Overview: Part II

- Friction, Forces and Wear
- Shakedown and Rolling Contact Fatigue (RCF)
- Curving Noise
- Corrugations

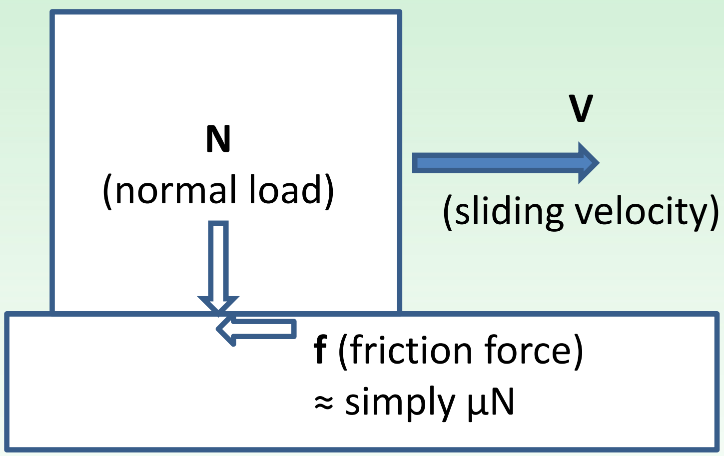
Friction, Forces and Wear

Recall: Rolling vs. Sliding Friction

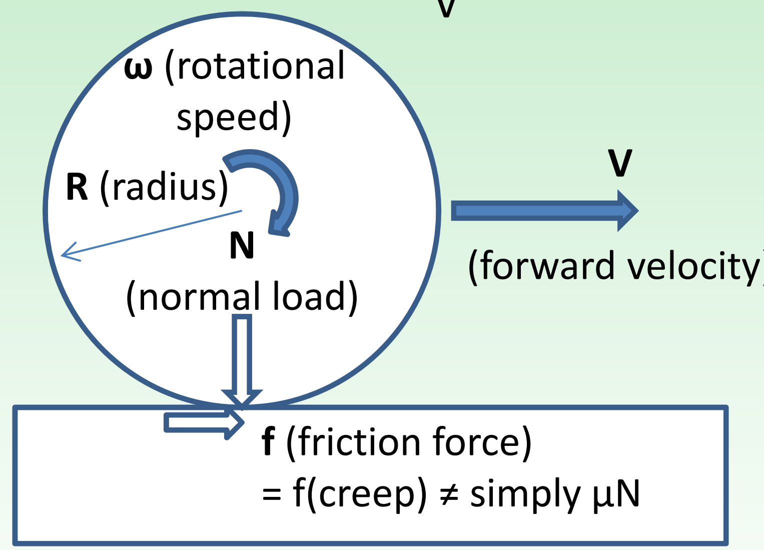
They are not the same!

μ: coefficient of (sliding) friction

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

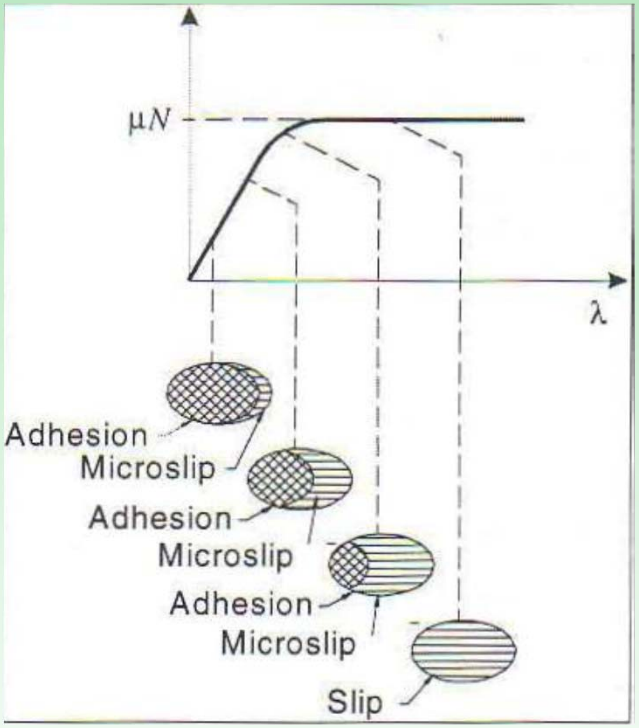


friction force shown as acting on block for positive sliding velocity

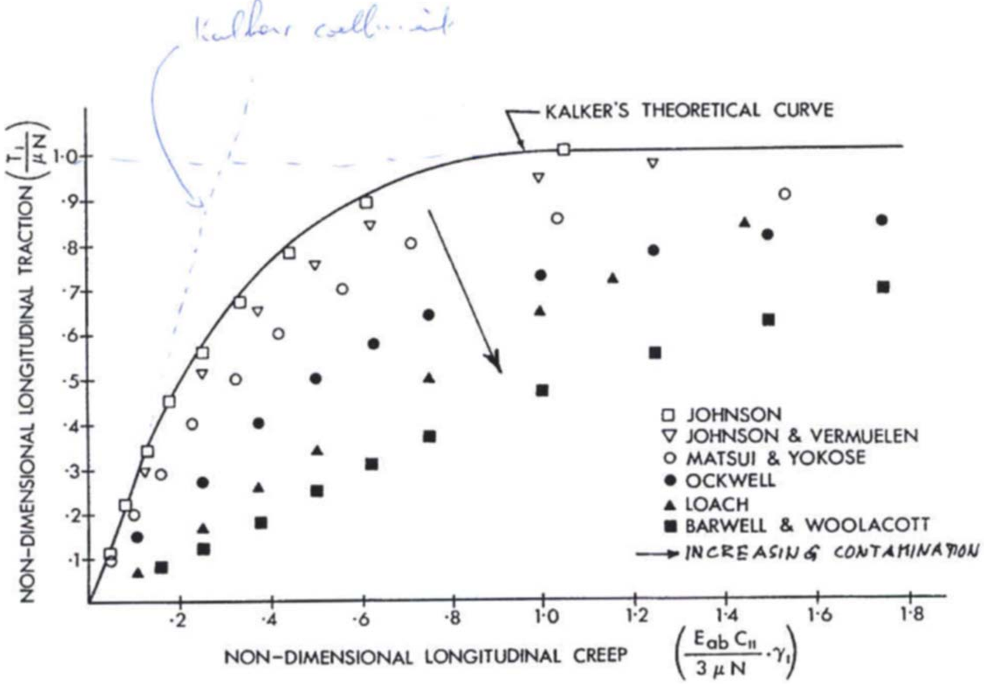


friction force shown as acting on wheel for positive creep

Traction/Creepage Curves



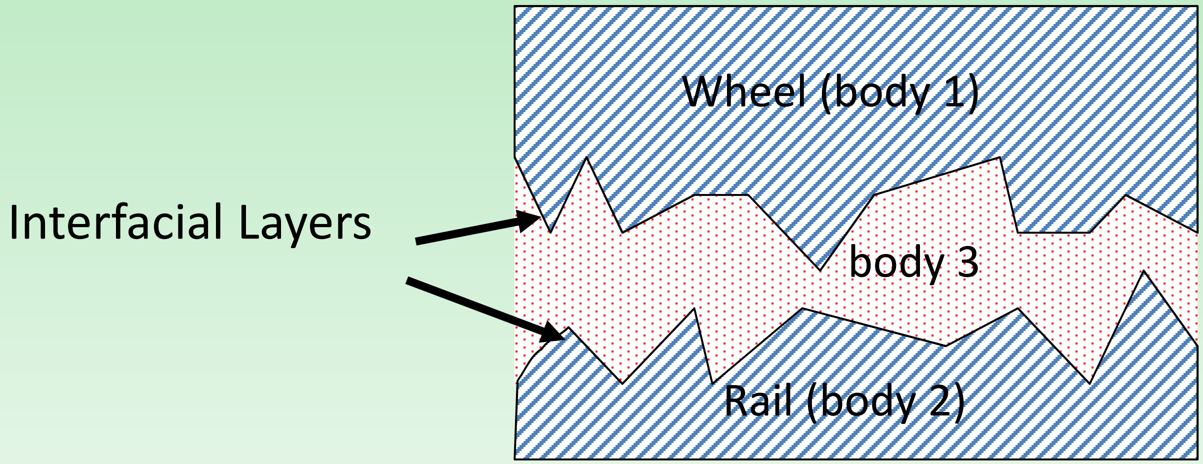
- The 1% boundary between "saturated" (pure sliding) and "unsaturated" (combined rolling-sliding) creepages is approximate and applies only to "well cleaned" and uncontaminated steel surfaces. As the surfaces become contaminated the traction curve "saturates" at higher creepage (see Figure 7). For contaminated wheel/rail interface the saturation is typically reached between 2.5% to 6%.



Important Concept:

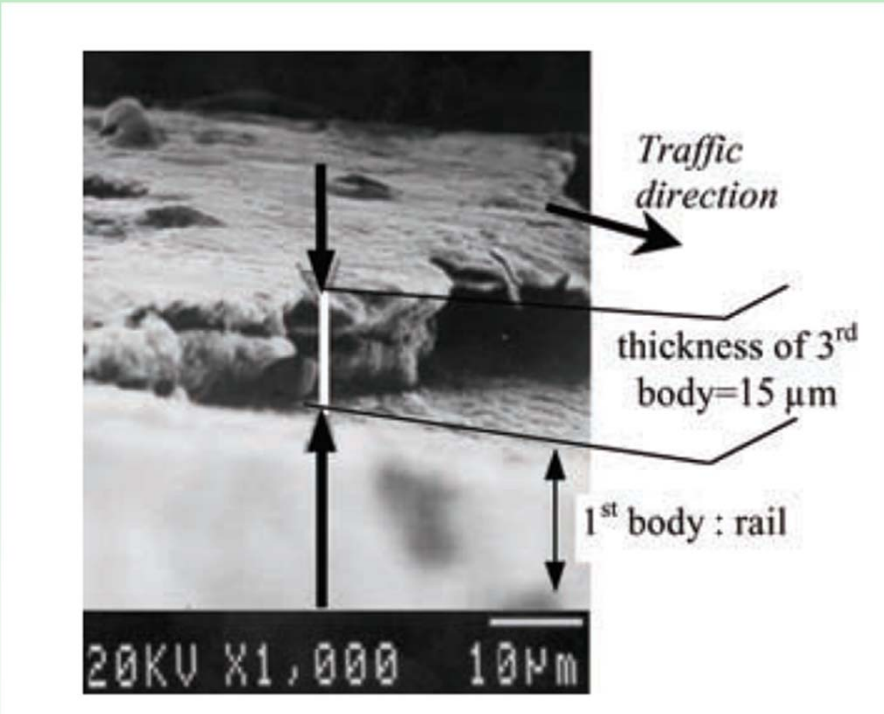
- Sometimes, forces give rise to creepage (e.g. traction, braking)
- Other times, creepage gives rise to forces (e.g. curving)

Third Body at Wheel/Rail Contact

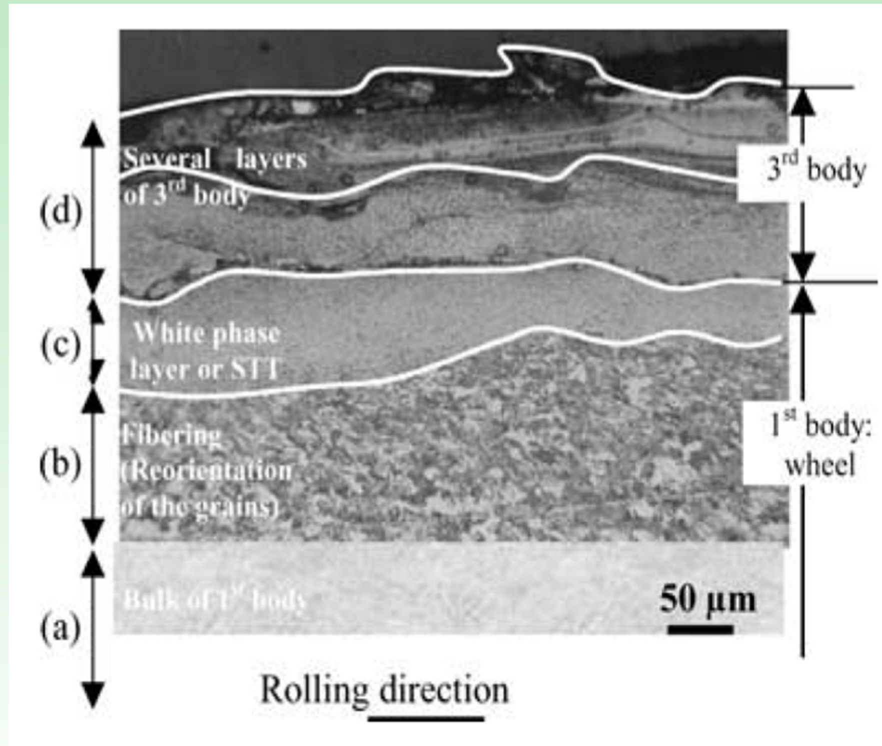


- Third Body is made up of iron oxides, sands, wet paste, leaves etc….
- Third Body separates wheel and rail surface, accommodates velocity differences and determines wheel/rail friction.
- Wheel/Rail friction depends on the shear properties / composition of the third body layer.

Third Body Layer – Micron Scale



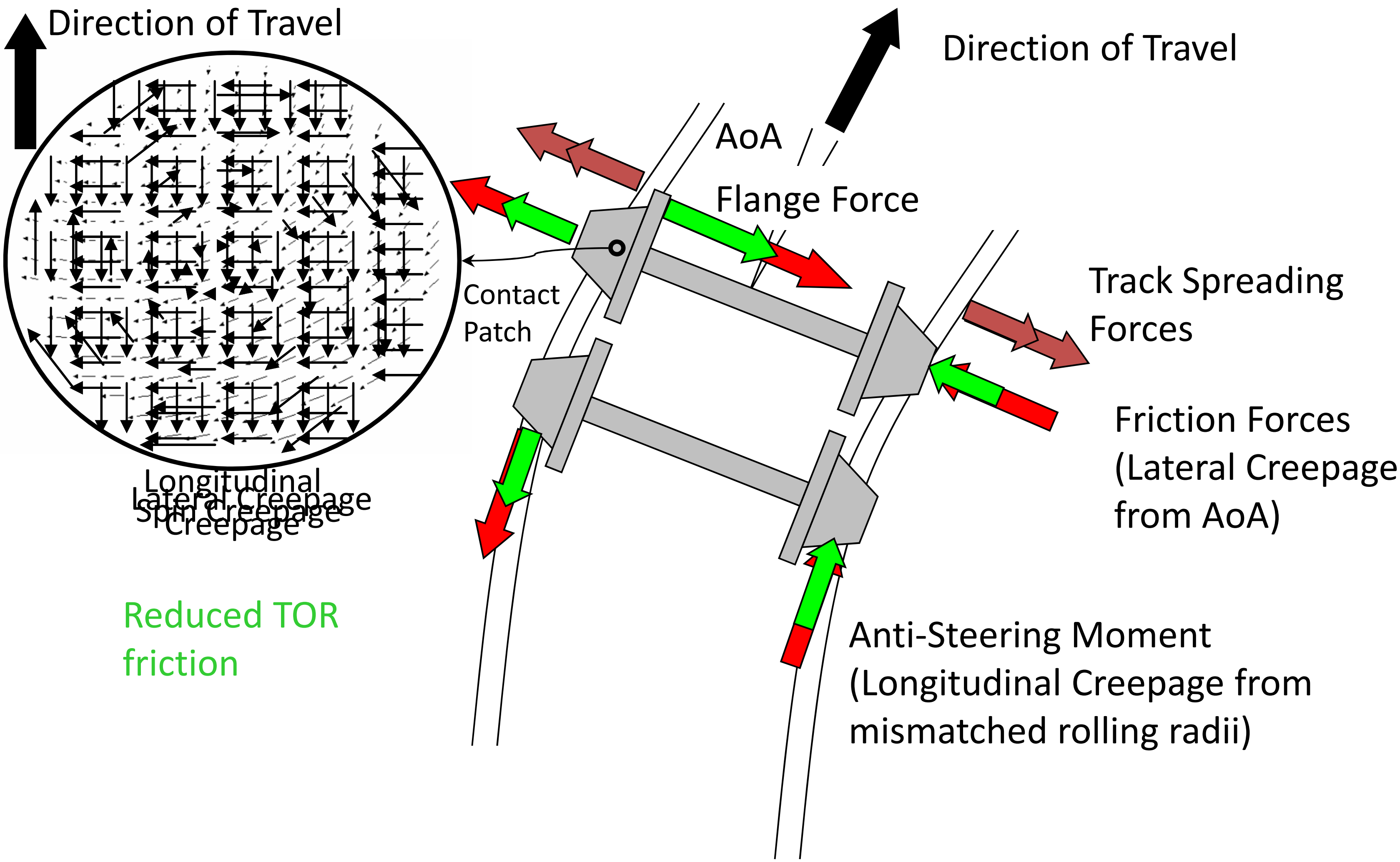
Rail



Wheel

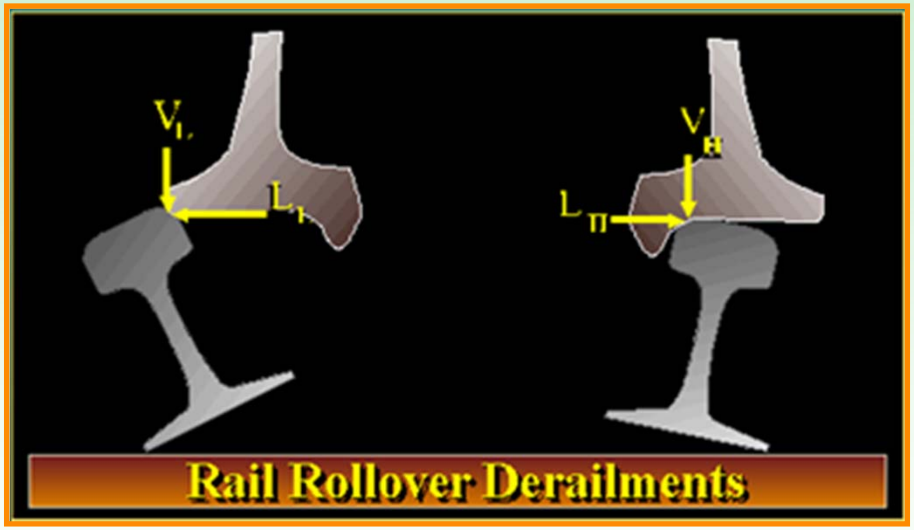
Y.Berthier, S. Decartes, M.Busquet et al. (2004). The Role and Effects of the third body in the wheel rail interaction. *Fatigue Fract. Eng. Mater Struct. 27, 423-436*

Curving Forces (101)



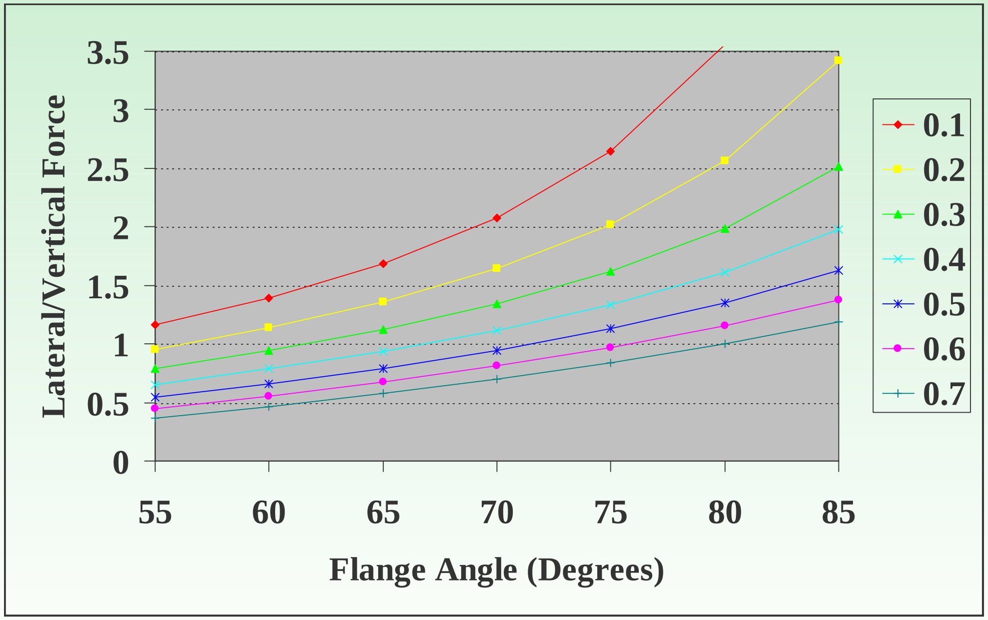
Reduced TOR friction

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



Impacts of High Lateral Loads: Plate Cutting, Gauge Widening

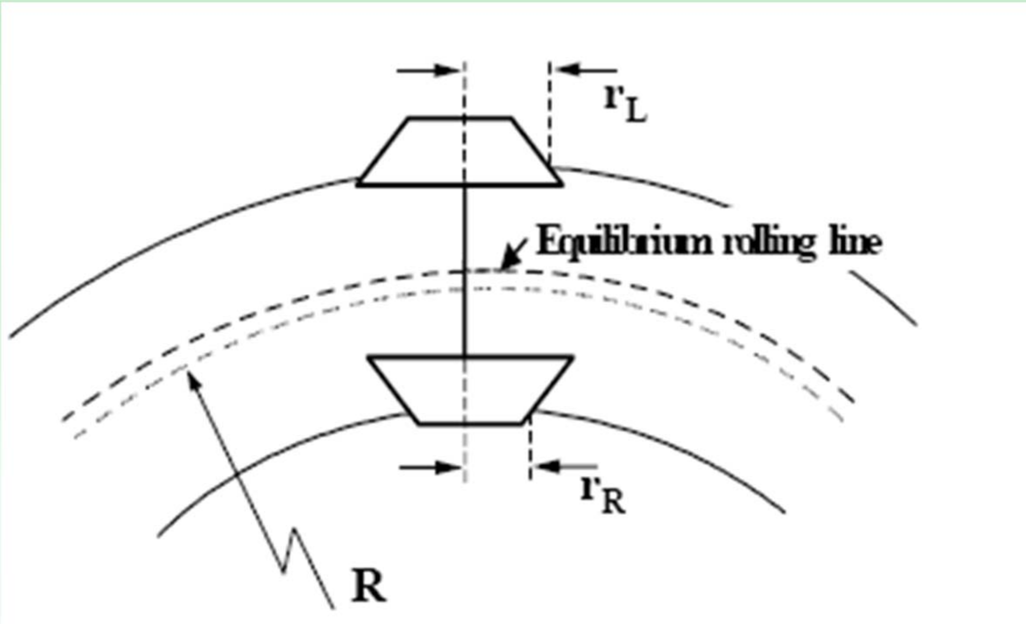
Impacts of High Lateral Loads: Wheel Climb Derailments



Impacts of High Lateral Loads: Fastener Fatigue / Clip Breakage

Curving Forces (201)

- Remember this?

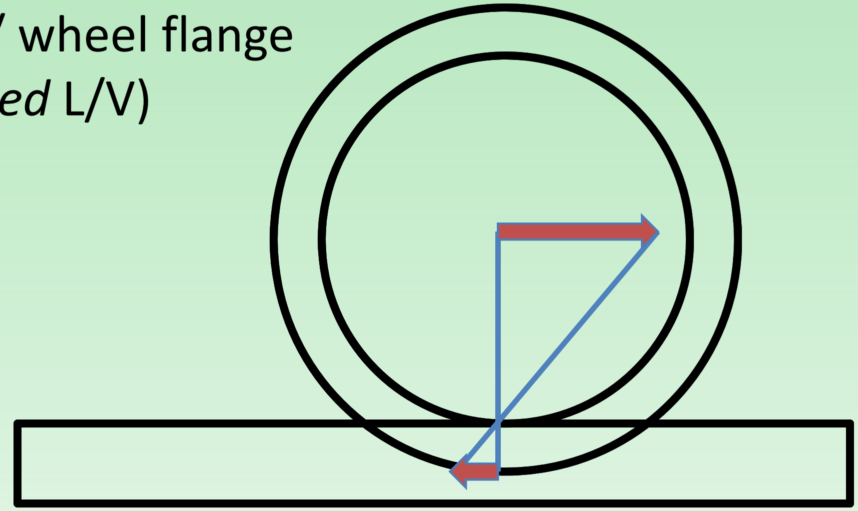


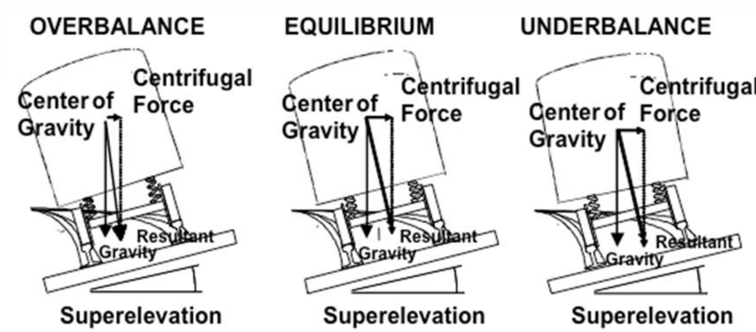
How often to we see a single (isolated) wheel set in operation?

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





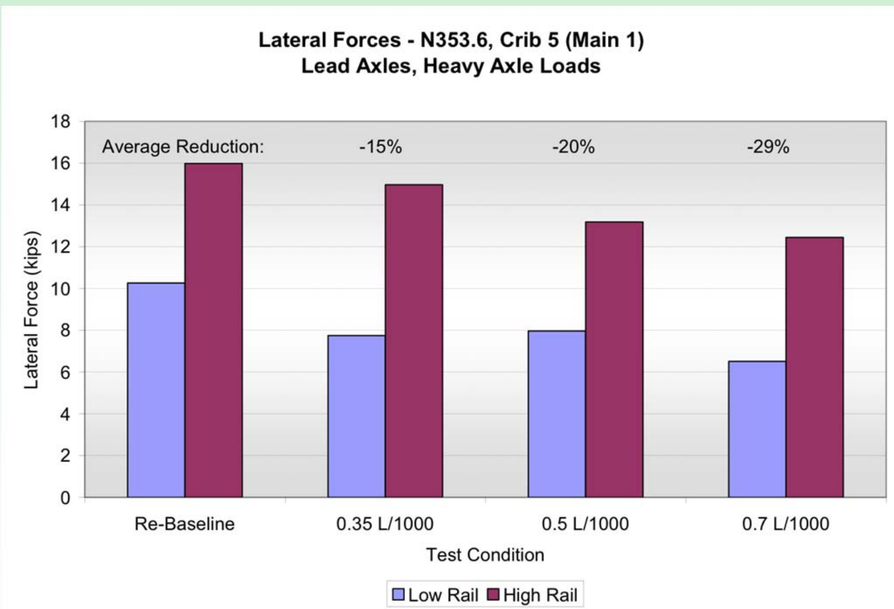
$$V_{\max} = \sqrt{\frac{E_a + 3}{0.0007D}}$$

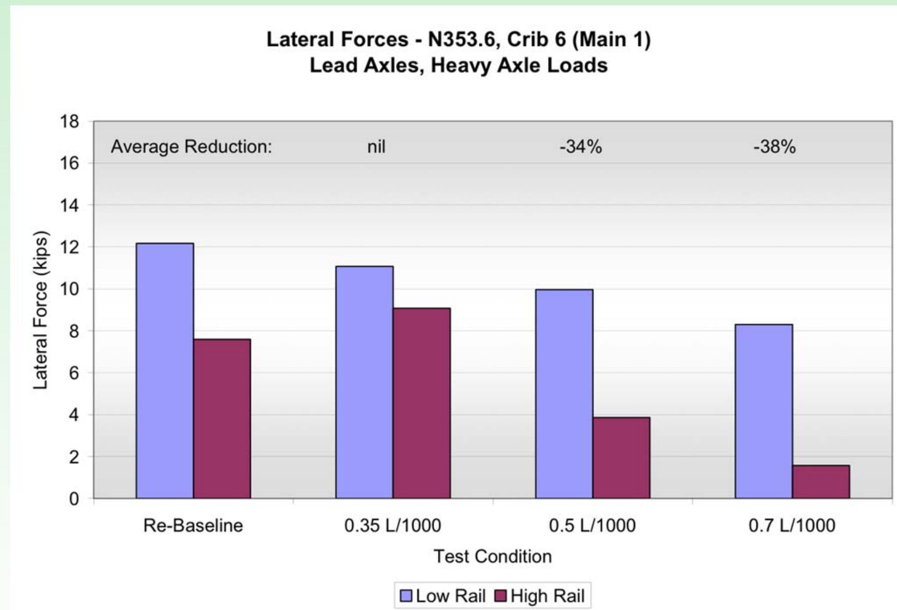
Amount of Underbalance

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

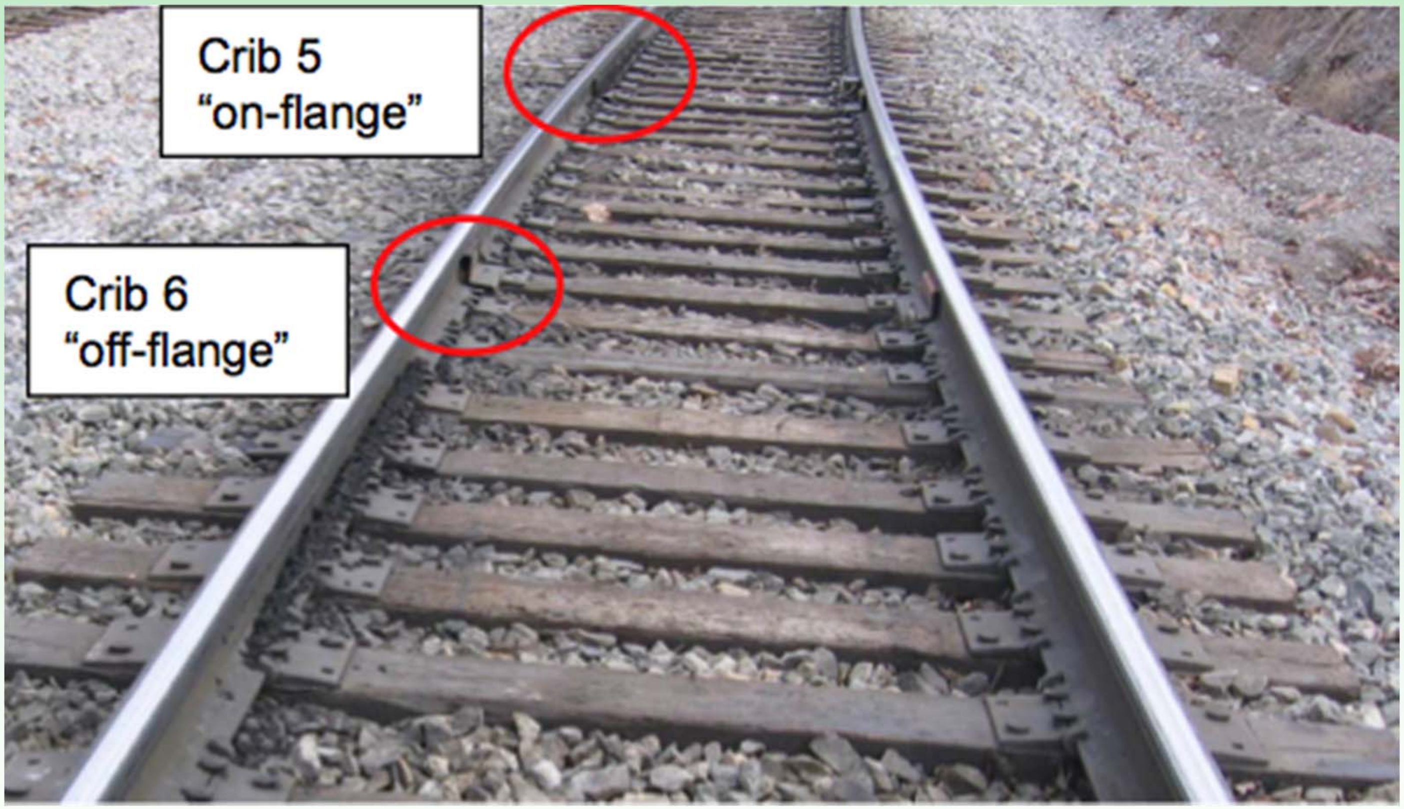
An example…

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



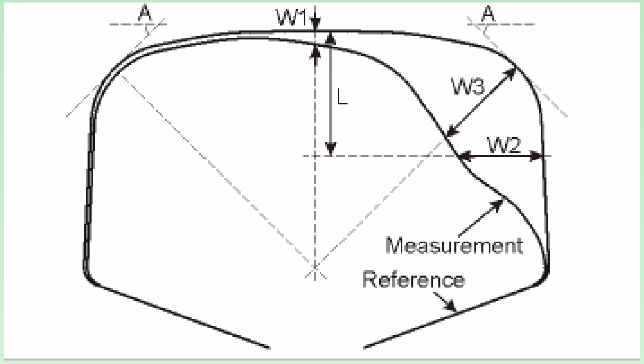


Mystery solved…



Rail Wear

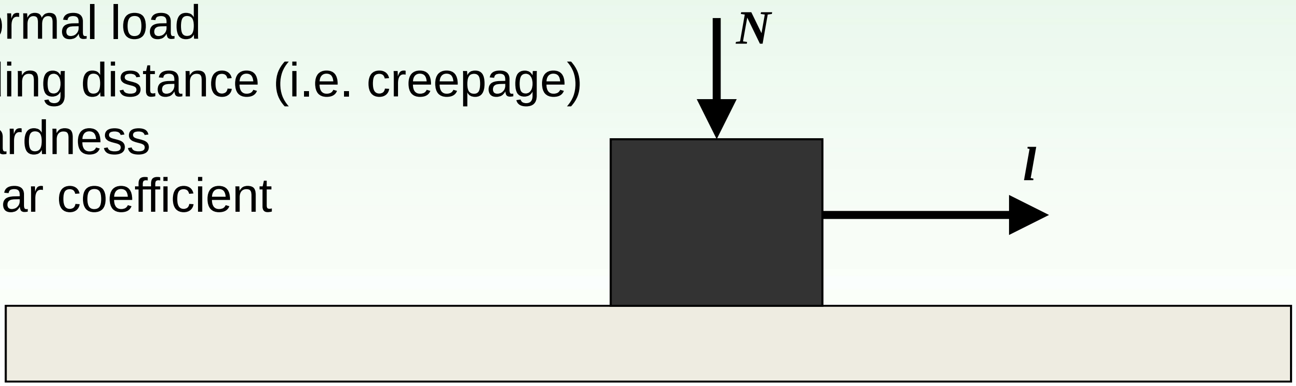
- Wear Types:
  - Adhesion
  - Surface Fatigue
  - Abrasion
  - Corrosion
  - Rolling Contact Fatigue
  - Plastic Flow



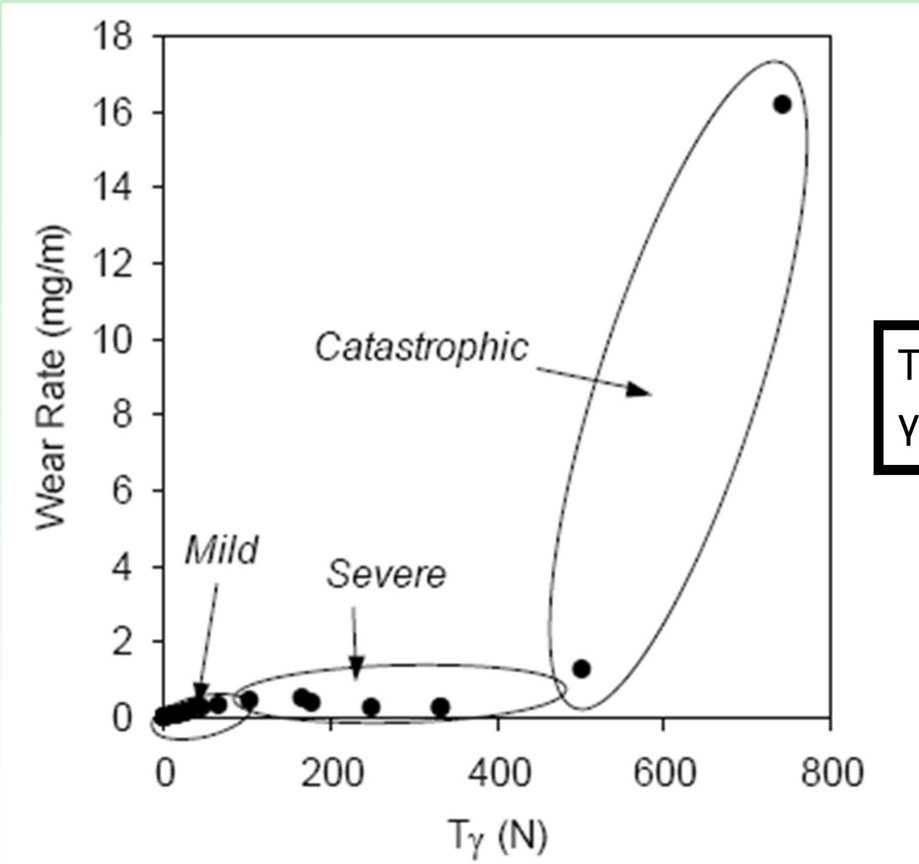
- "Archard" Wear Law: $$V = c\frac{Nl}{H}$$

c proportional to COF

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



Wear regimes



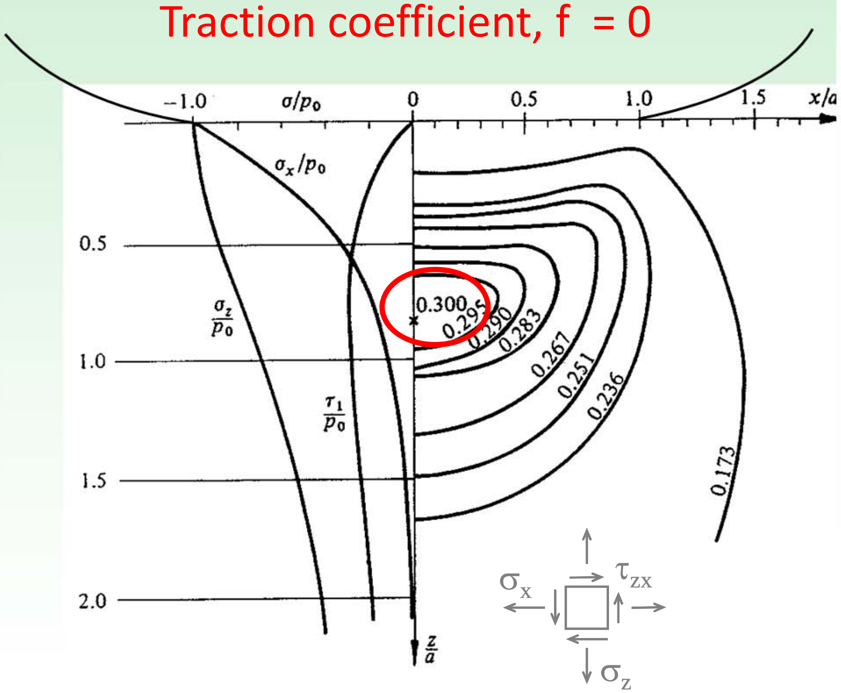
T = Tractive force
γ = Slip

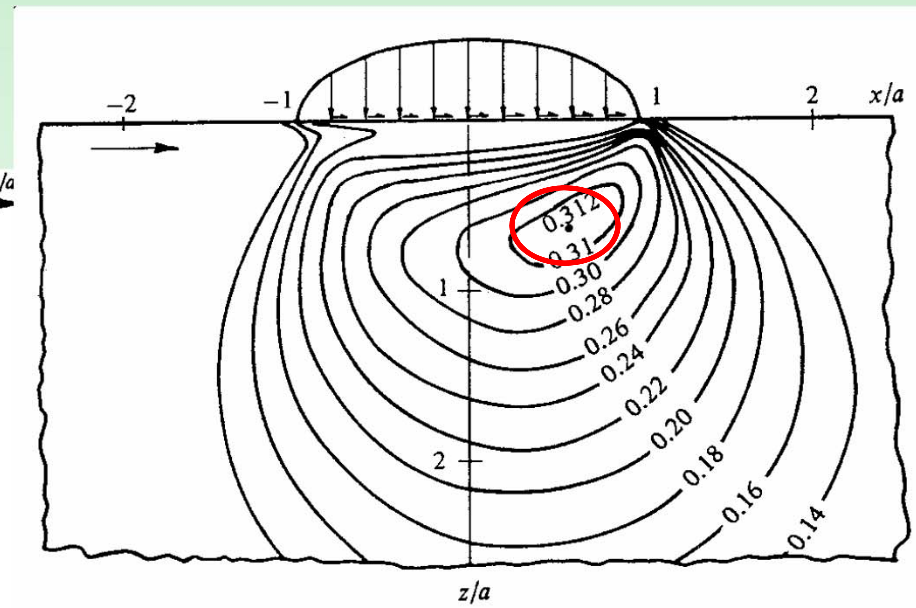
Shakedown and Rolling Contact Fatigue (RCF)

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



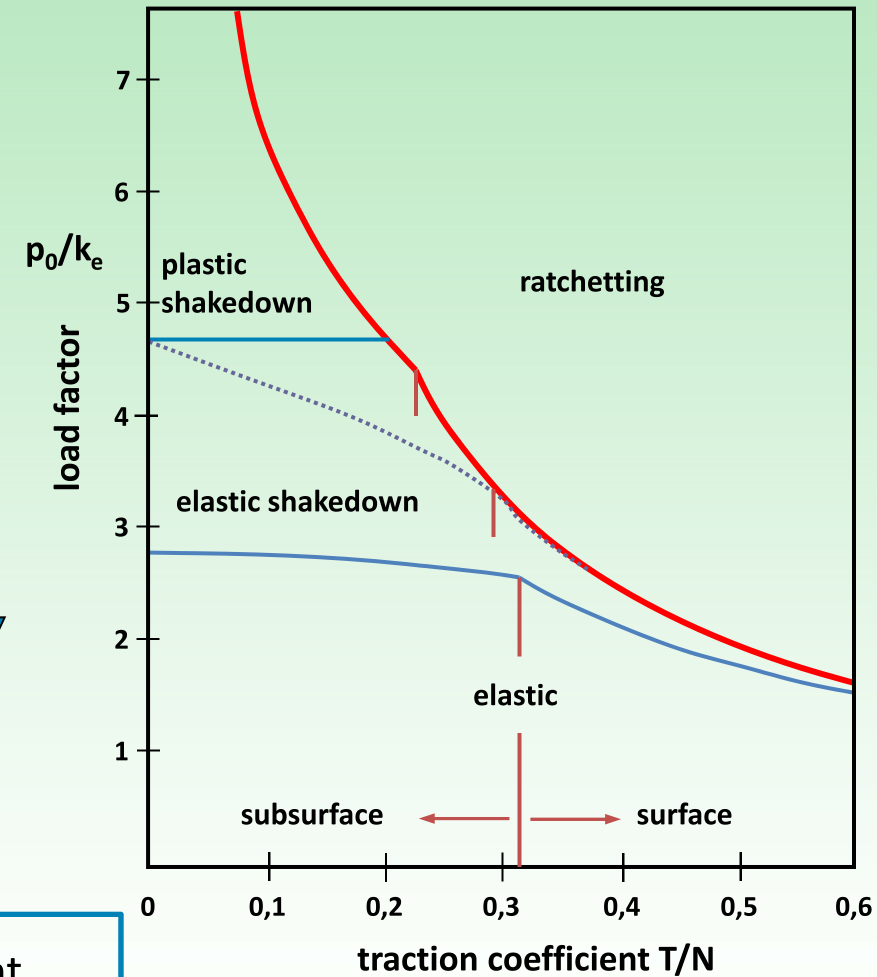


Traction coefficient, f = 0.2

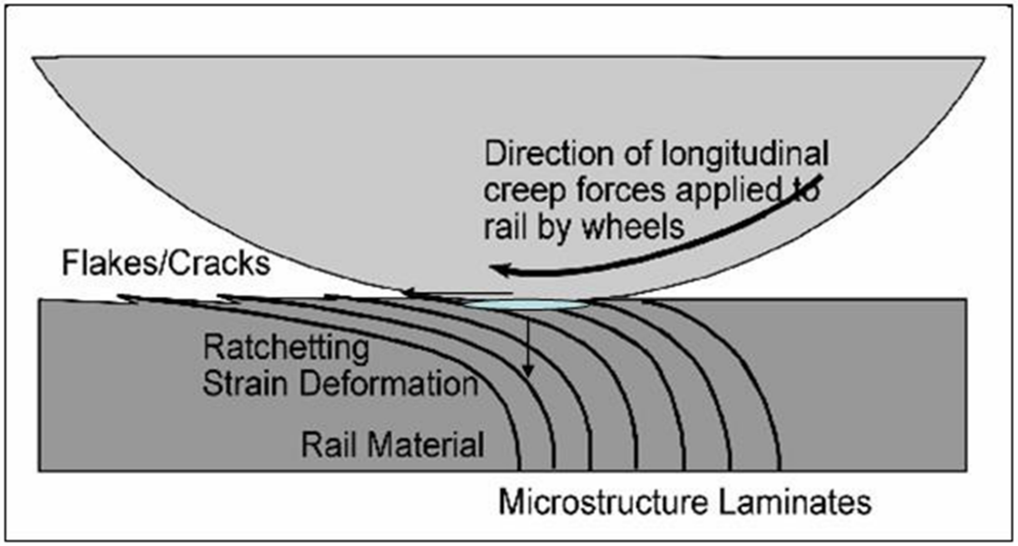
RCF Development: Shakedown

Increased Mat'l Strength

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

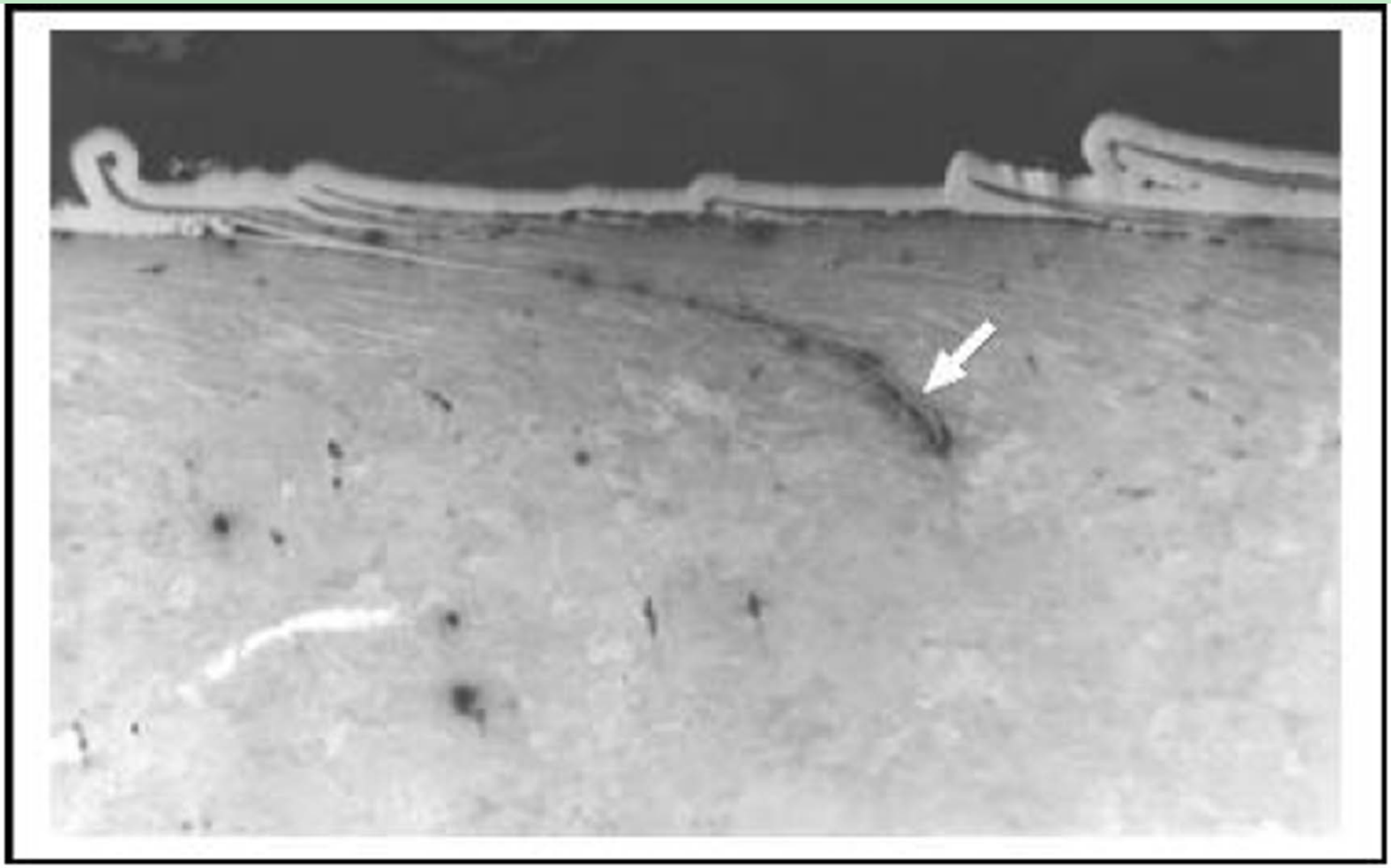


Reduced Traction Coefficient
(e.g. reduced friction)


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

Wheel Tread


←MLN 1 ON 13m 25½ch High rail
High Rail



Hydropressurization: effect of liquids on crack growth

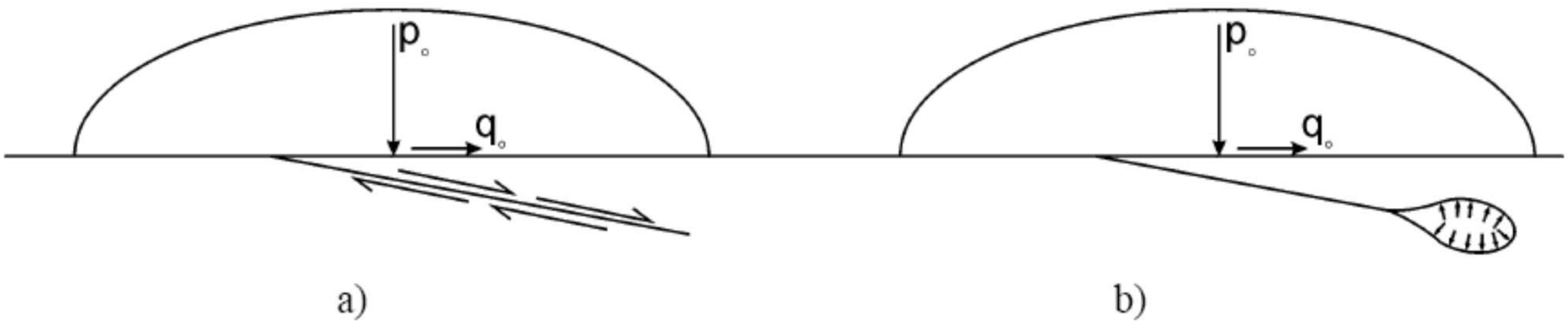
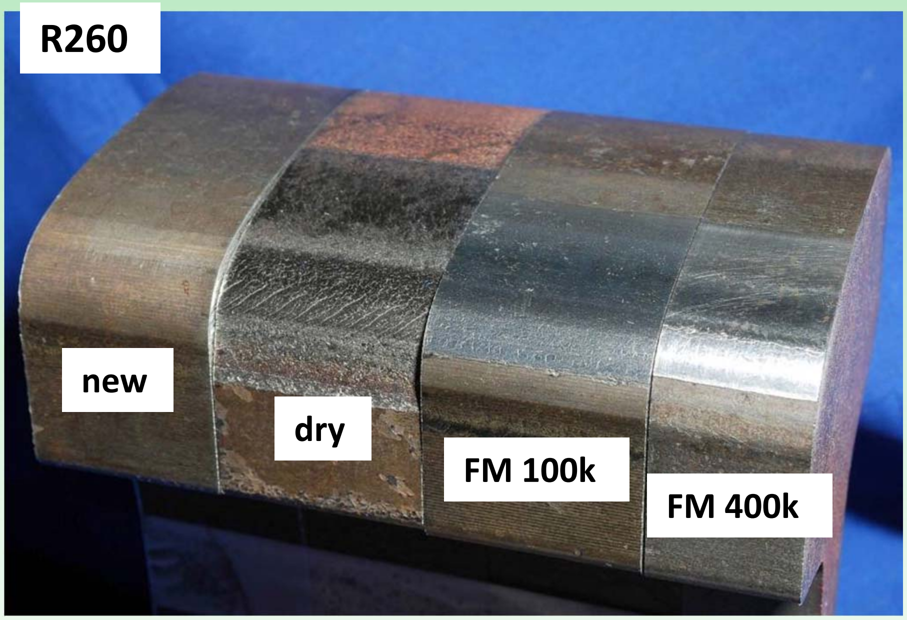
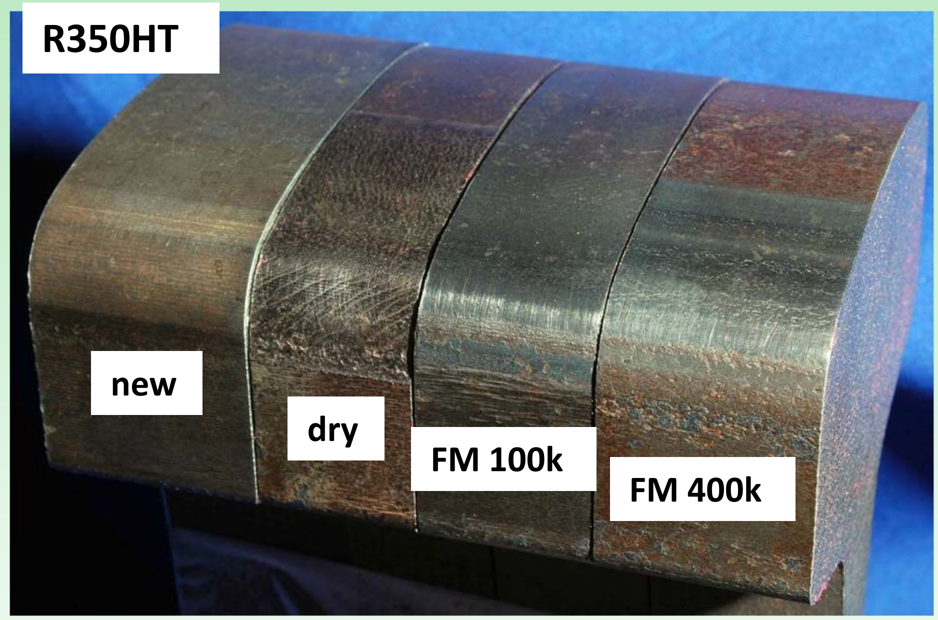
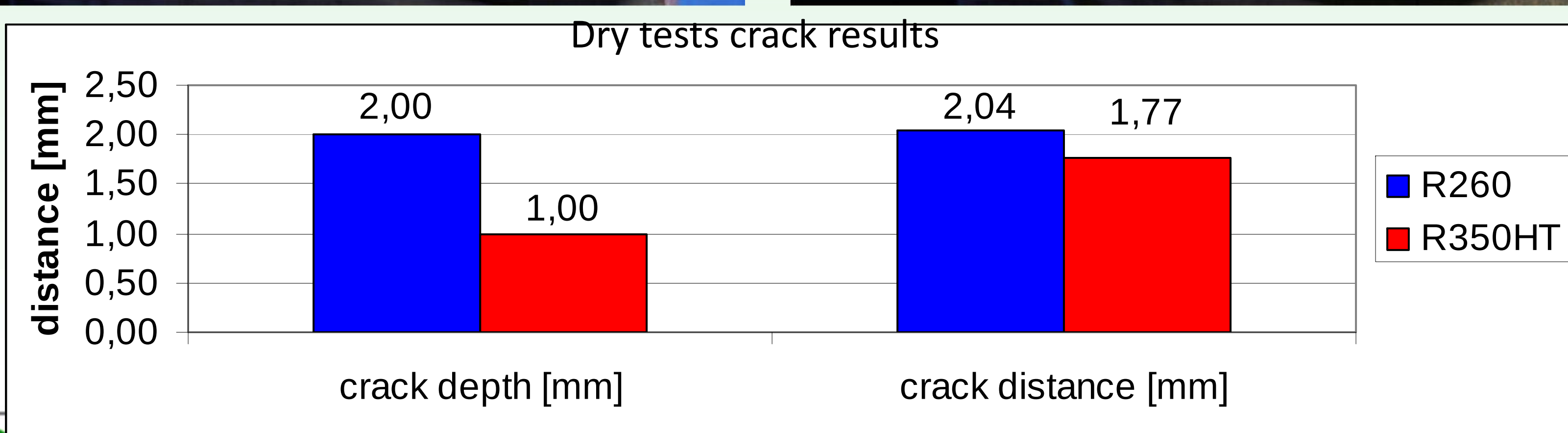


Figure 8: Influence of grease and water on crack propagation through a) control of crack-face friction, and b) hydraulic pressurization of the crack tip.

Wear and RCF
wheel/rail rig test results







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

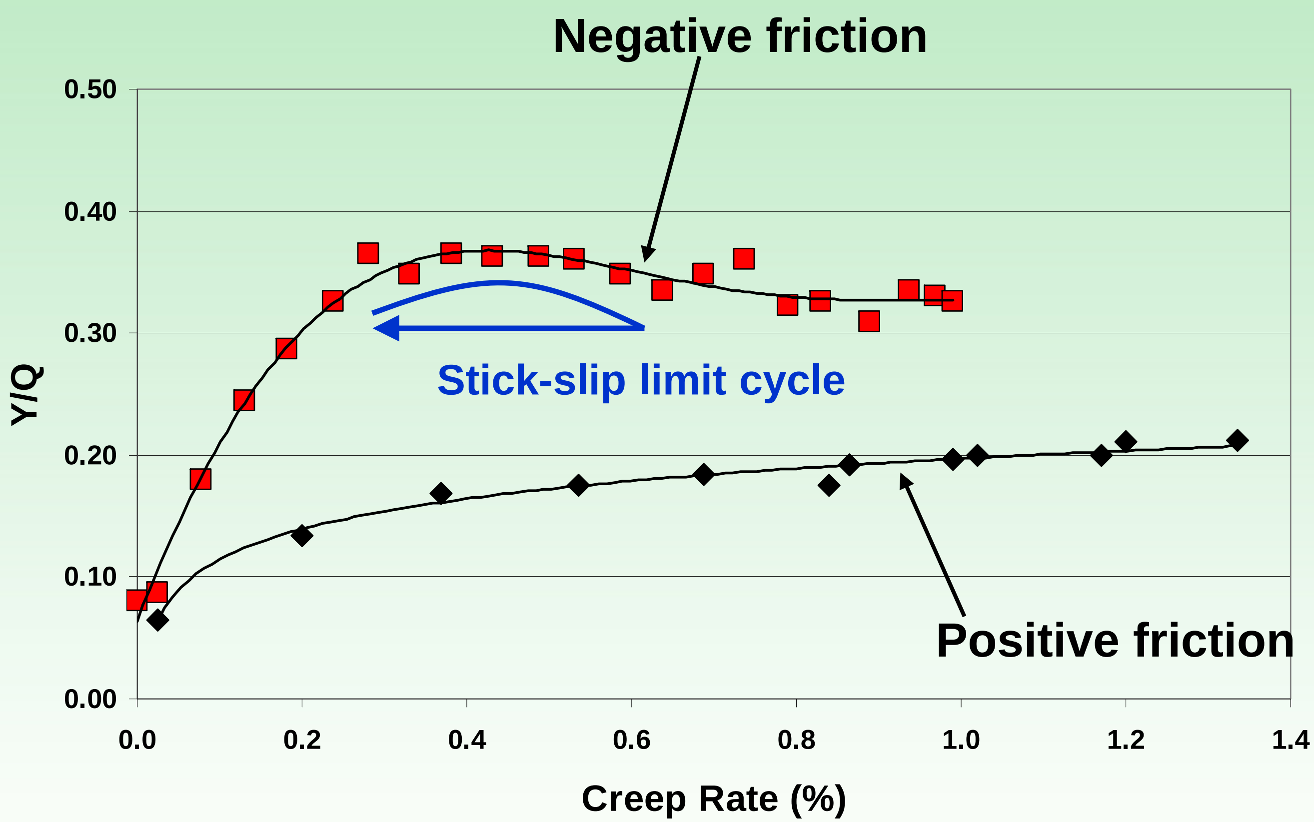
Top of rail wheel squeal noise

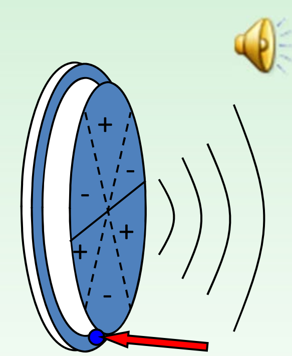
- High pitched, tonal squeal (predominantly 1000 – 5000 Hz)
- Prevalent noise mechanism in "problem" curves, usually < 300m radius
- Related to both negative friction characteristics of Third Body at tread / top of rail interface and absolute friction level
  - Stick-slip oscillations

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

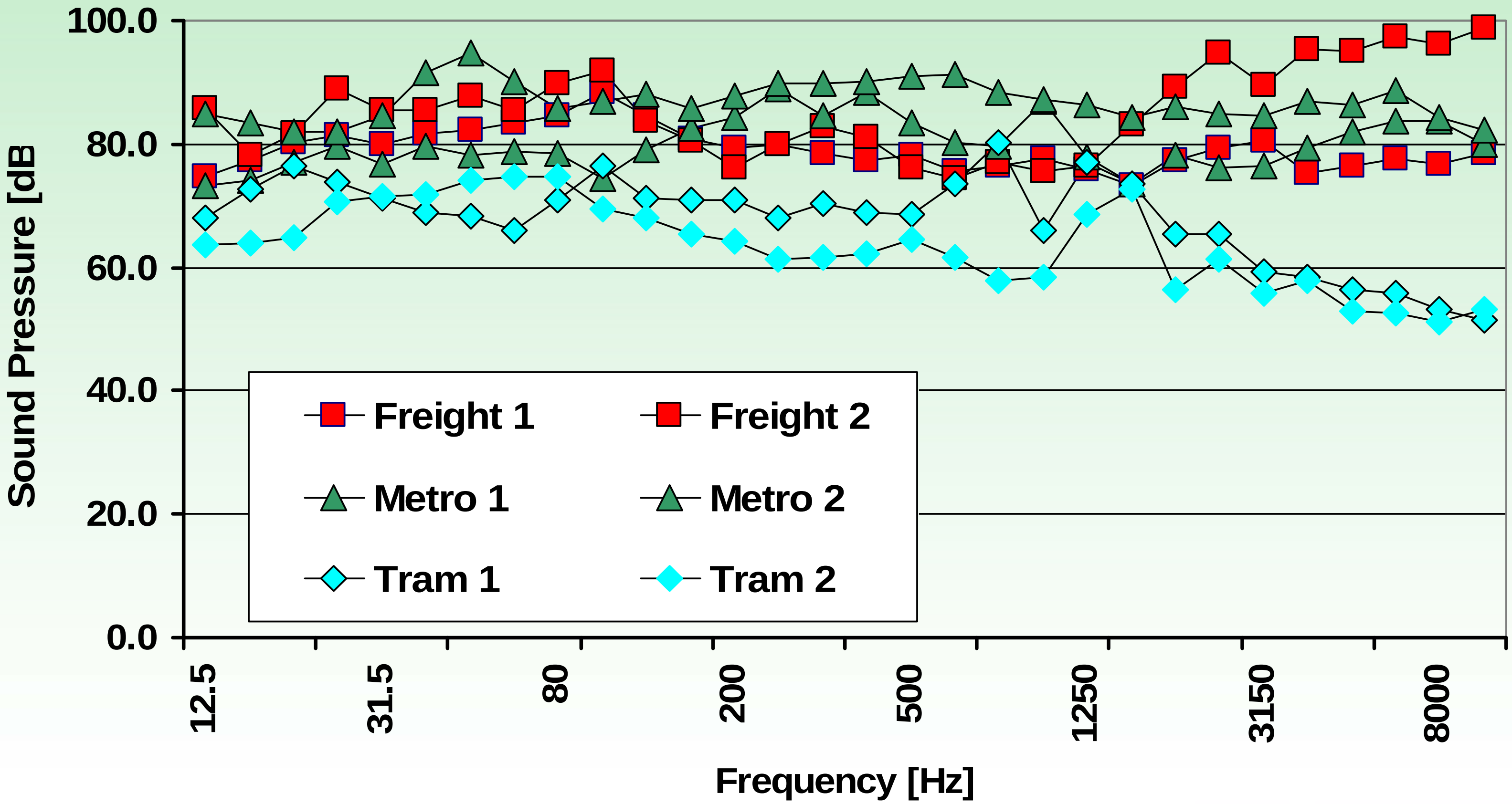
Absolute Friction Levels and Positive/Negative Friction





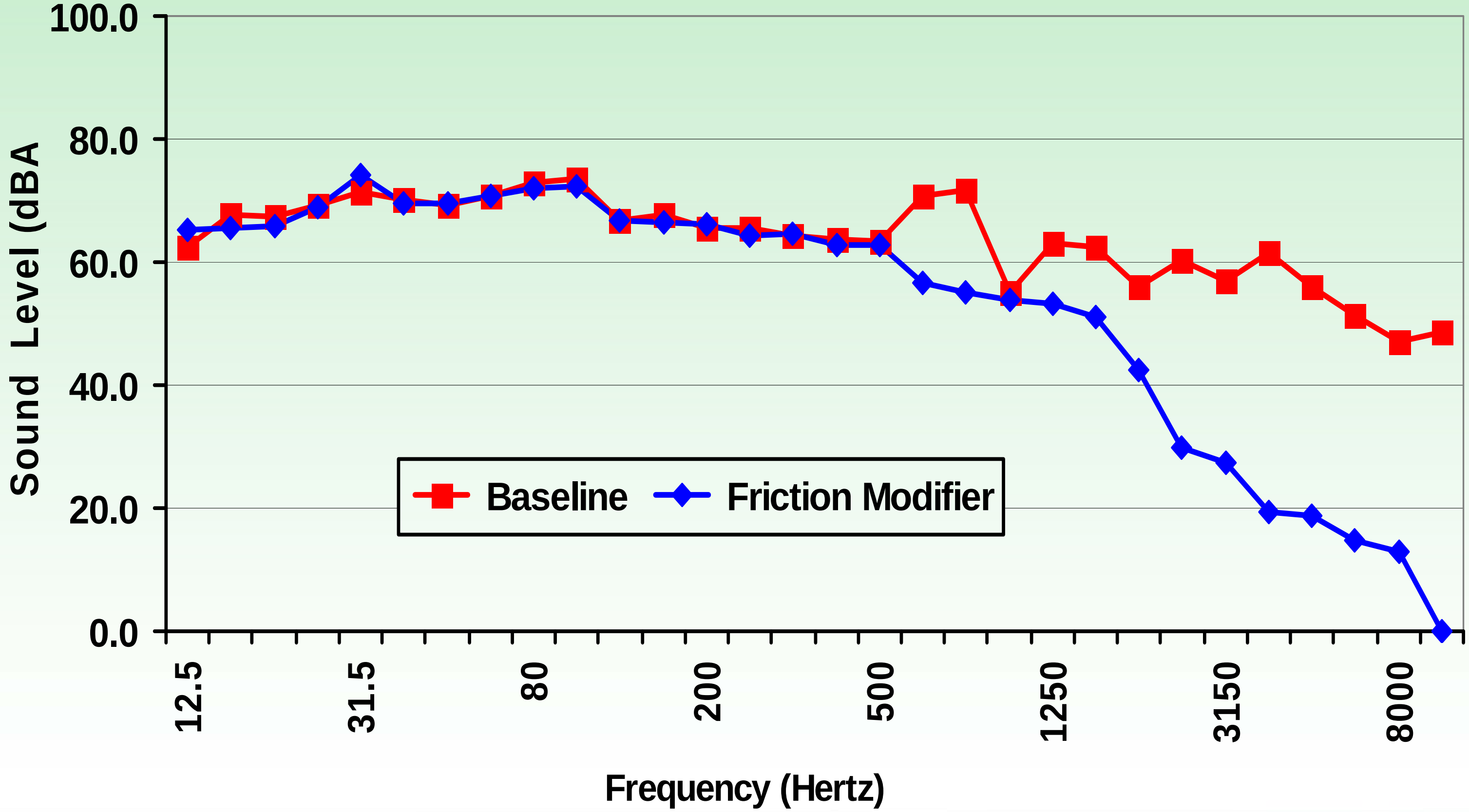
* Replotted from: "Matsumoto a, Sato Y, Ono H, Wang Y, Yamamoto Y, Tanimoto M & Oka Y, Creep force characteristics between rail and wheel on scaled model, *Wear,* Vol 253, Issues 1-2, July 2002, pp 199-203.

Sound spectral distribution for different wheel / rail systems

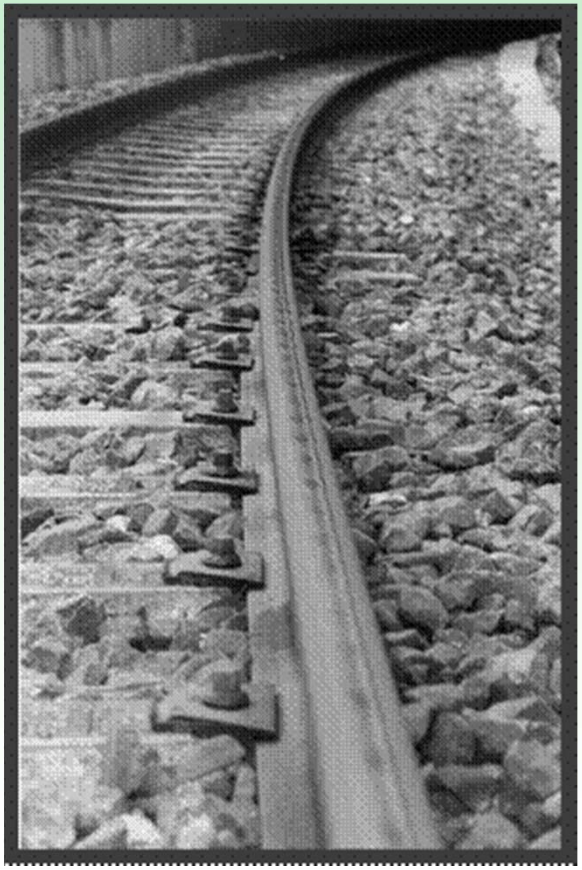


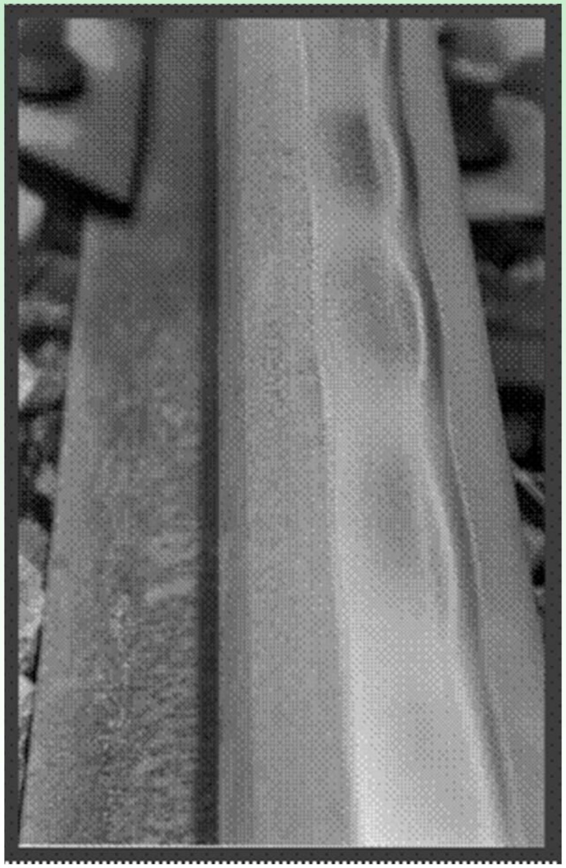
Effect of friction characteristics on spectral sound distribution: Trams

Effect of friction characteristics on spectral sound distribution: Trams

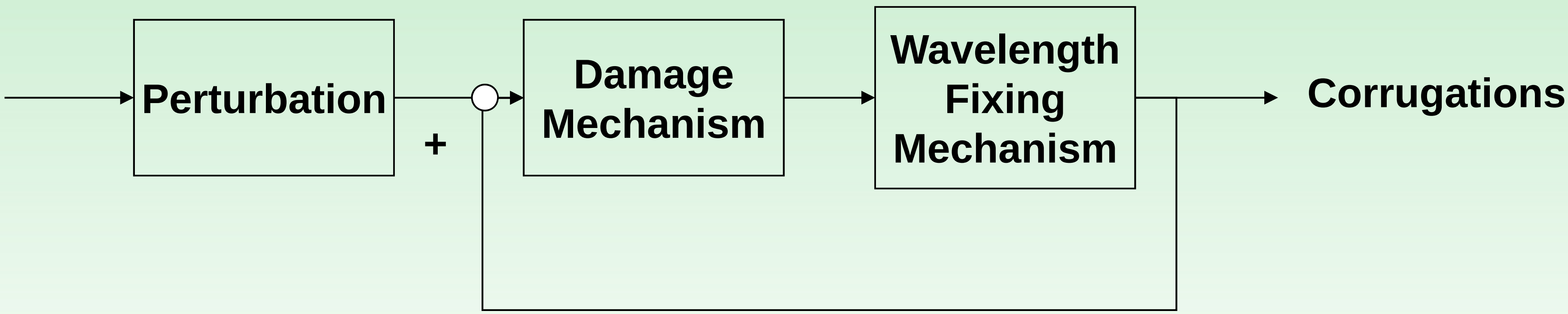


Corrugations (Short Pitch)





Corrugation formation: common threads

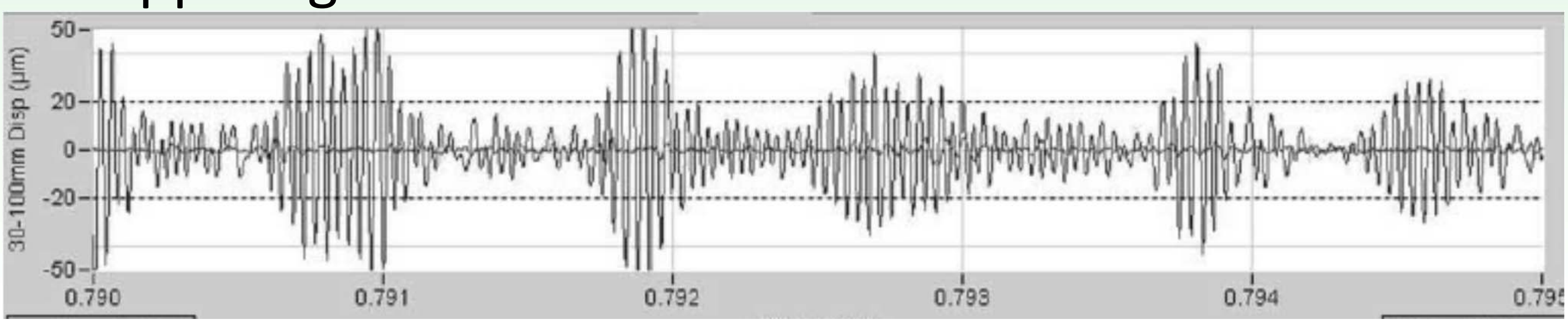


$$\boxed{\lambda = v/f}$$

	Type	Wavelength-fixing mechanism	Where?	Typical frequency (Hz)	Damage mechanism	Relevant figures	References	Treatments[1] Demonstrably successful	Treatments[1] 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

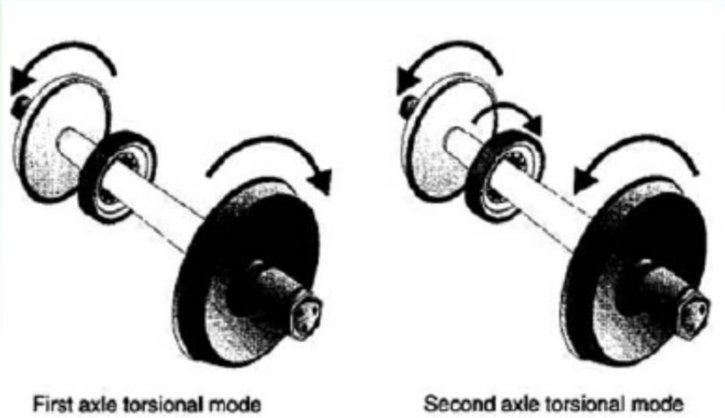
Pinned-Pinned corrugation ("roaring rail")

- 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 sleeper pitch (ca 0.9 m) – 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



Questions & Discussion