WRI 2021 Principles Course
Introduction and Overview

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A quick fact…

- Rail transportation meets 9% of global mobility demand, while generating 0.7% of total energy-related CO2 emissions.
- By comparison, 22% of total energy-related CO2 emissions are generated by other transportation modes.

J. Mendes dos Santos, "Keynote- ABB: Let's Write the Future of Rail," presented at the CUTRIC Canadian Smart Rail Technology Conference, Nov. 23, 2020.

… and a favorite quote

"The solution to most of the world's problems…

… is more trains"

- Ward Powell

Ward and Fay Powell at the top of the Duquesne Incline, Pittsburgh (2006)

Overview

- Morning:
  - Session 1: Wheel-Rail Contact Mechanics (Kevin Oldknow)
  - Session 2: Track Structures, Components and Geometry (Gary Wolf)
  - Session 3: Vehicle Types, Suspensions and Components (Elton Toma)
  - Session 4: Vehicle-Track Interaction & Dynamics (Rob Caldwell)

- Afternoon:
  - Session 5: Wheel-Rail Damage Mechanisms (Richard Stock)
  - Session 6: Vehicle-Track Measurement Technologies (Matt Dick)
  - Session 7: Maintaining the Optimized Wheel-Rail Interface (Eric Magel)
  - Session 8: Special Trackwork in Heavy Haul (Brad Kerchof)

Principles of
Wheel Rail Contact Mechanics

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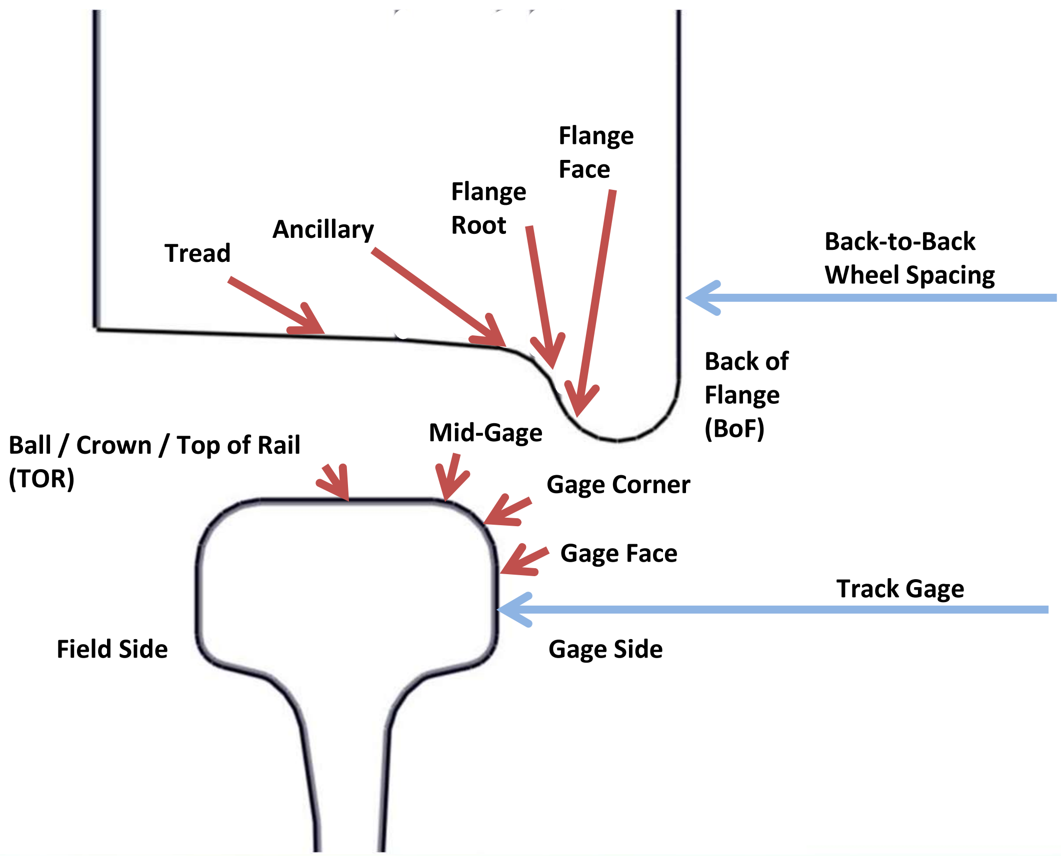
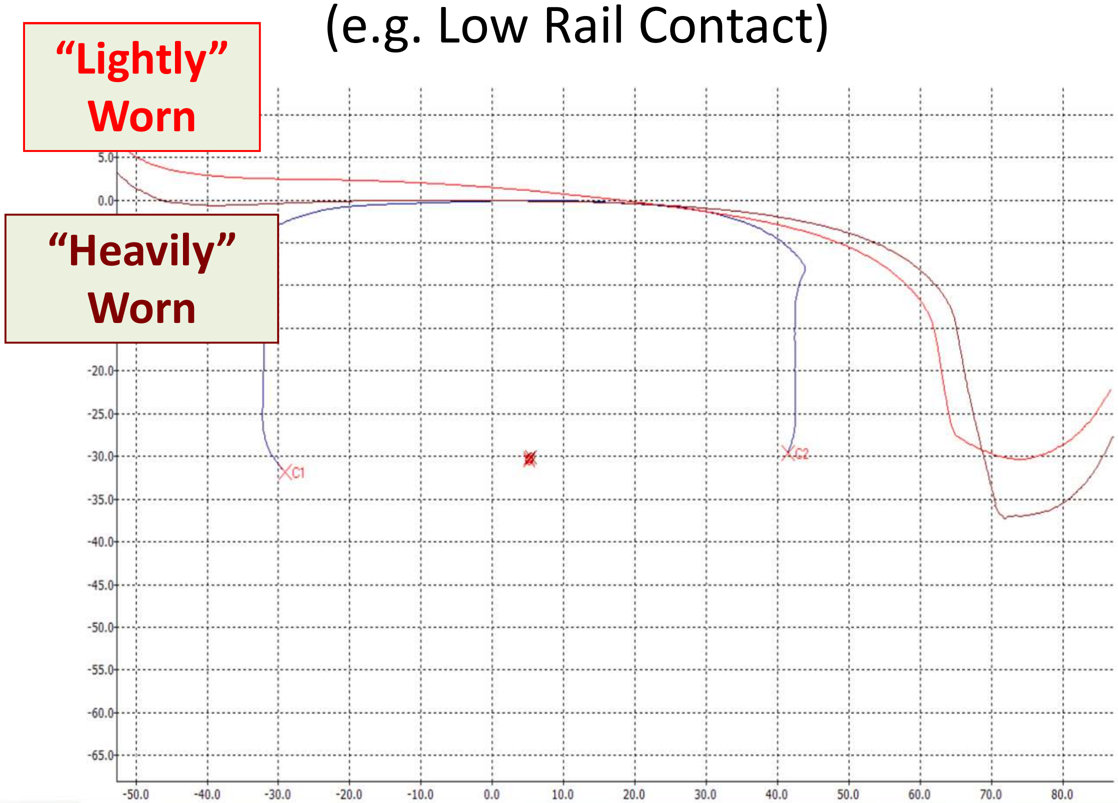
Overview

- The Wheel / Rail Interface Anatomy and Key Terminology
- The Contact Patch and Contact Pressures
- Creepage and Traction Forces
- The “Third Body Layer” and Traction/Creepage

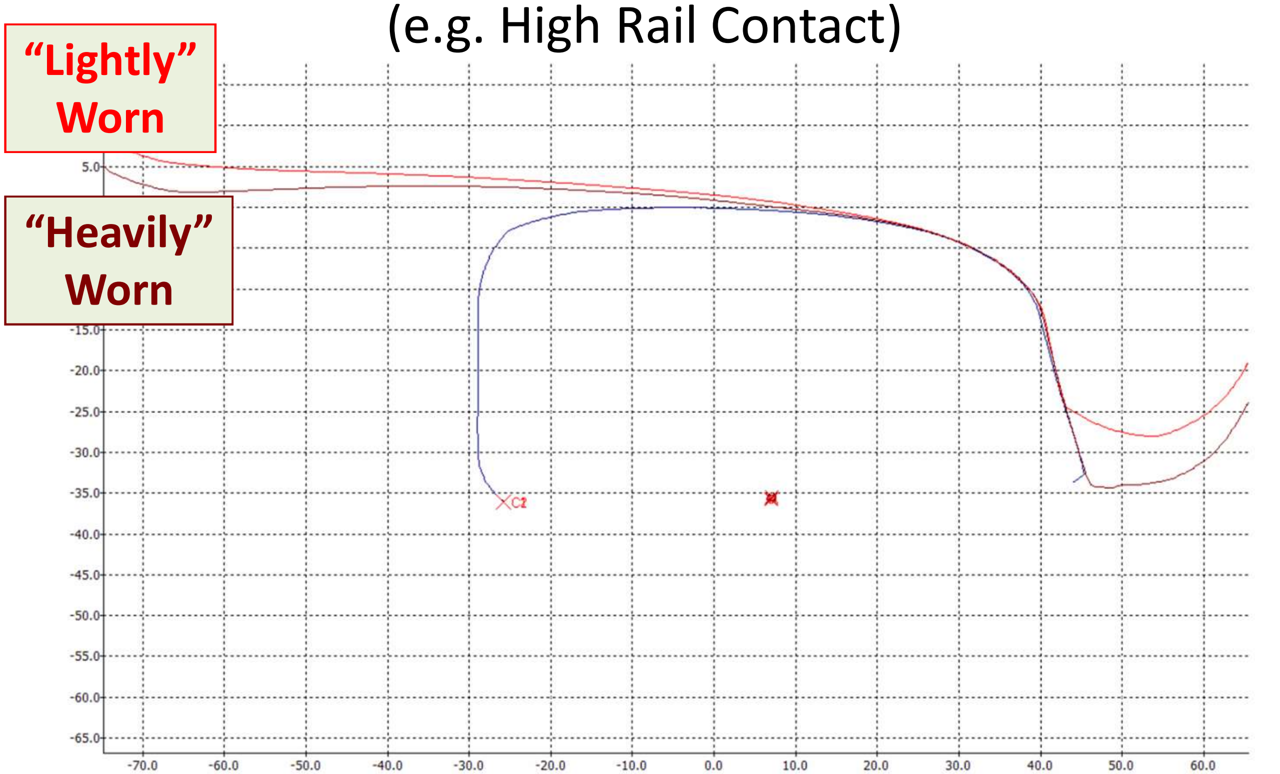
The Wheel / Rail Interface and Key Terminology



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

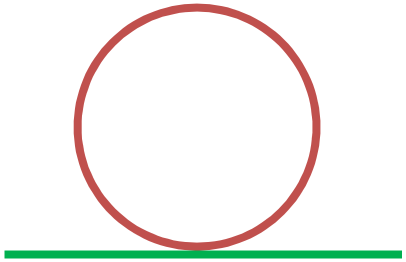


The Wheel / Rail Interface and Key Terminology (e.g. High Rail Contact)



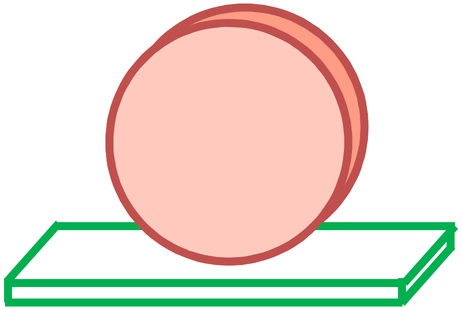
The Contact Patch and Contact Pressures

- 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?

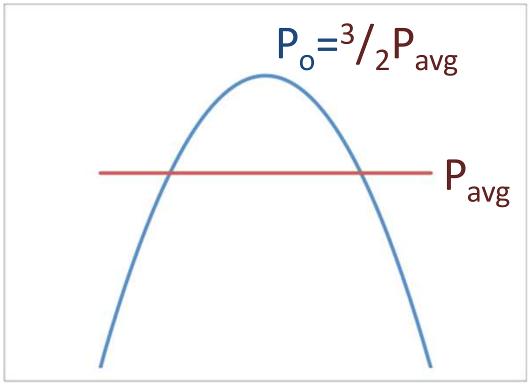


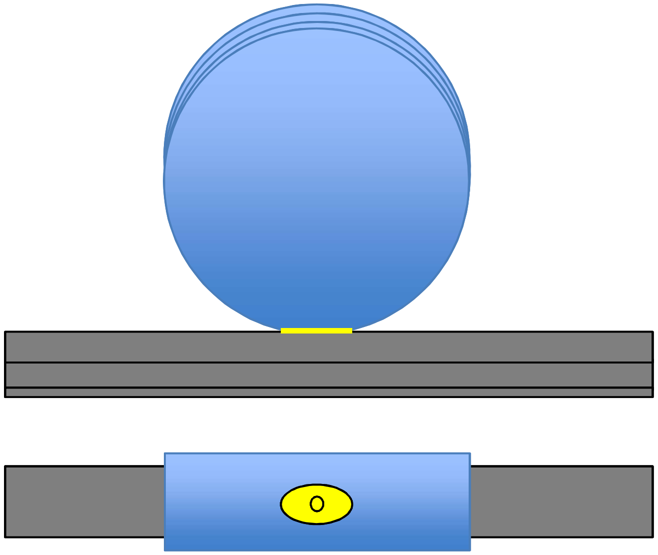
- Question #2: Given Force and Area, how do we calculate pressure?

- 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 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



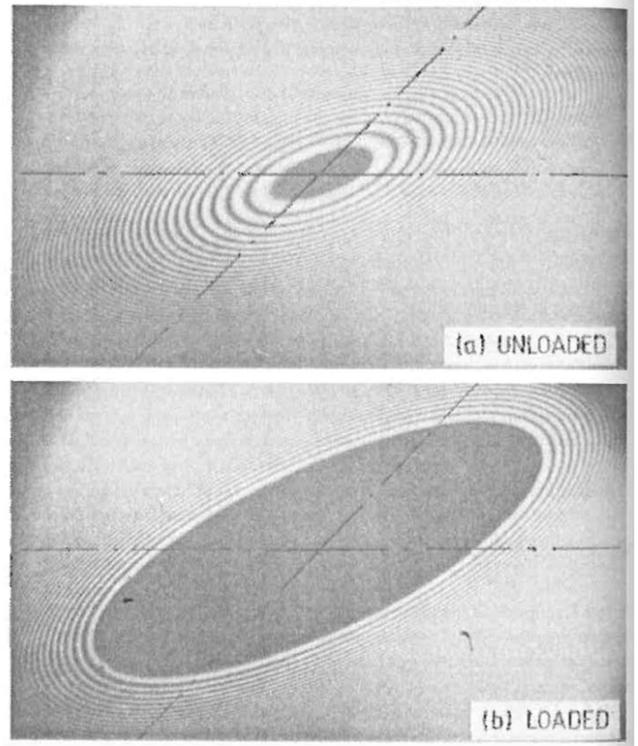


- Contact theory was subsequently broadened to apply to rolling contact (Carter and Fromm) with non-elliptical contact and arbitrary creepage (Kalker; *more on this later…*)

Hertzian Contact

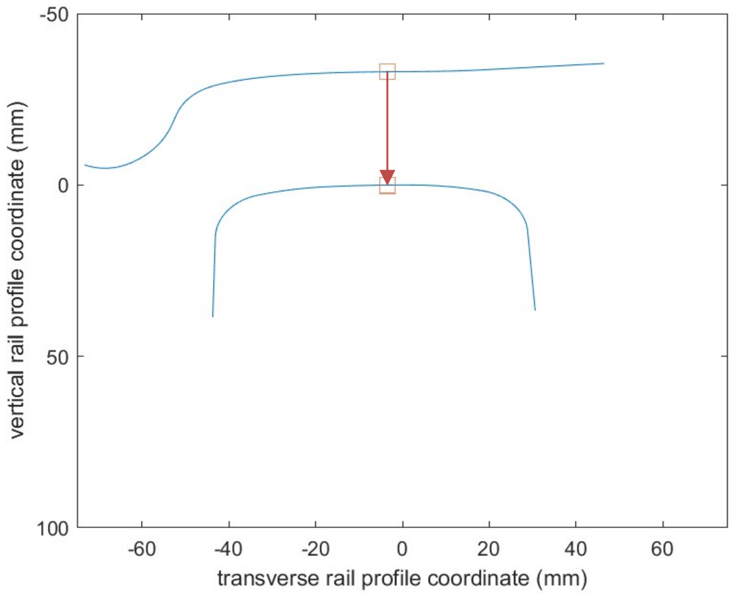
- Interference fringes
  - Patterns created by the reflection of light between two surfaces in close proximity (Hooke 1664, Newton 1717)
  - Used by Hertz (1882) to study the deformation of curved surfaces under load
  - Hertzian "point contact" is shown to the right (two cylindrical lenses with axes inclined at 45^o):

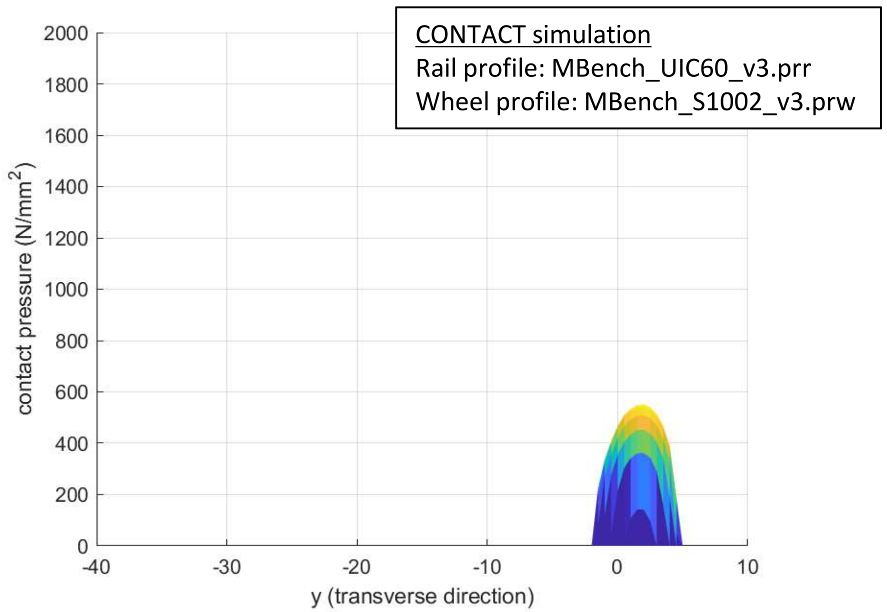
Fig. 4.1. Interference fringes at the contact of two equal cylindrical lenses with their axes inclined at 45°: (*a*) unloaded, (*b*) loaded.



Johnson, K.L. (1986) Contact Mechanics, Cambridge University Press

Hertzian Contact

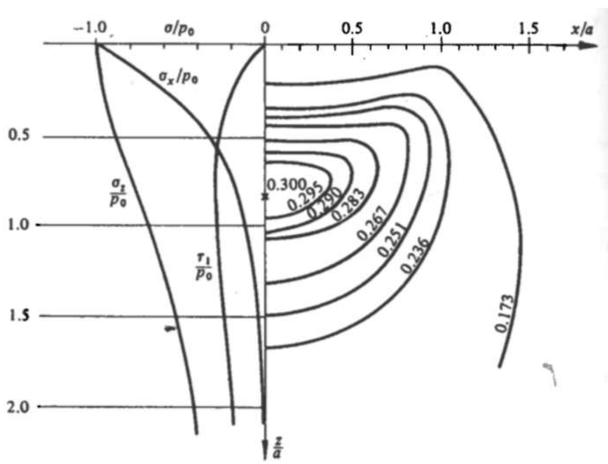


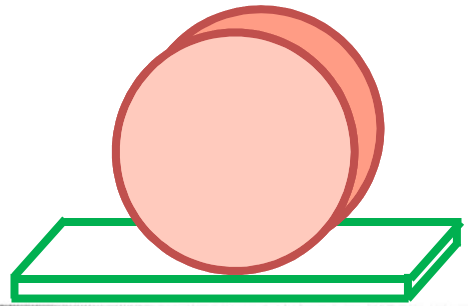


Vertical Load: 1 kN

Line Loading

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





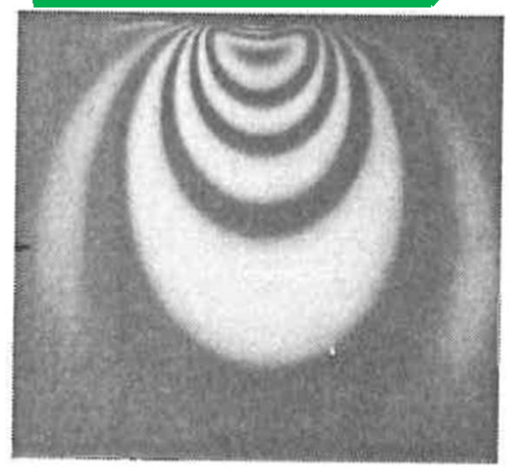
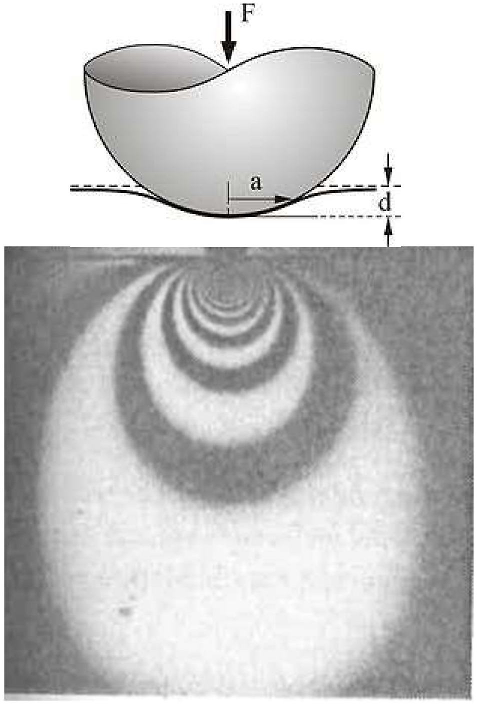


Photo-elastic fringe patterns showing contours of principle shear stress)

Johnson, K.L. (1986) Contact Mechanics, Cambridge University Press

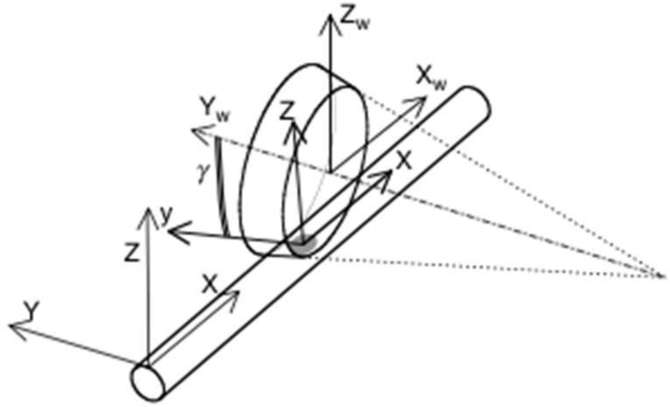
Point Loading

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

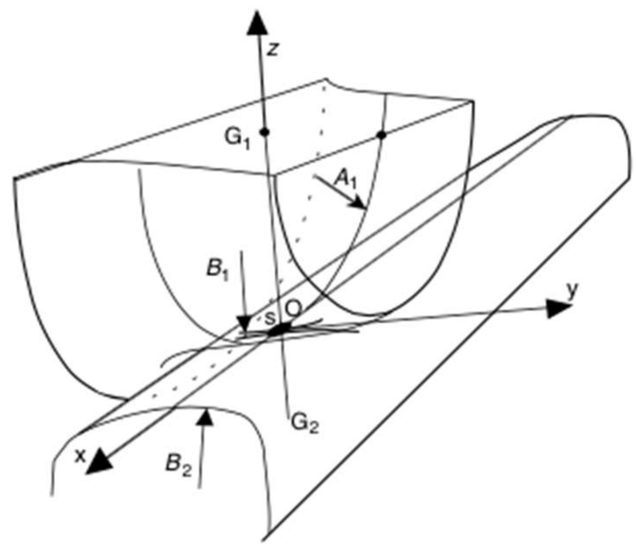


Johnson, K.L. (1986) Contact Mechanics, Cambridge University Press

Hertzian Contact at the Wheel / Rail Interface



Rail, wheel and contact frames.



Hertzian contact: the railway case.

Iwnicki, S. (2006) Handbook of Railway Dynamics, CRC Press

Example: Contact Pressures for a Stationary Vehicle

- Consider a heavy-axle load freight car (286,000 lb gross weight), standing at rest on tangent track.
- The wheel treads are in (approximate) single point contact with the top of rail surfaces at each contact point.
- Each contact patch is (approximately) circular, with a radius of 8mm.
- What is the estimated peak pressure (in MPa) in each contact area?

SOLUTION:

VERTICAL LOAD (PER WHEEL) $F_N = \frac{286,000 \text{ lbf}}{8}$

$= 35.75 \text{ kips} = 159 \text{ kN}$

AREA OF CONTACT PATCH $= \pi r^2$ $(r = 8\text{mm})$

$= 1.61 \times 10^{-3} \text{ m}^2$

AVERAGE PRESSURE:

$$\bar{P} = F_N / \pi r^2 = 7.91 \times 10^8 \text{ Pa}$$

$= 791 \text{ MPa}$

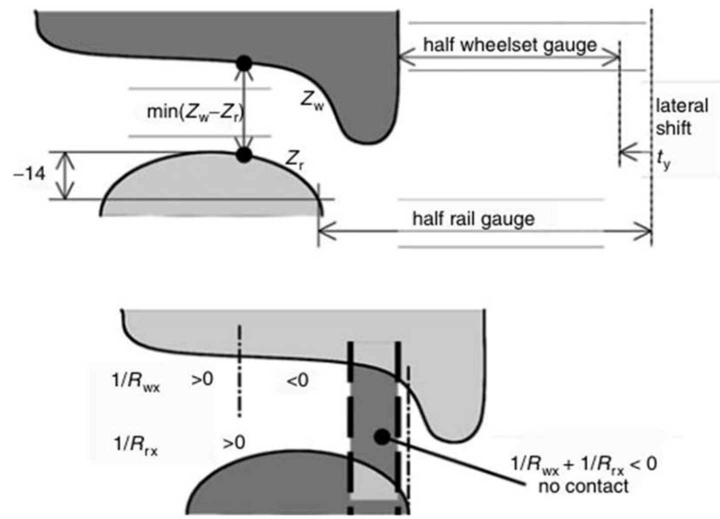
=> PEAK PRESSURE

$$P_0 = \frac{3}{2} \bar{P} = \frac{3F_N}{2\pi r^2}$$

$= 1.186 \times 10^9 \text{ Pa}$

$= 1,186 \text{ MPa}$

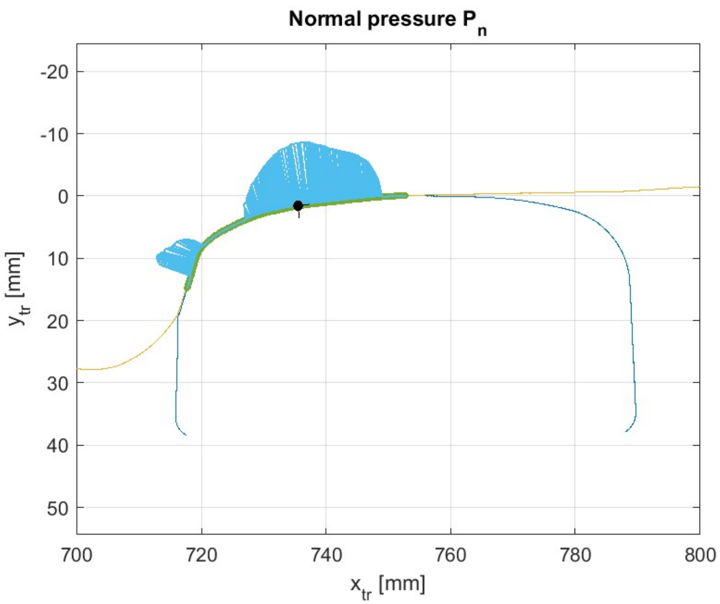
Conformal and 2-Point Contact

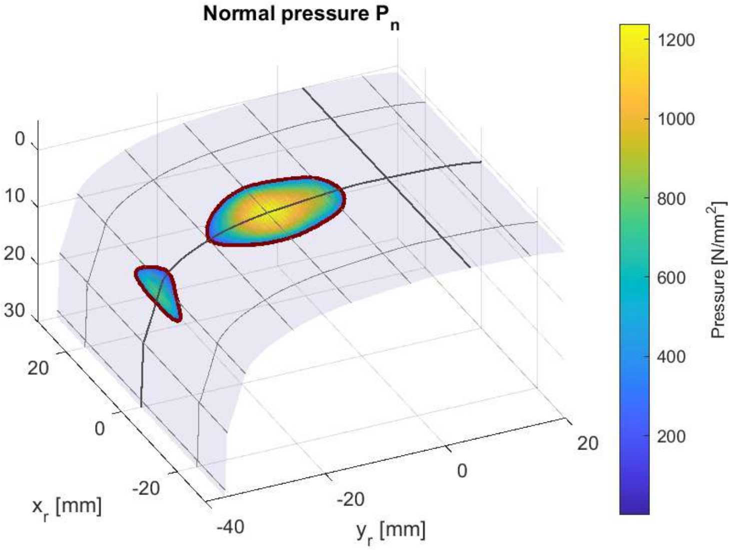


Corresponding curvatures between the wheel and the rail.

Iwnicki, S. (2006) Handbook of Railway Dynamics, CRC Press

Hertzian & Non-Hertzian Contact





Creepage, Friction and Traction Forces

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

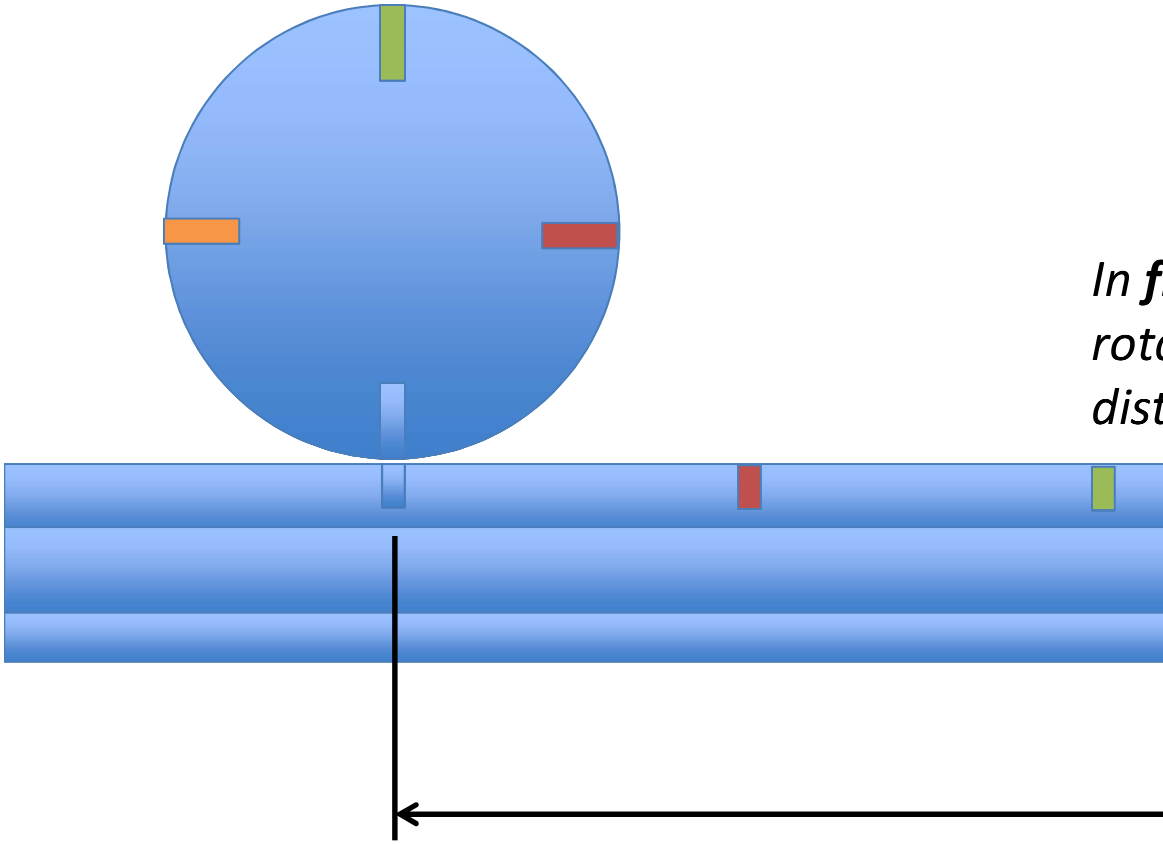
Why is **creepage** at the Wheel/Rail Interface important?

- 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*?...

- 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



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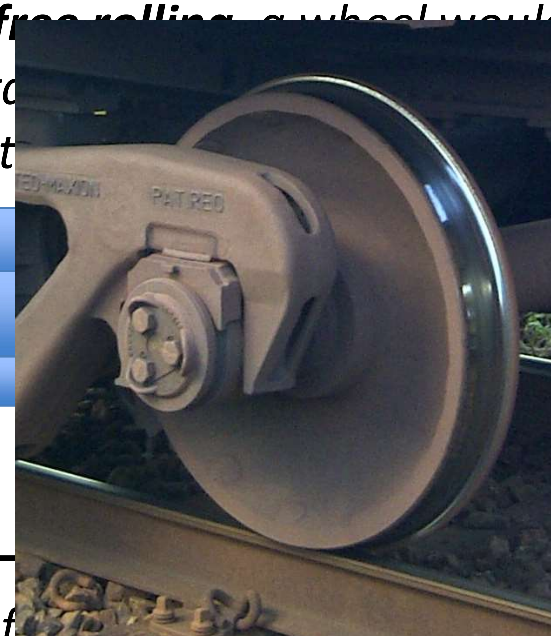
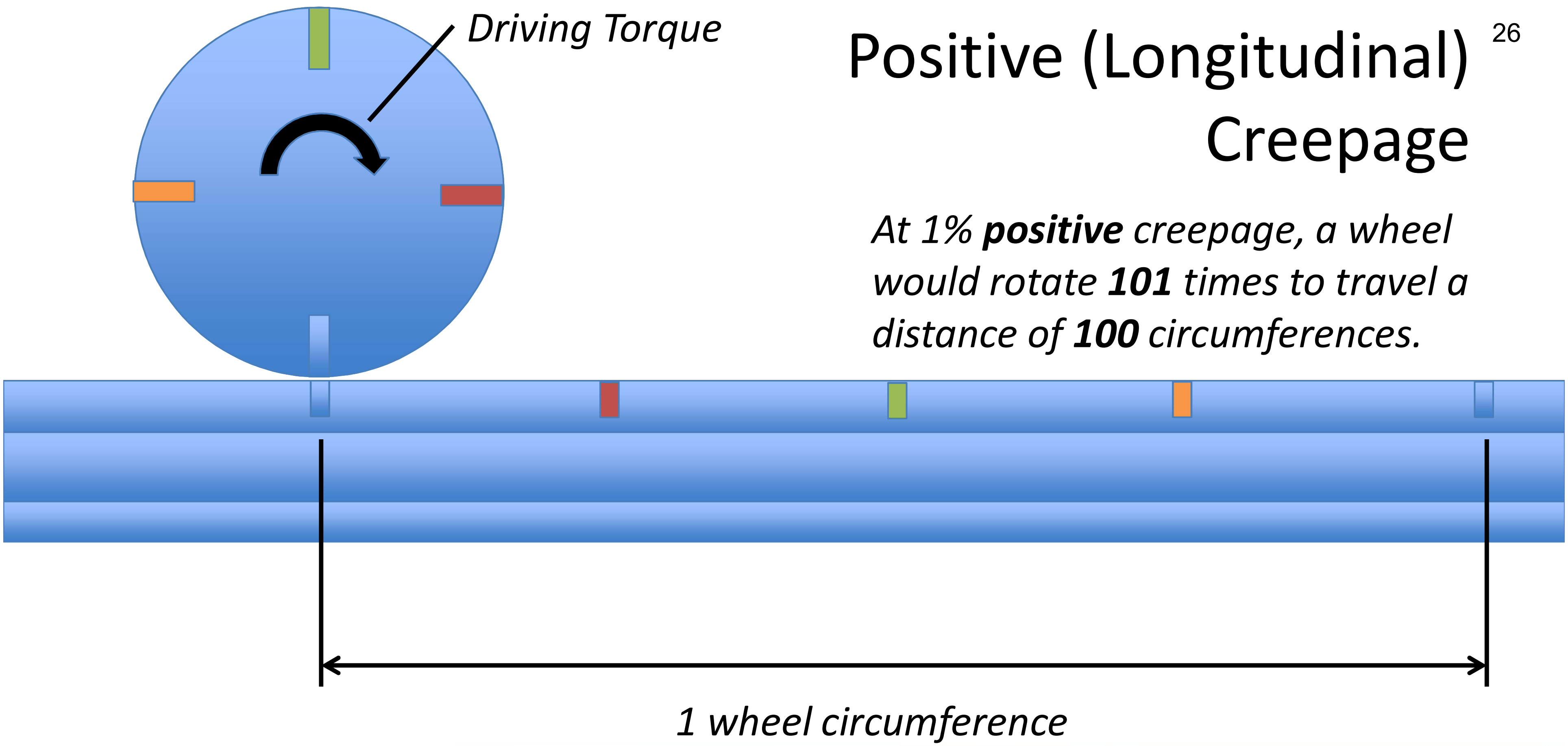


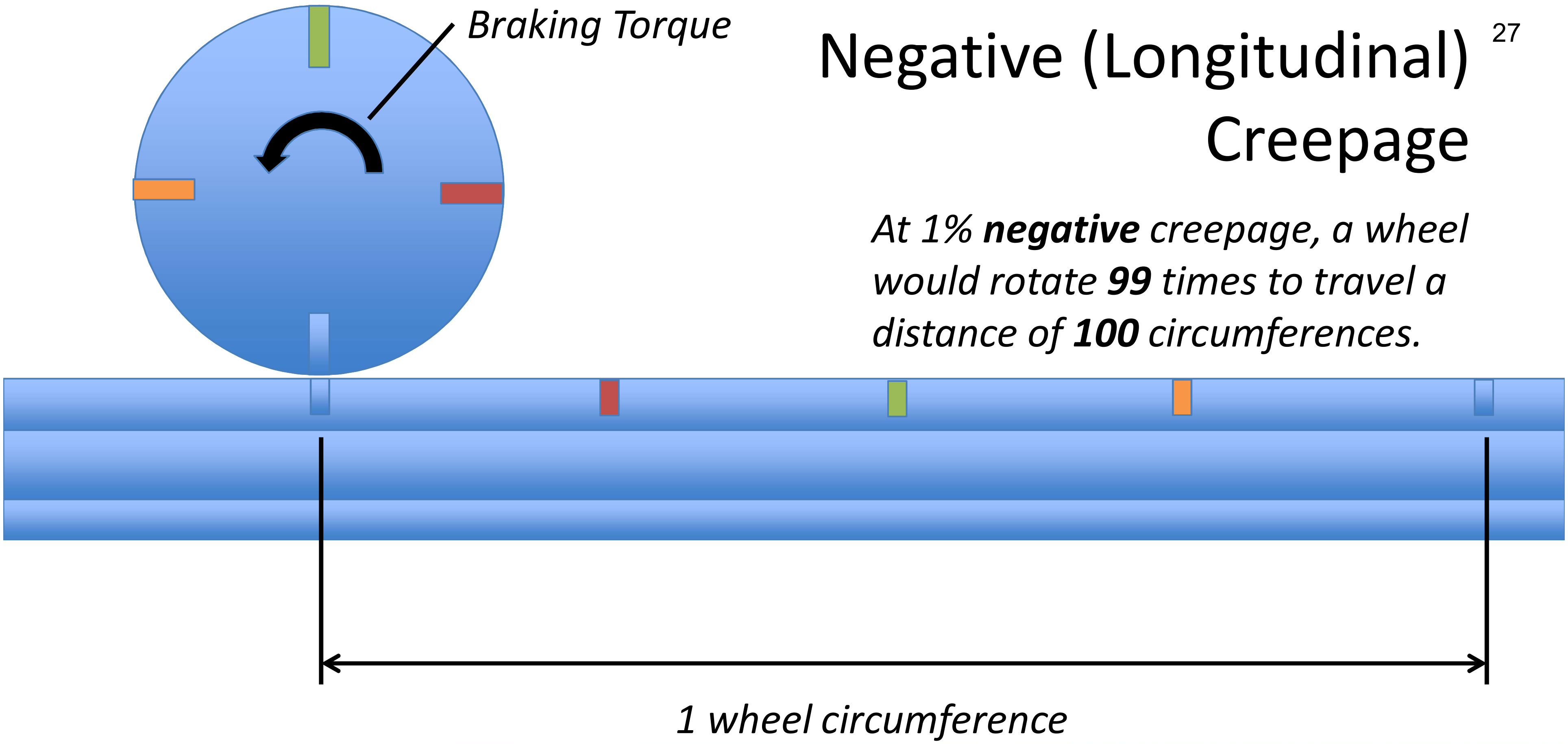
1 wheel circumf

Positive (Longitudinal) Creepage

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



Negative (Longitudinal) Creepage



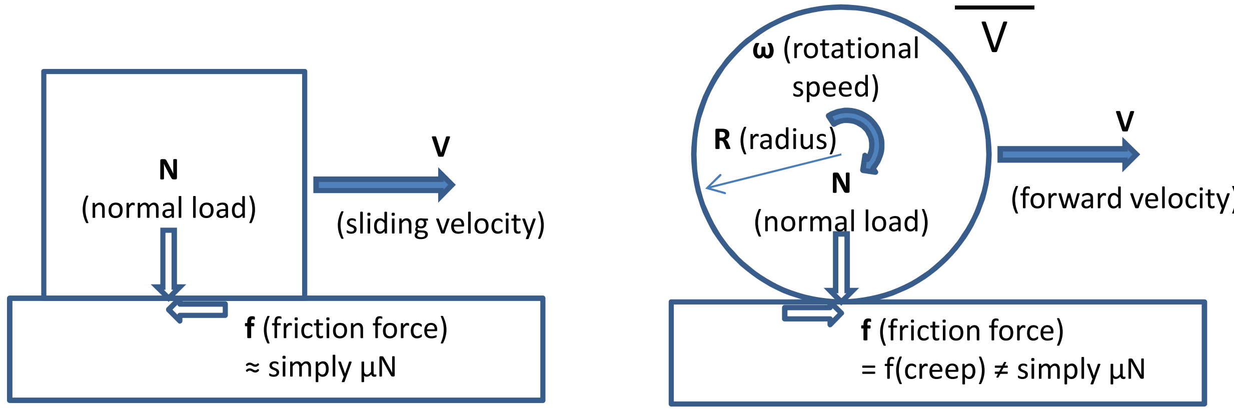
*At 1% **negative** creepage, a wheel would rotate **99** times to travel a distance of **100** circumferences.*

Rolling vs. Sliding Friction
They are not the same!

μ: coefficient of (sliding) friction

creep:

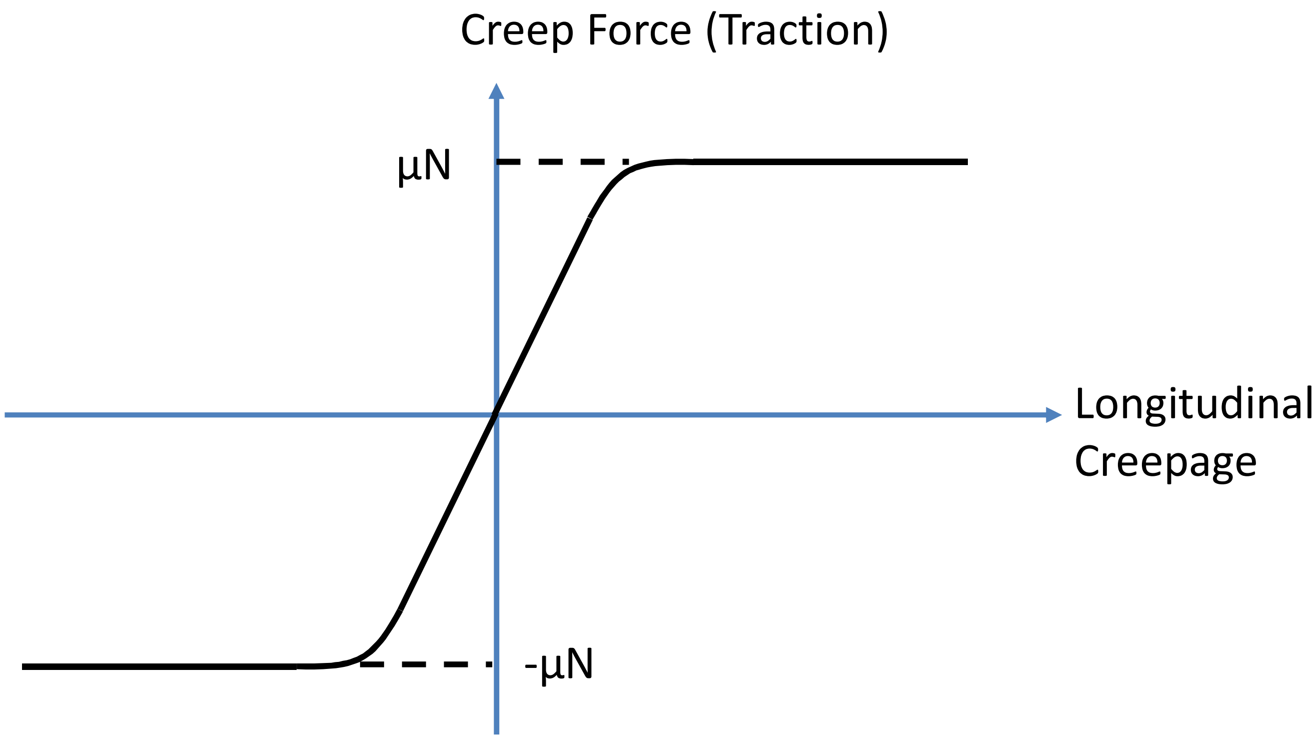
$$\frac{R\omega - V}{V}$$



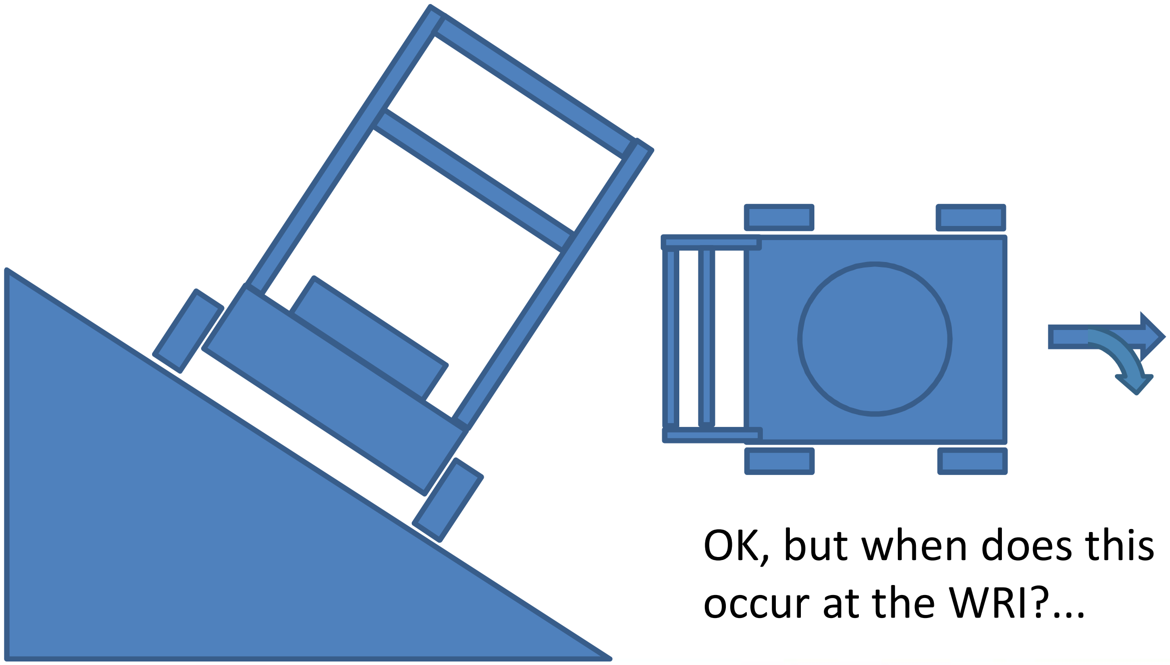
friction force shown as acting on block for positive sliding velocity

friction force shown as acting on wheel for positive creep

The Traction-Creepage Curve

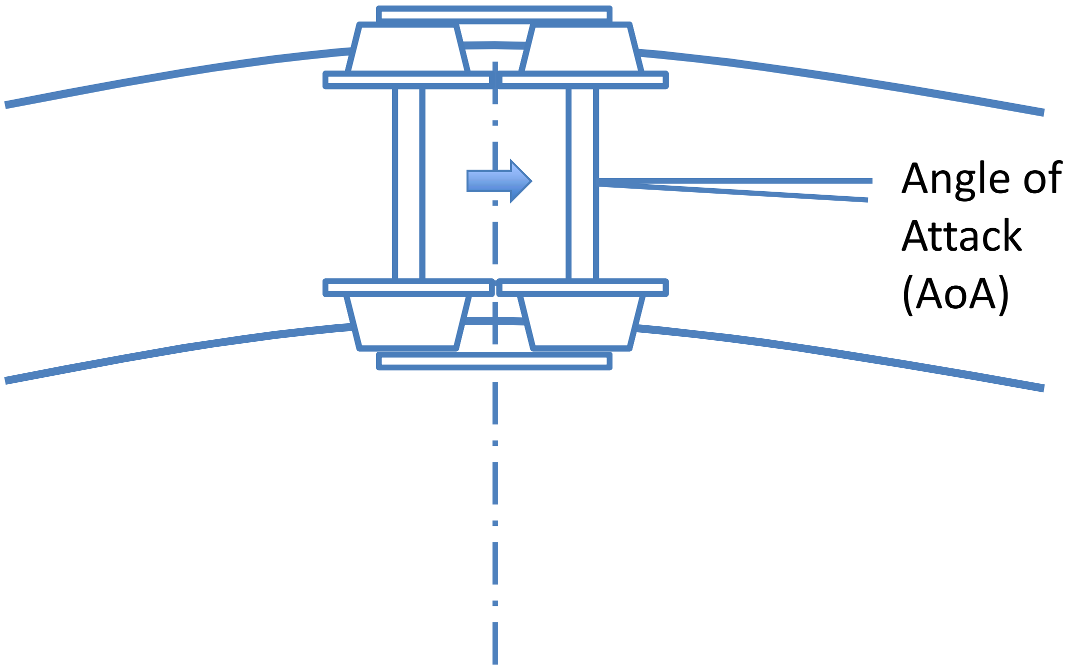


Lateral creepage
Imagine pushing a lawnmower across a steep slope…

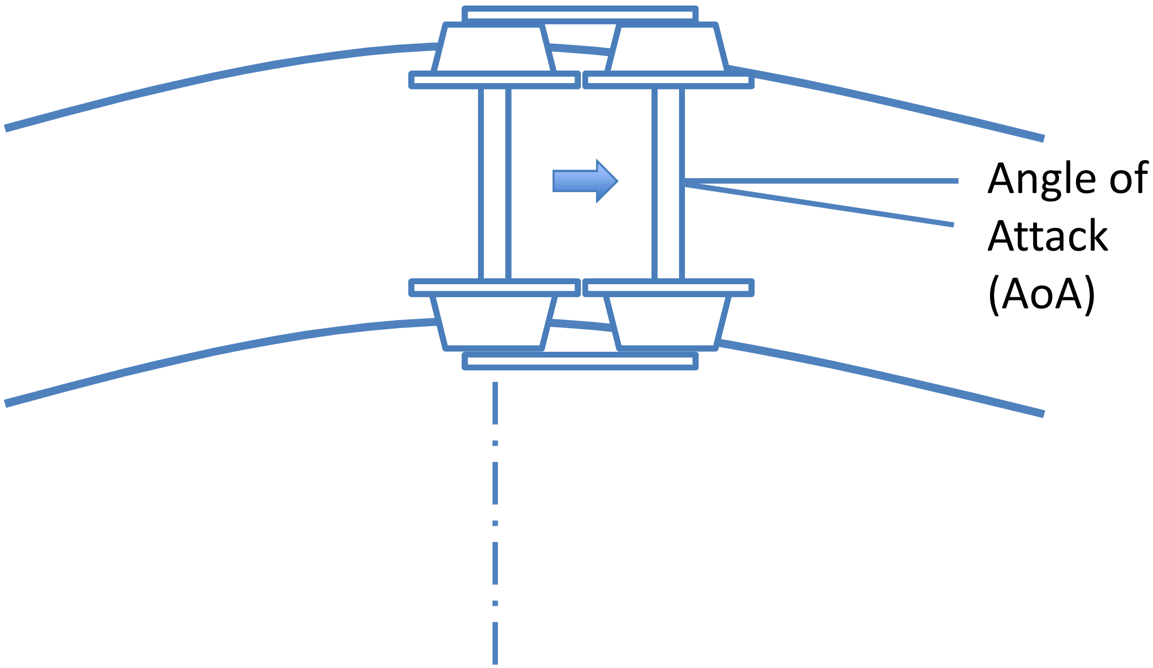


OK, but when does this occur at the WRI?...

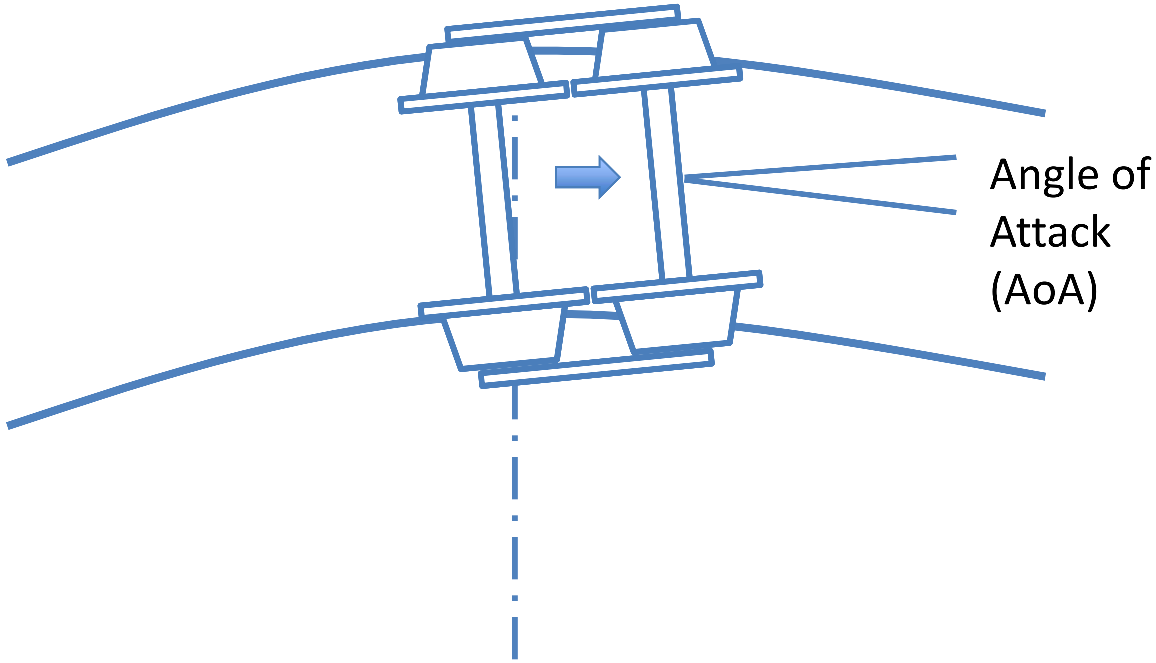
Steering in "Steady State" Curving ("Mild" Curves)



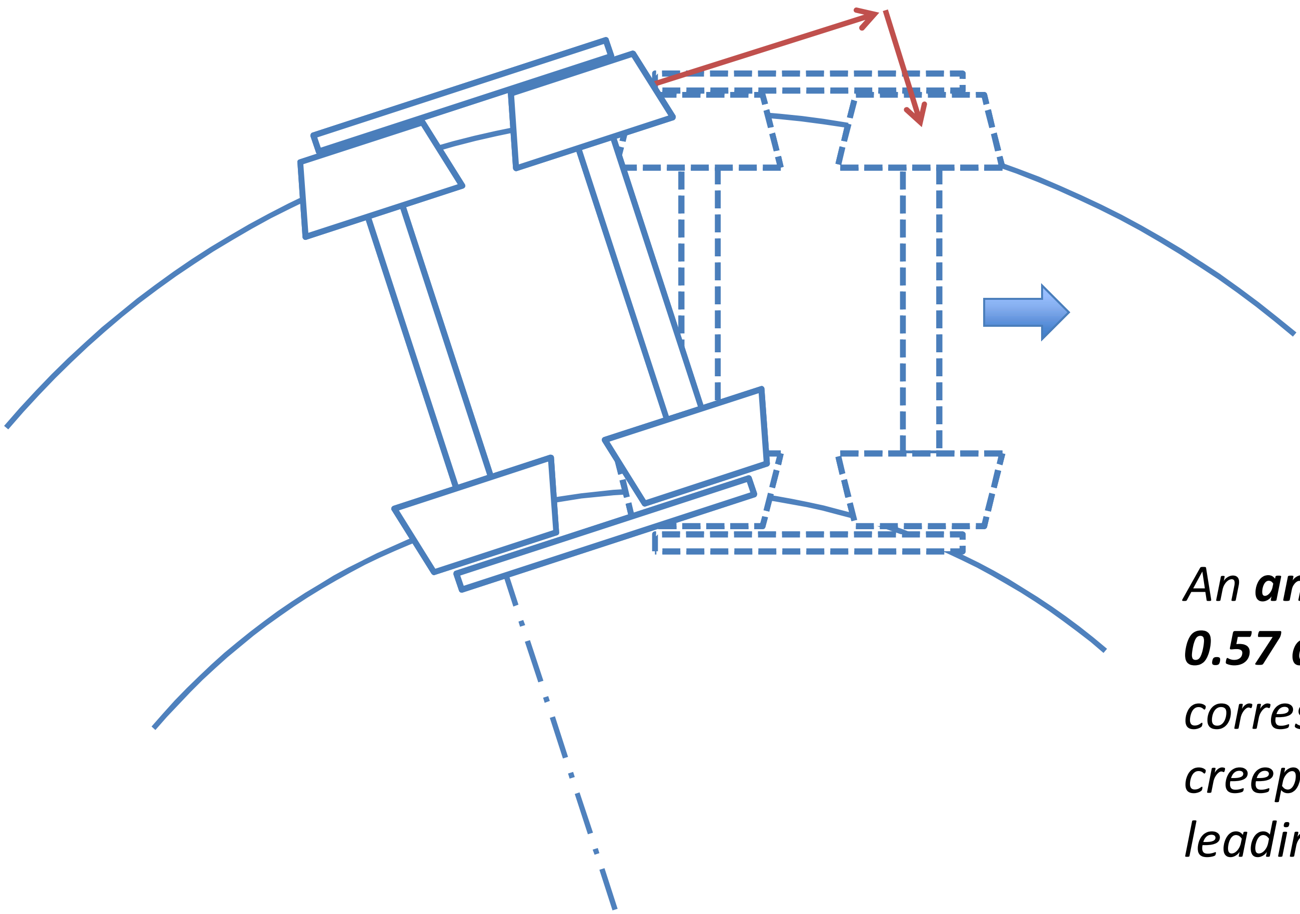
Steering in "Steady State" Curving ("Sharp" Curves)



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

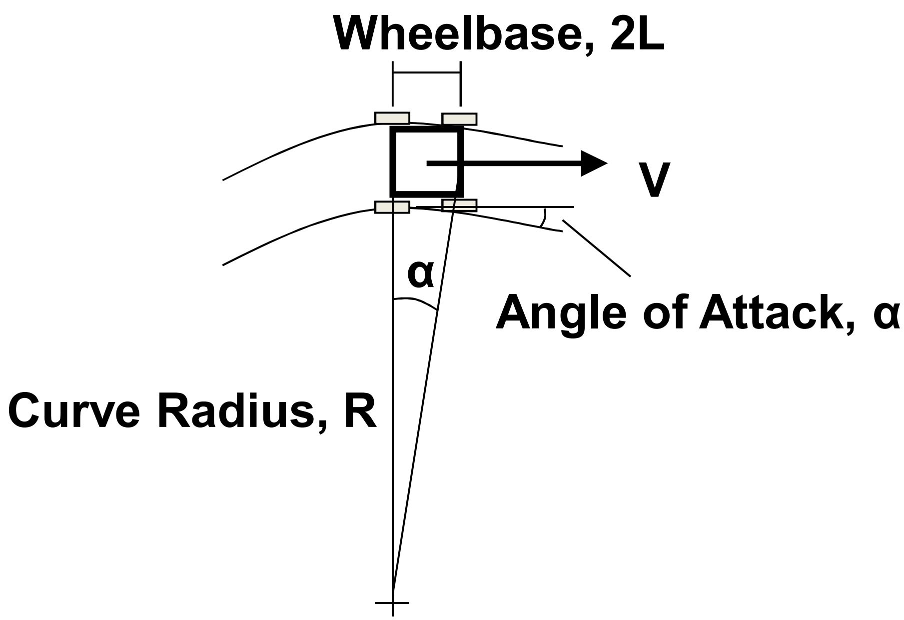


Lateral Creepage



*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')

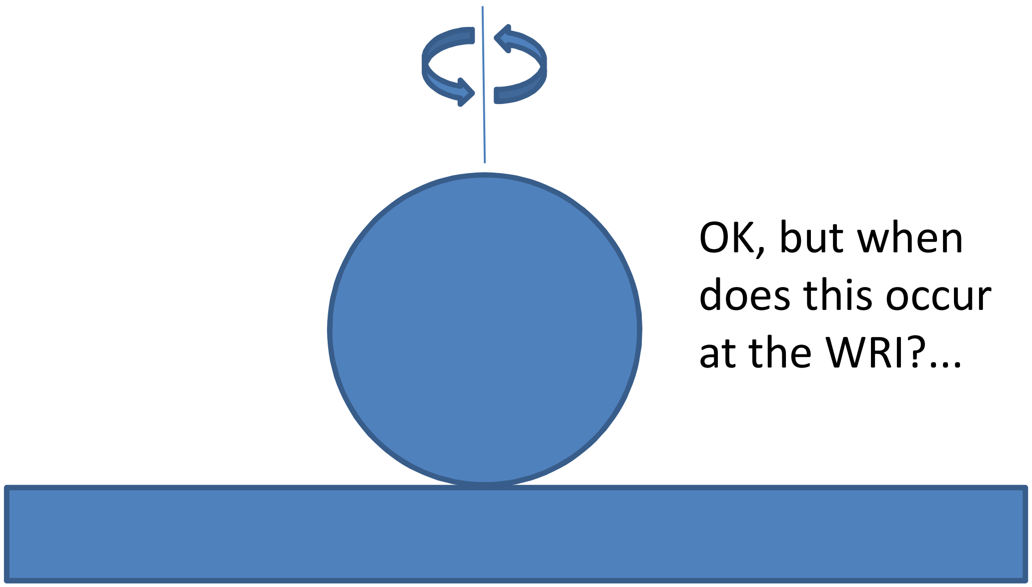
70" WHEELBASE (2L = 5.83')

LEADING AXLE ANGLE OF ATTACK:

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

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

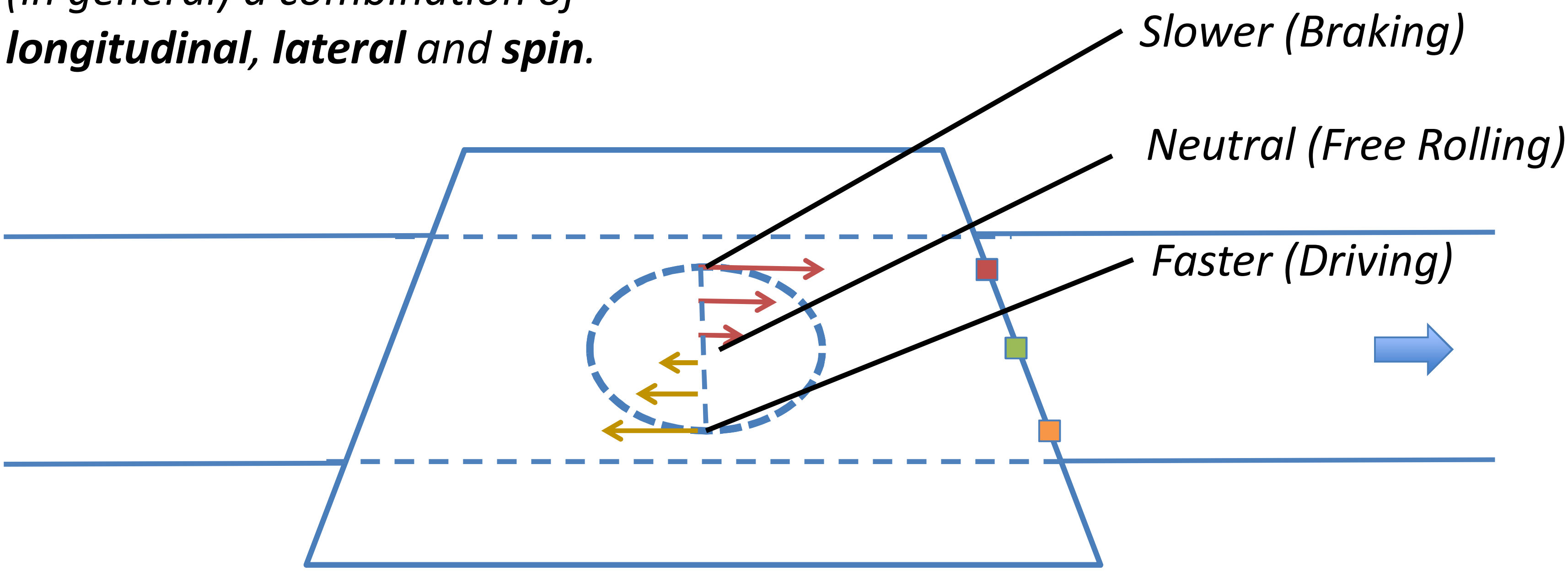
Spin Creepage
Think of spinning a coin on a tabletop….



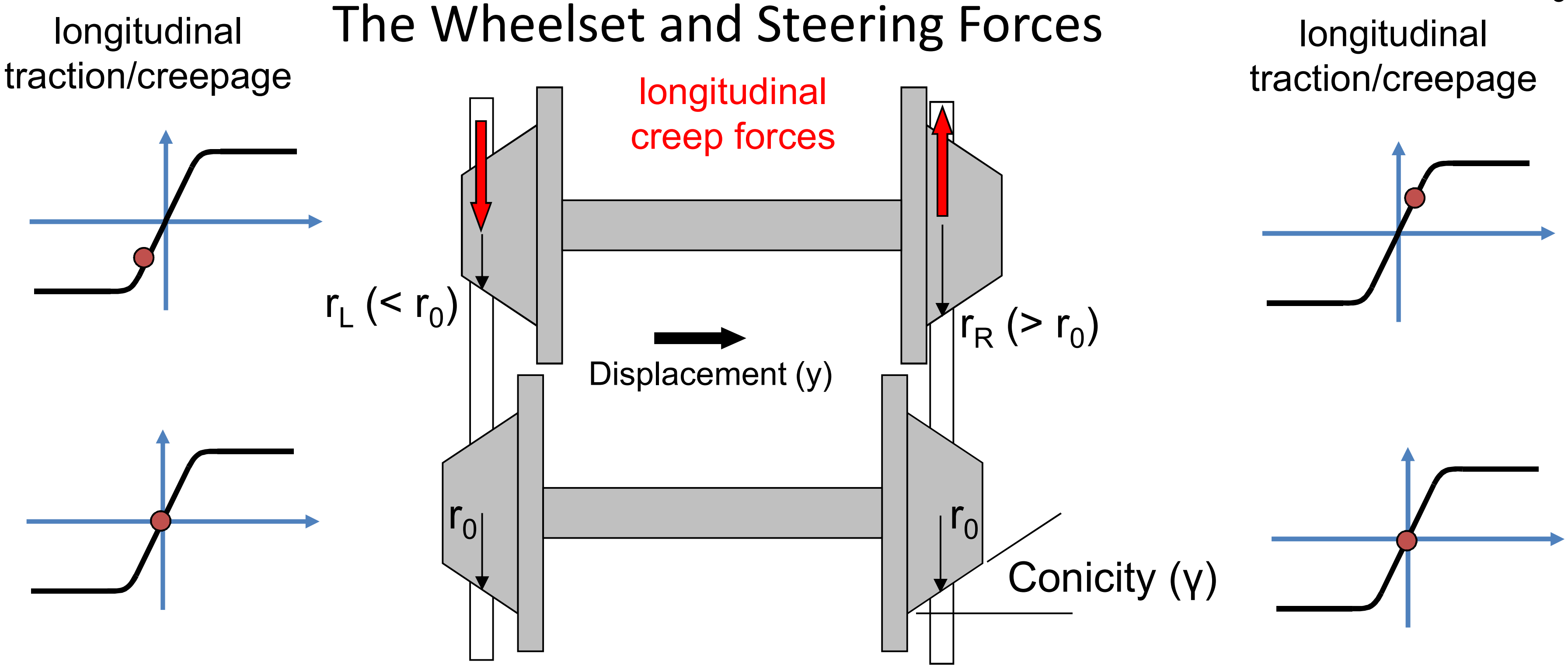
OK, but when does this occur at the WRI?...

Spin Creepage

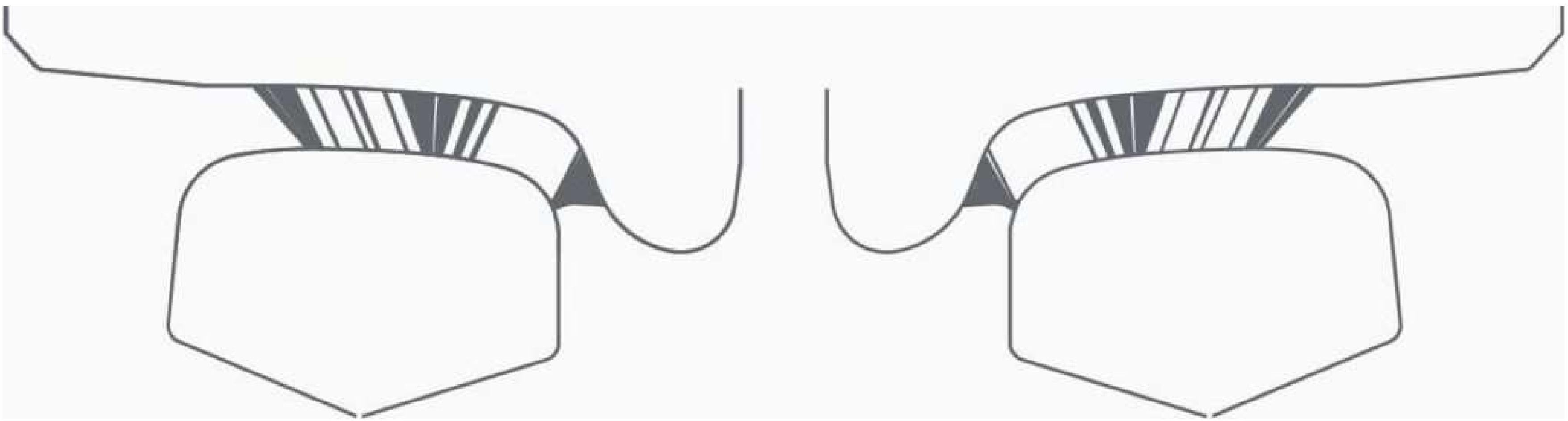
*The **net creepage** vector at the wheel/rail interface is (in general) a combination of **longitudinal**, **lateral** and **spin**.*



The Wheelset and Steering Forces

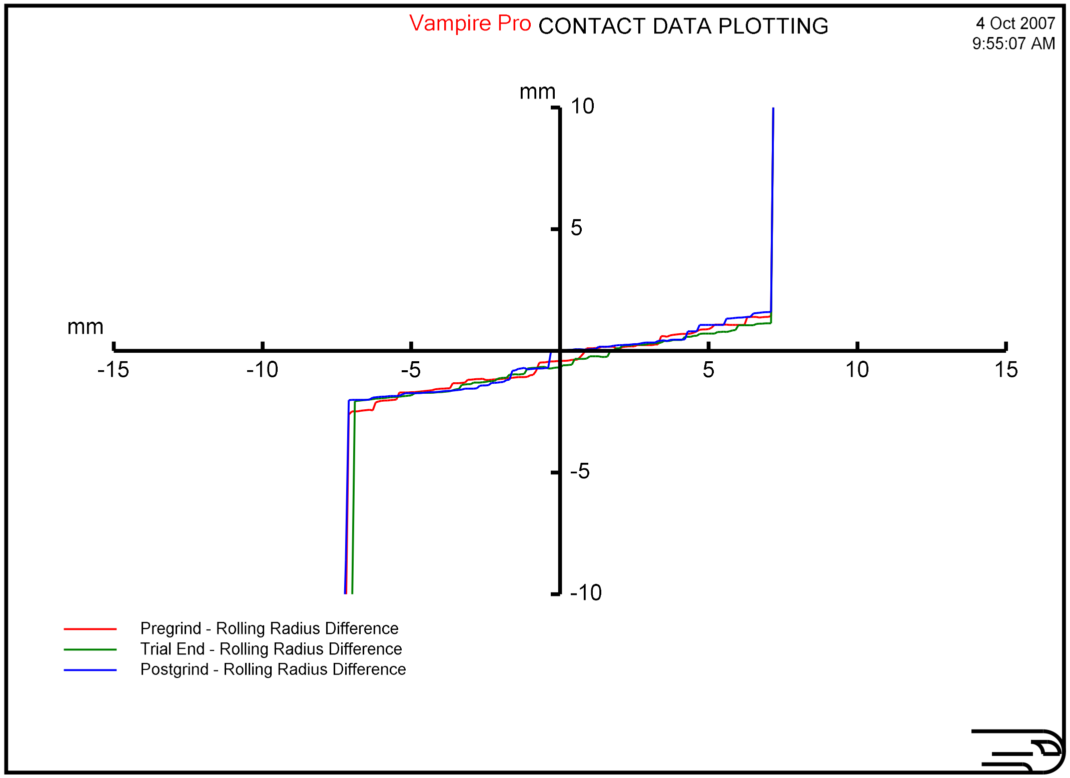


Potential Contact and Equivalent Conicity



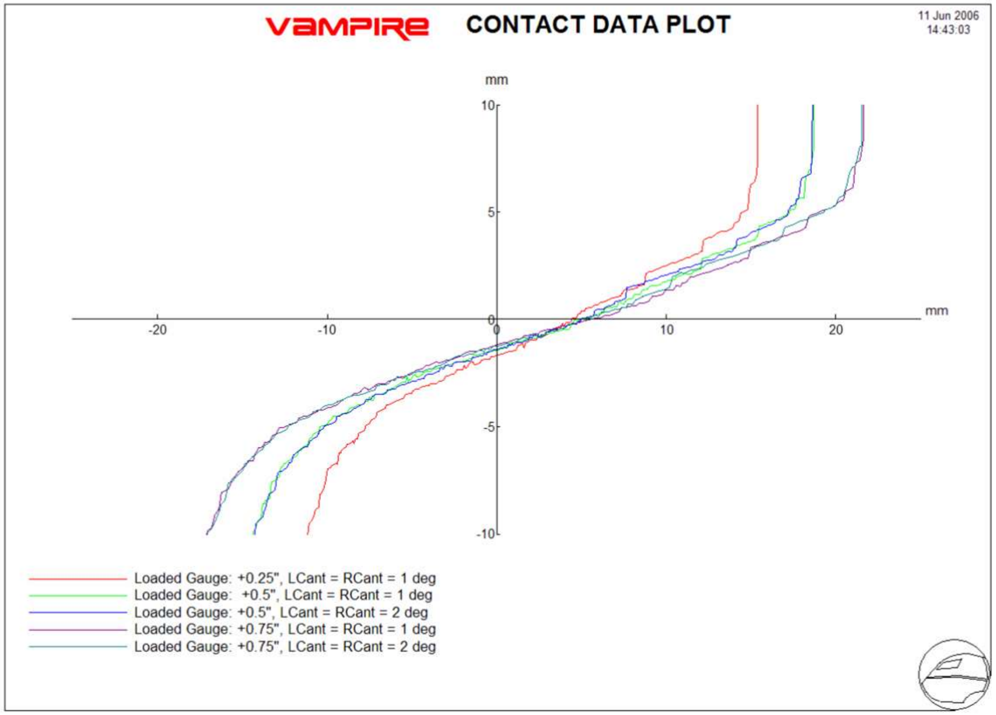
Source: https://greenwood.dk/railway/instruments/miniprof-bt-twinhead/

Effective Conicity



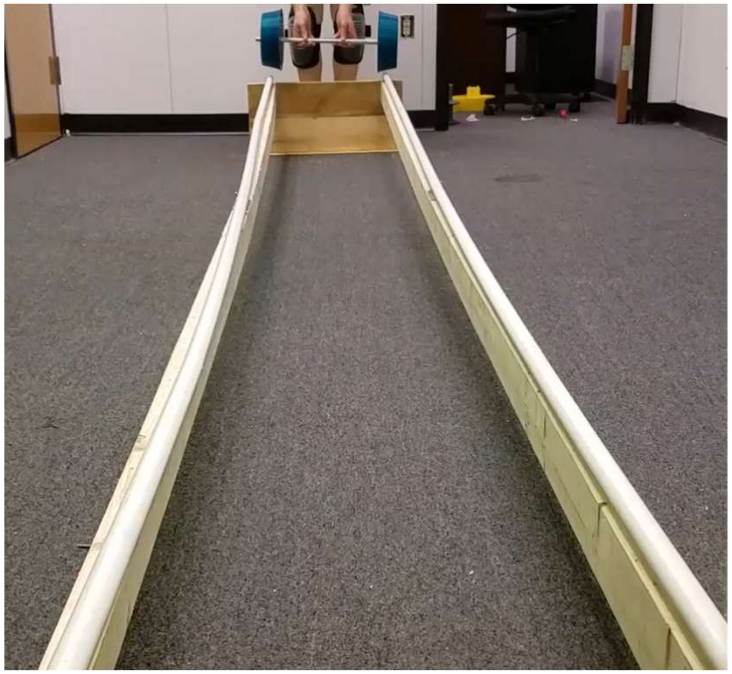
Rolling Radius Difference

Effective Conicity (Worn Wheels)



VAMPIRE Plot

Demonstration*: Steering forces in tangent track



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

Important Concept:

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

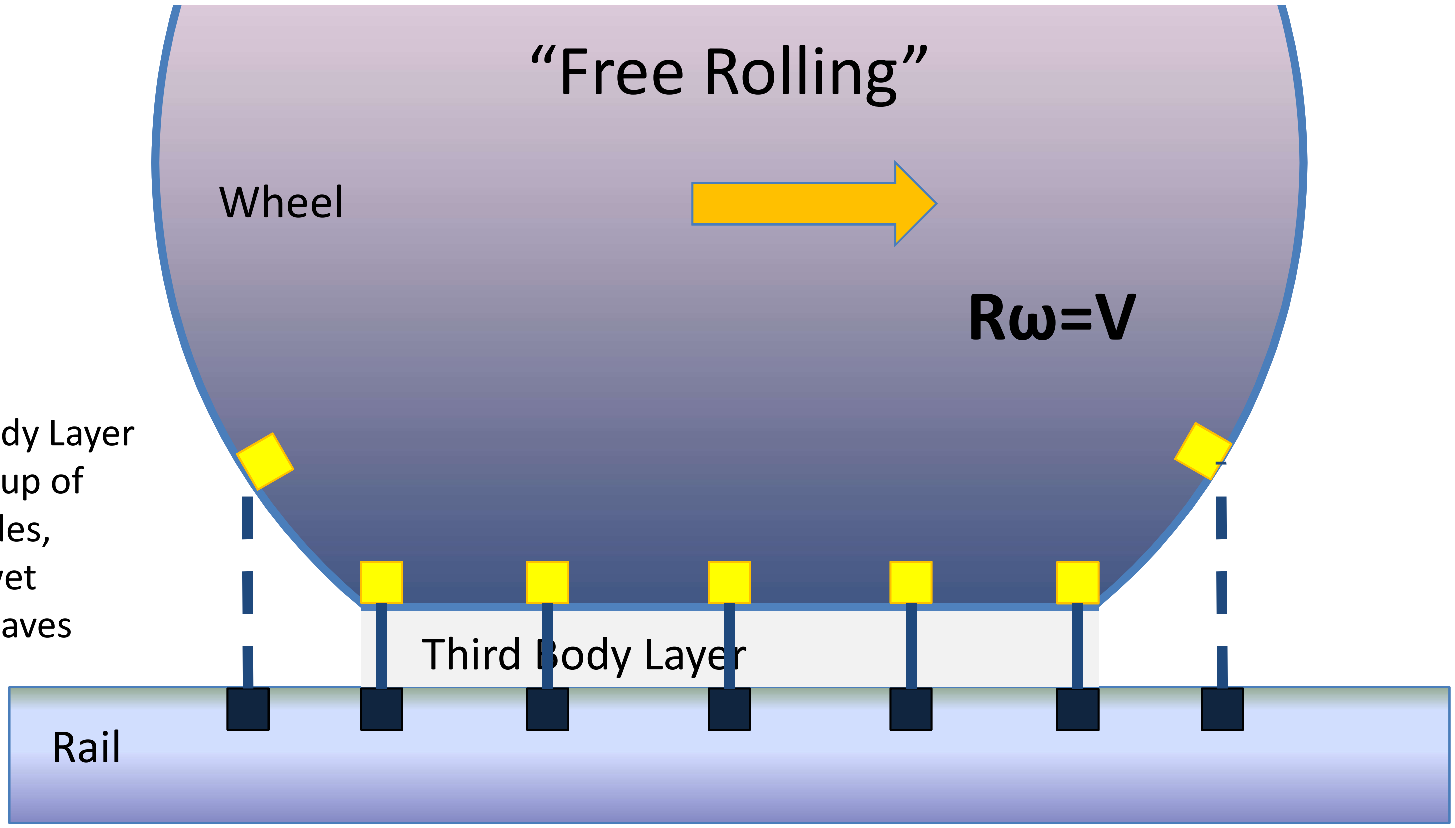
- Other times, creepage gives rise to forces (e.g. curving)

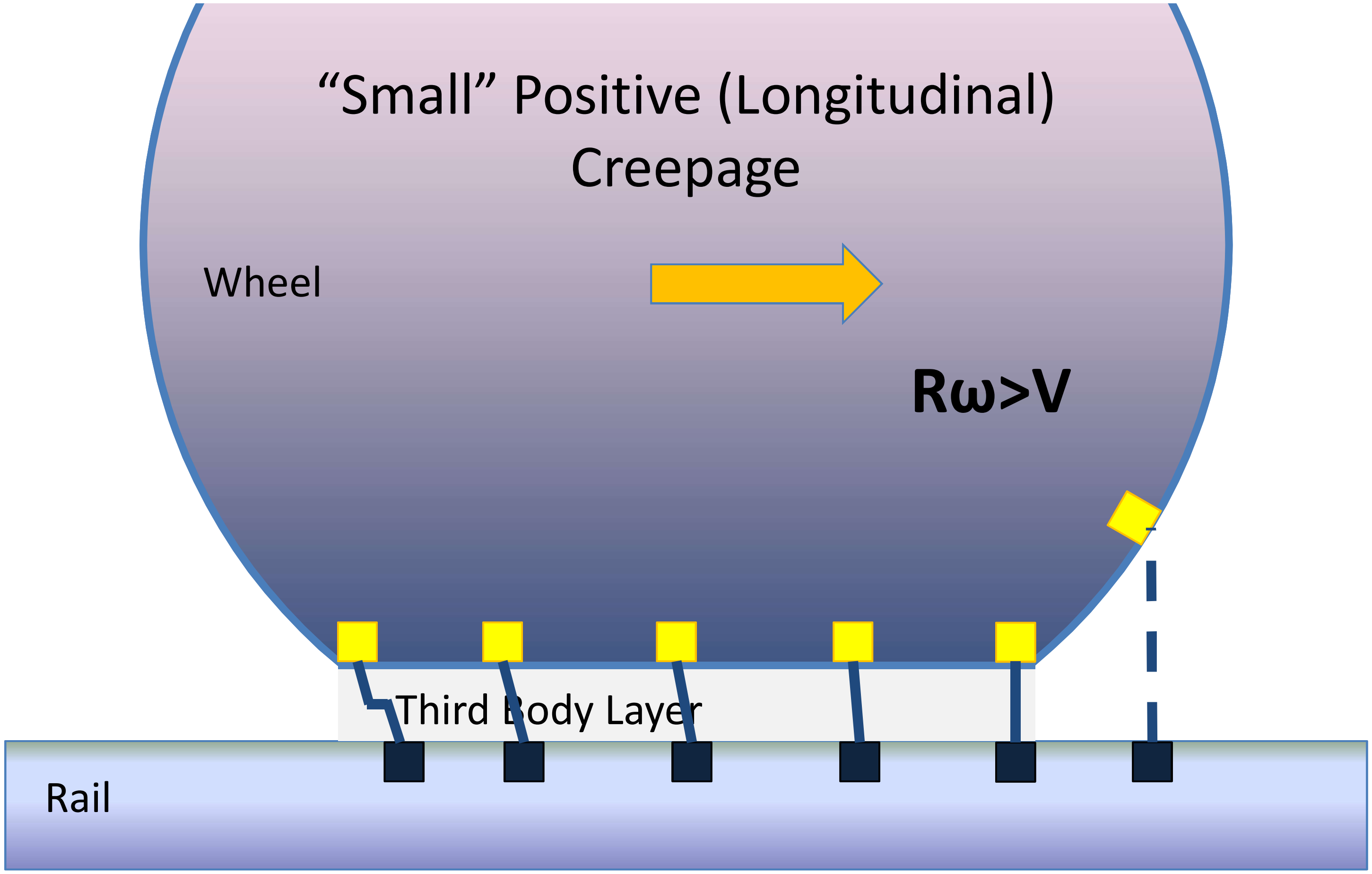
Part 3

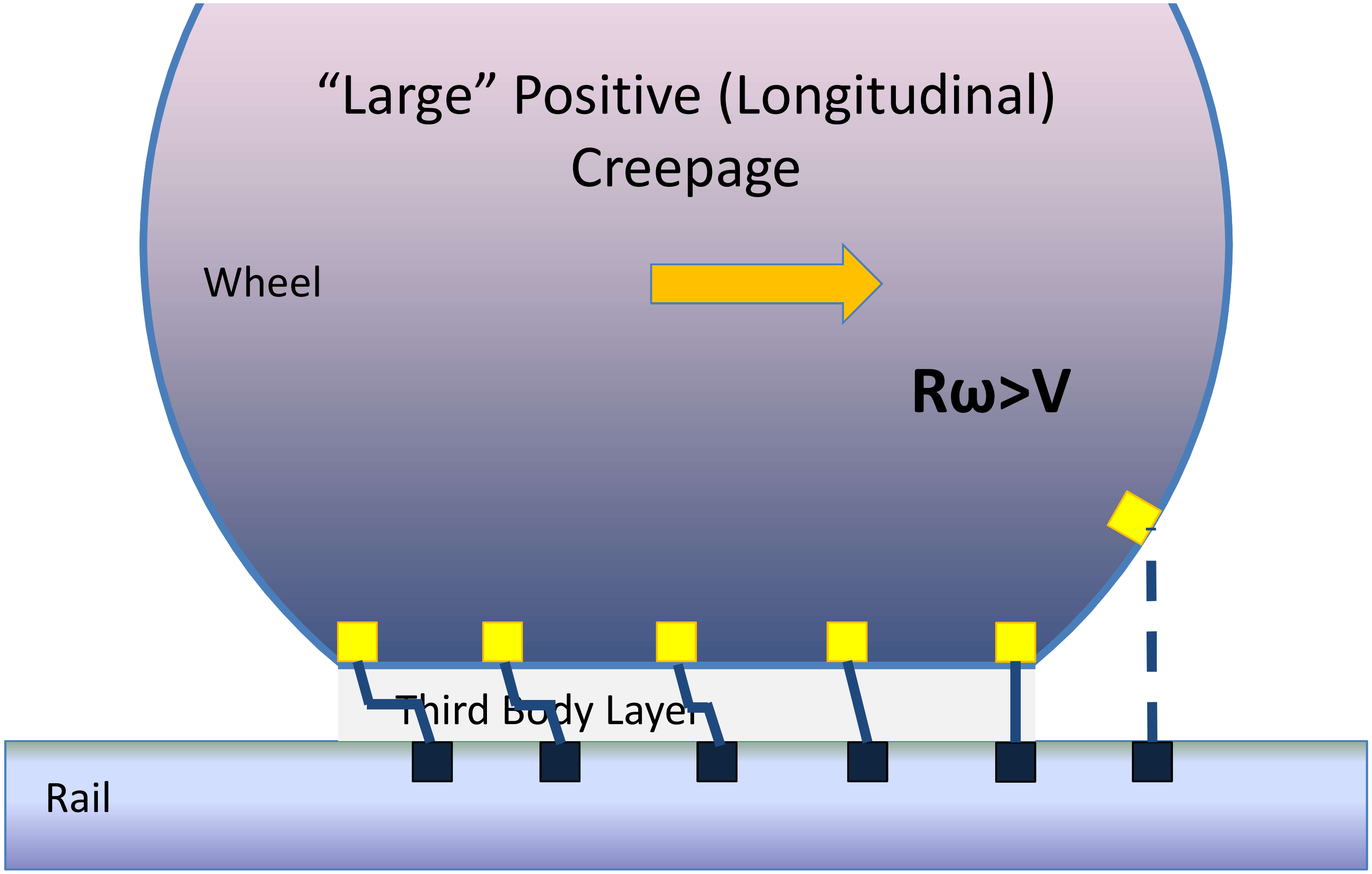
- The Third Body Layer and Traction / Creepage

The Third Body Layer and Traction / Creepage

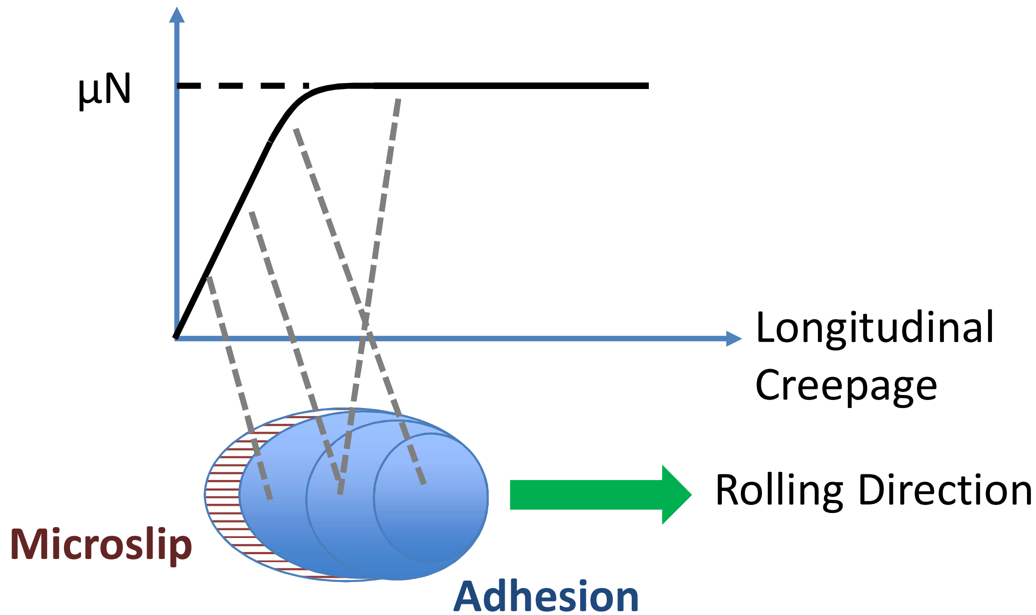
- Third Body Layer is made up of iron oxides, sands, wet paste, leaves etc….



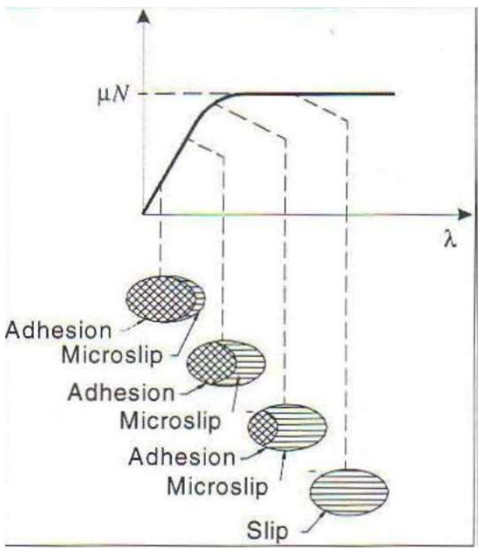

"Small" Positive (Longitudinal) Creepage
Wheel
Rω>V
Third Body Layer
Rail

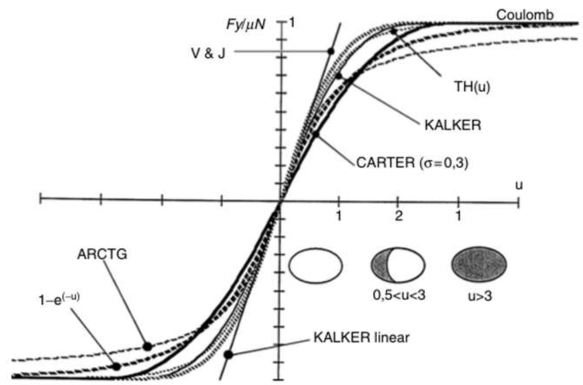

"Large" Positive (Longitudinal) Creepage
Wheel
Rω>V
Third Body Layer
Rail

The Traction-Creepage Curve



Traction/Creepage Curves





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

Summary

- The Wheel / Rail Interface Anatomy and Key Terminology
- The Contact Patch and Contact Pressures
- Creepage and Traction Forces
- The “Third Body Layer” and Traction/Creepage

Questions & Discussion