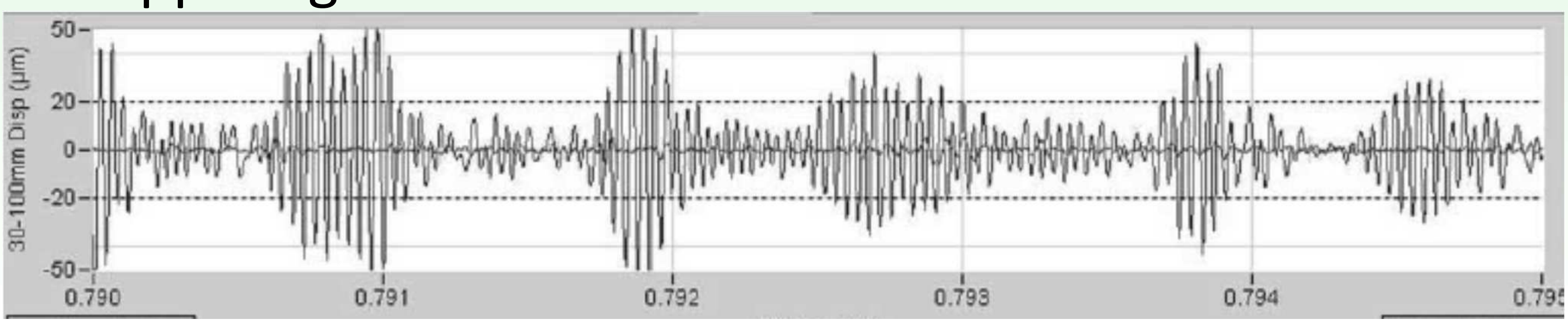


$$\boxed{\lambda = v/f}$$

	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 *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

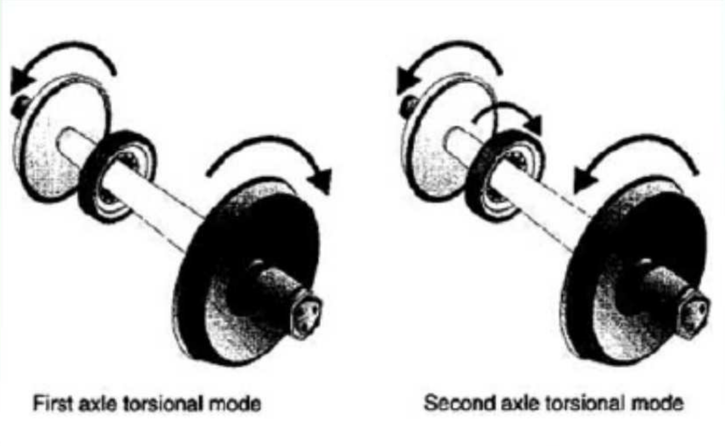
Pinned-Pinned corrugation (“roaring rail”)

- 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



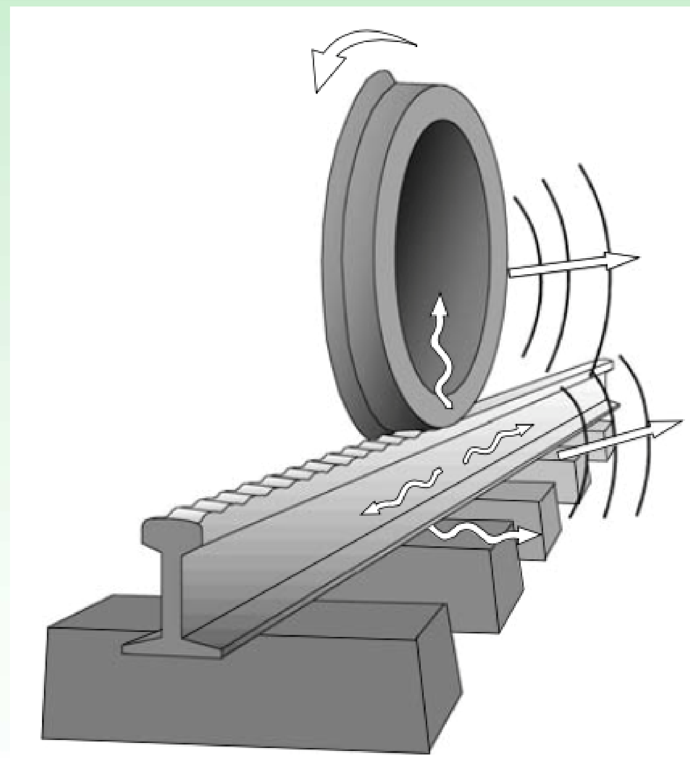
Rutting

- 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



Recalling Question #3: How is the noise captured in these two sound files generated at the wheel/rail interface?

- File #1:
- File #2:



Summary

- Returning to our objectives, we have reviewed:
  - The Wheel / Rail Interface and Key Terminology
  - The Contact Patch and Contact Pressures
  - 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)
  - Curving Noise
  - 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 and passenger rail systems.

Questions & Discussion