Vehicle-Track Interaction & Dynamics

WRI2025 30th ANNIVERSARY

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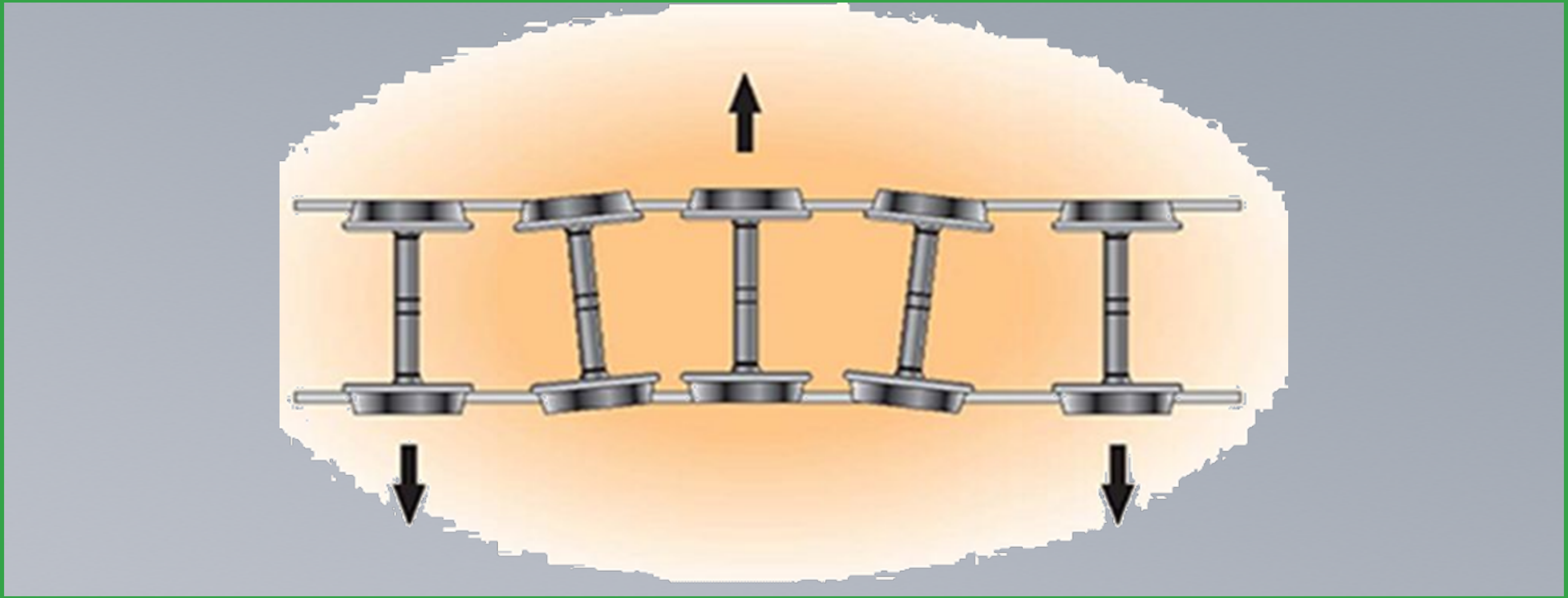

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Agenda

1. Vehicle steering, stability, and curving forces
2. Wheel-rail profile design and performance
3. Vehicle-track interaction derailment mechanisms and risk assessment
   a. Wheel climb
   b. Rail rollover

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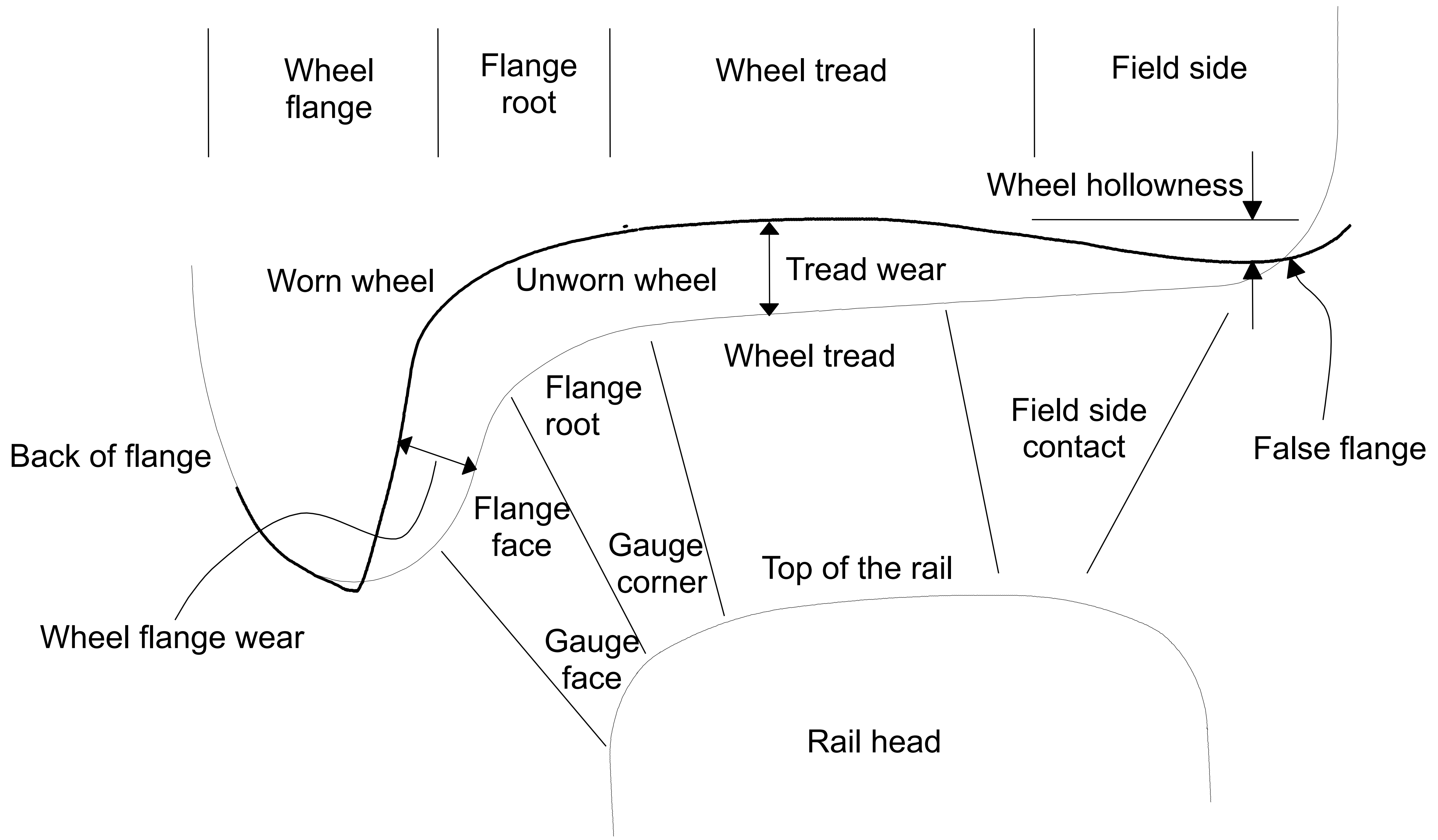
Terminology



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WHEELSET & VEHICLE STEERING

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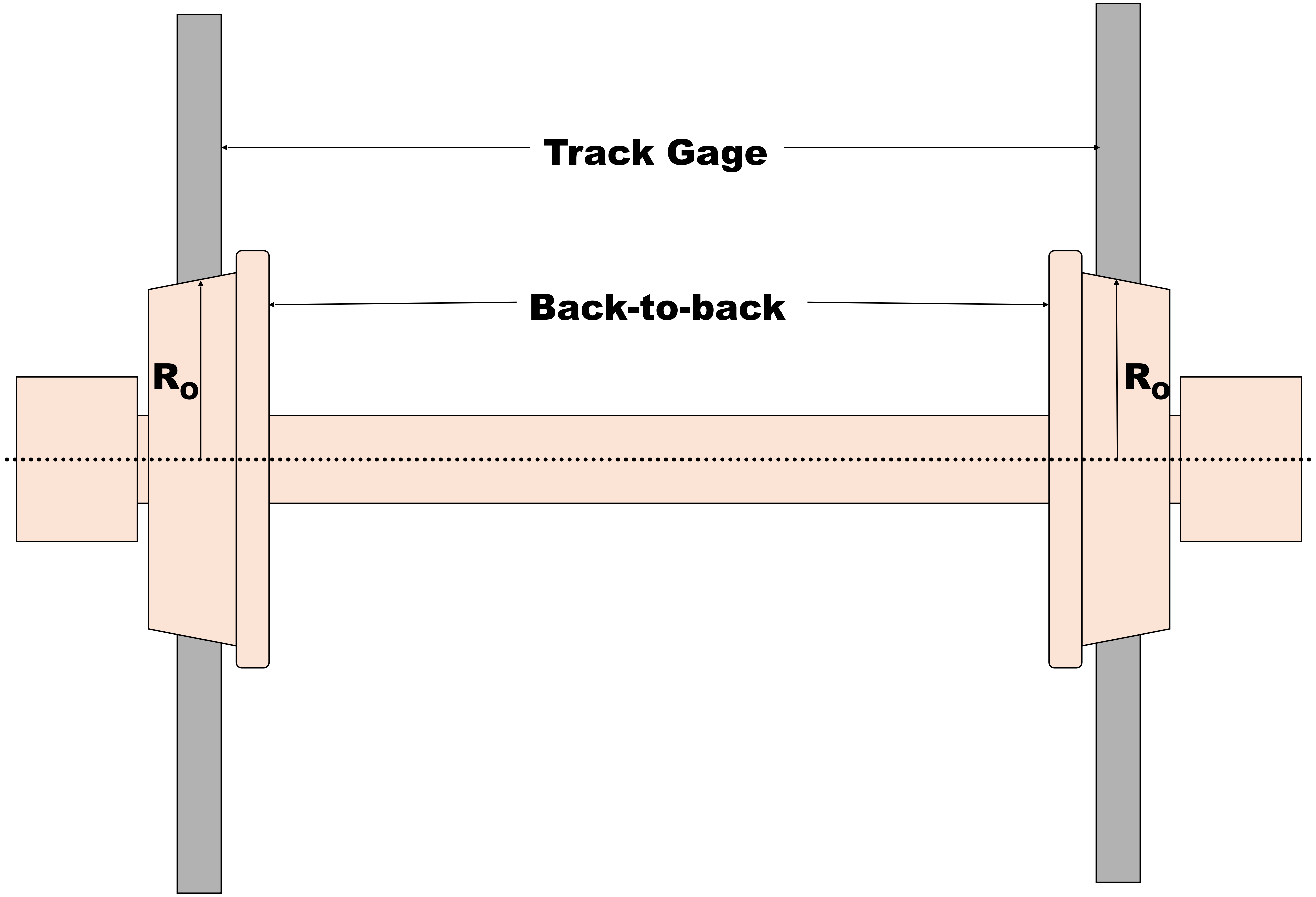
The Free Rolling Wheelset



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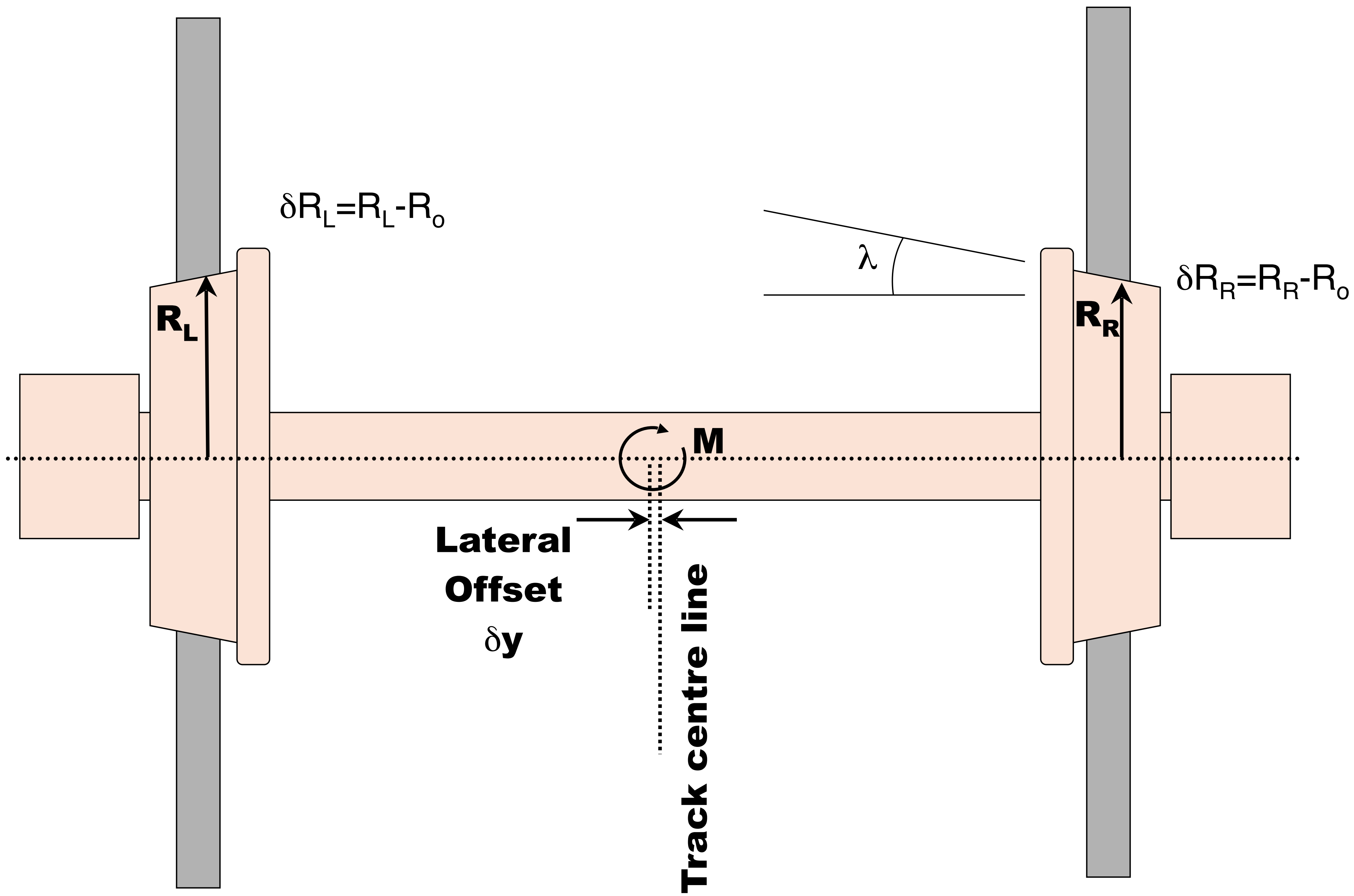
The Free Rolling Wheelset



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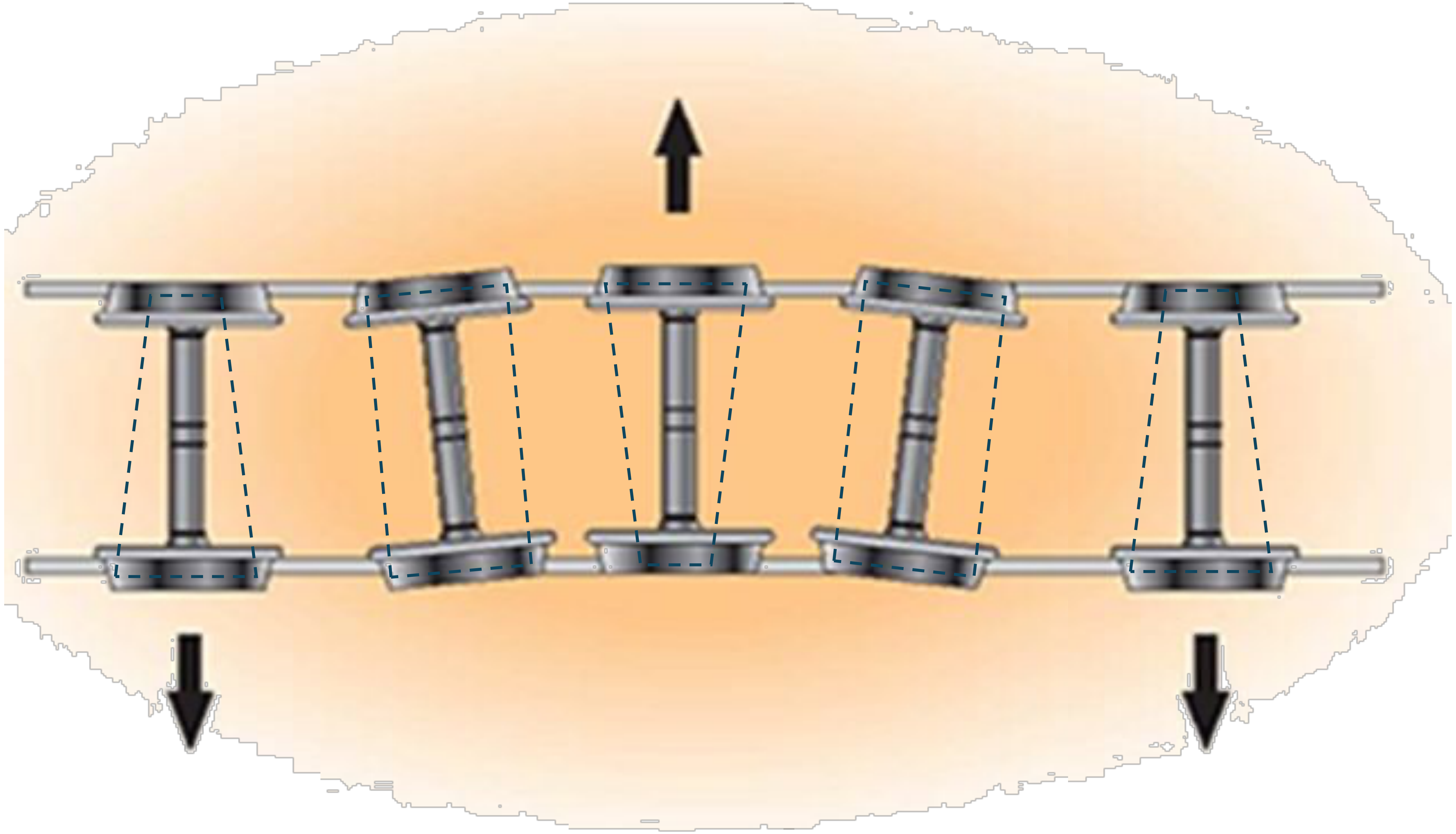
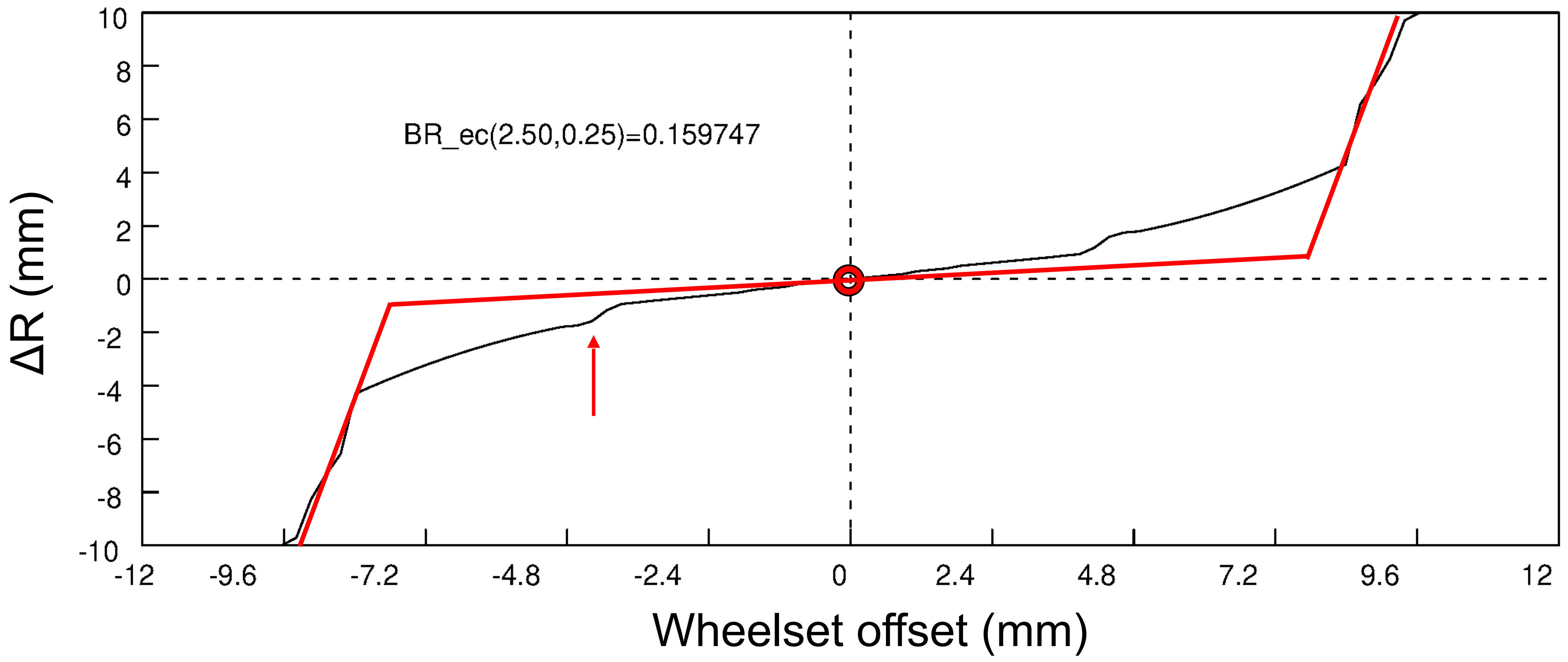
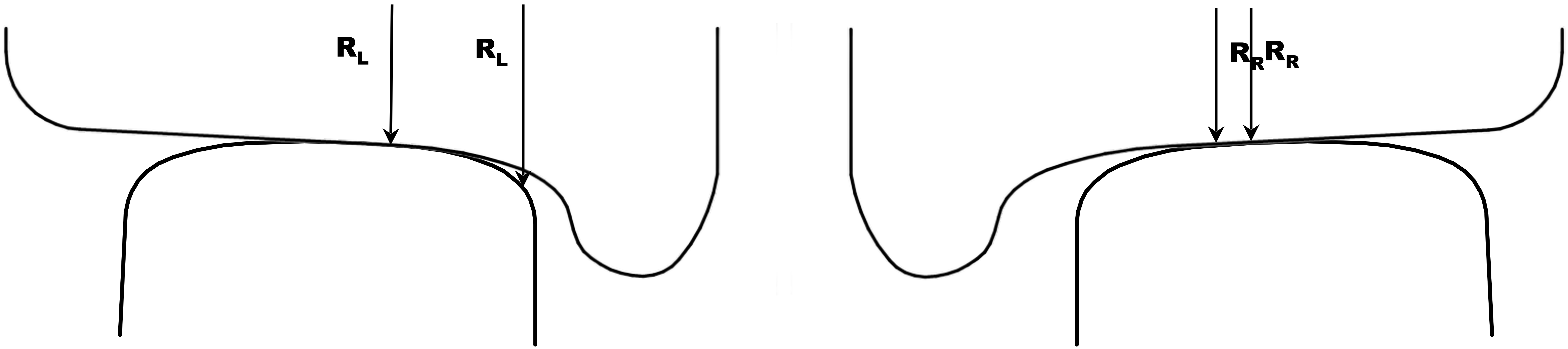
The Free Wheelset - Hunting



Conicity


BR_ec(2.50,0.25)=0.159747
ΔR (mm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-9.6
-7.2
-4.8
-2.4
0
2.4
4.8
7.2
9.6
12
Wheelset offset (mm)


R_L
R_L
R_R R_R

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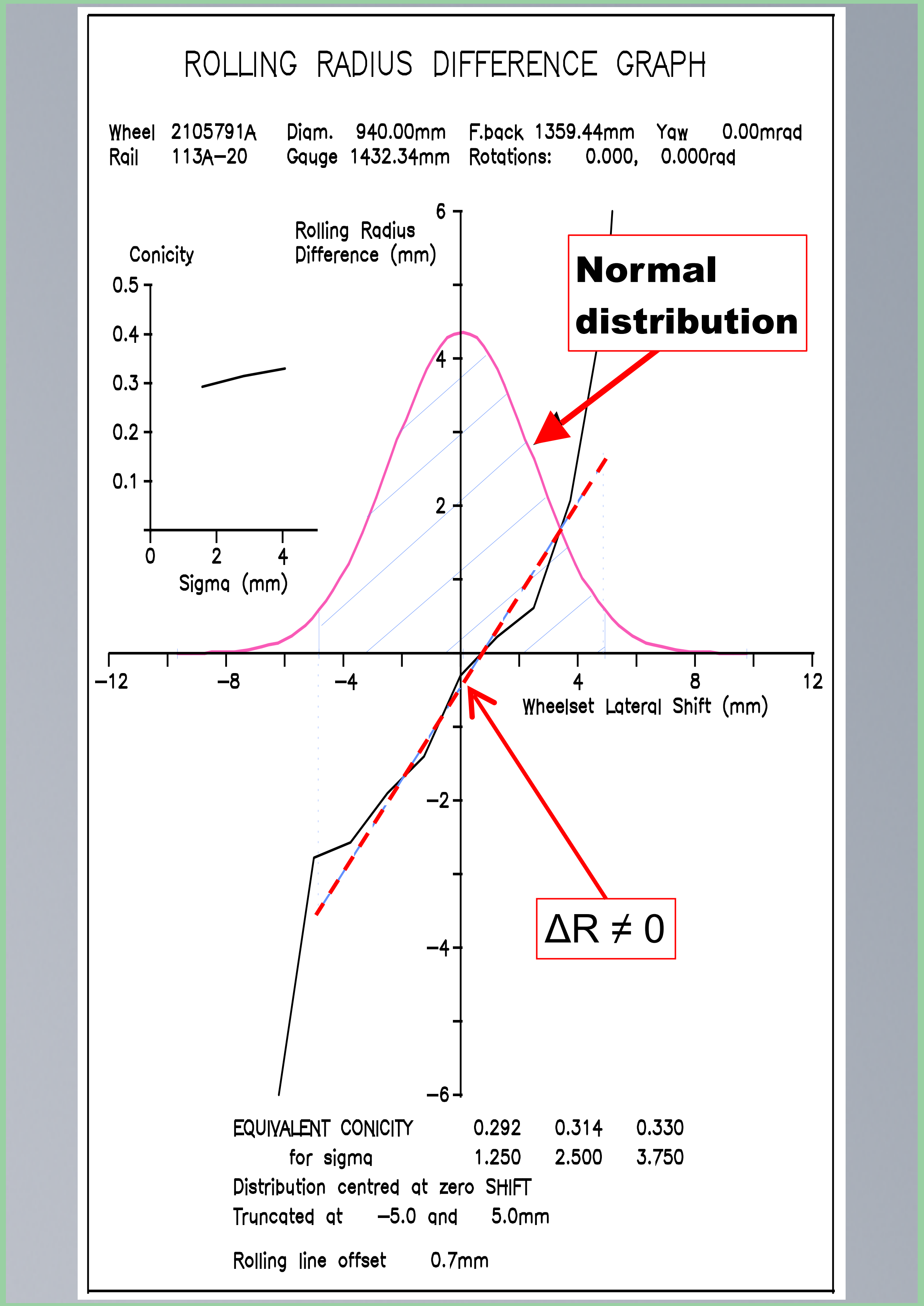
Equivalent Conicity from the ΔR Plot

- British Rail derivation

$$\lambda_e = \frac{1}{2}\int \frac{N(y)\left(r_R - r_L\right)}{y} dy$$



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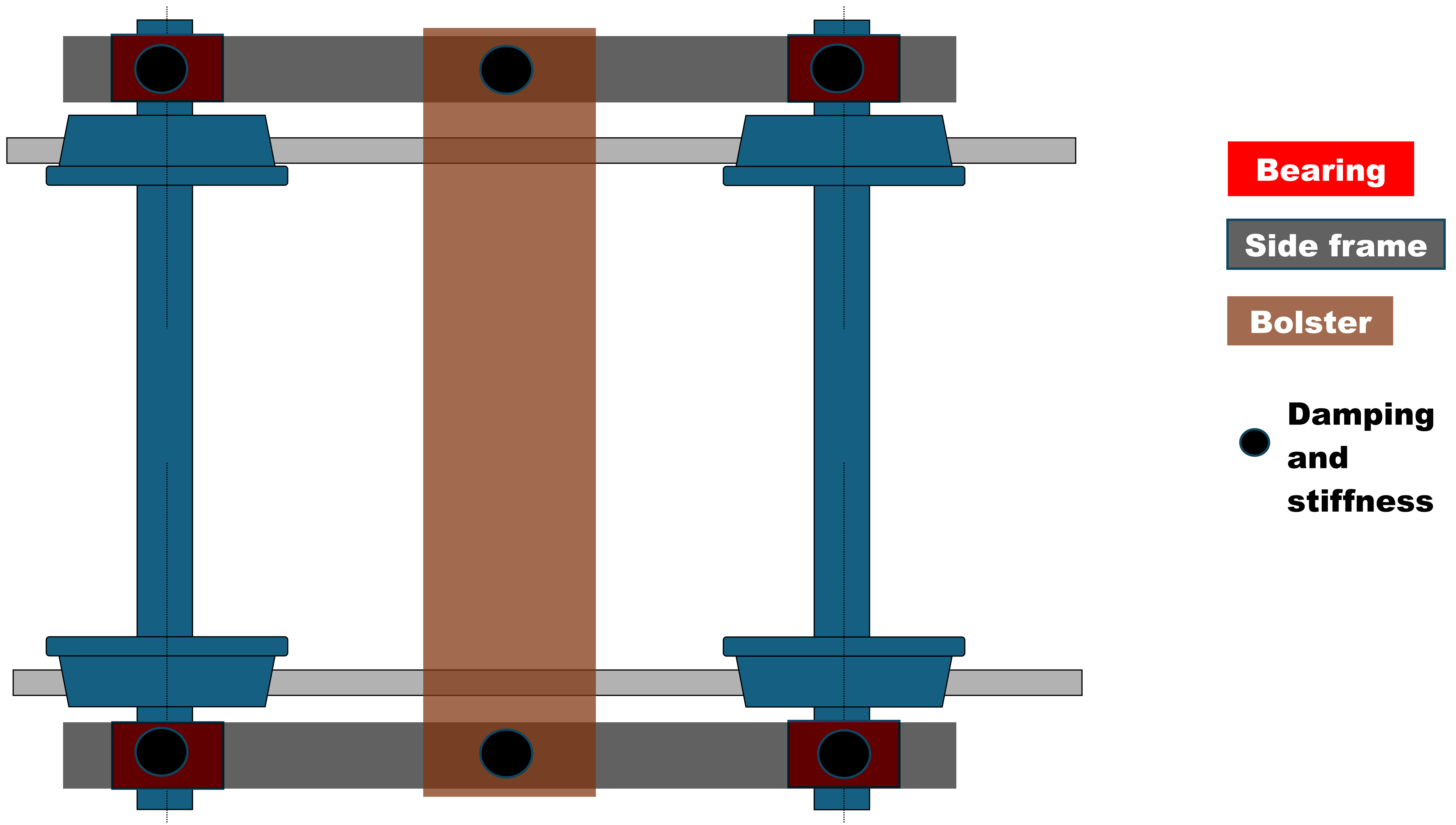
A Truck Can Provide Stability



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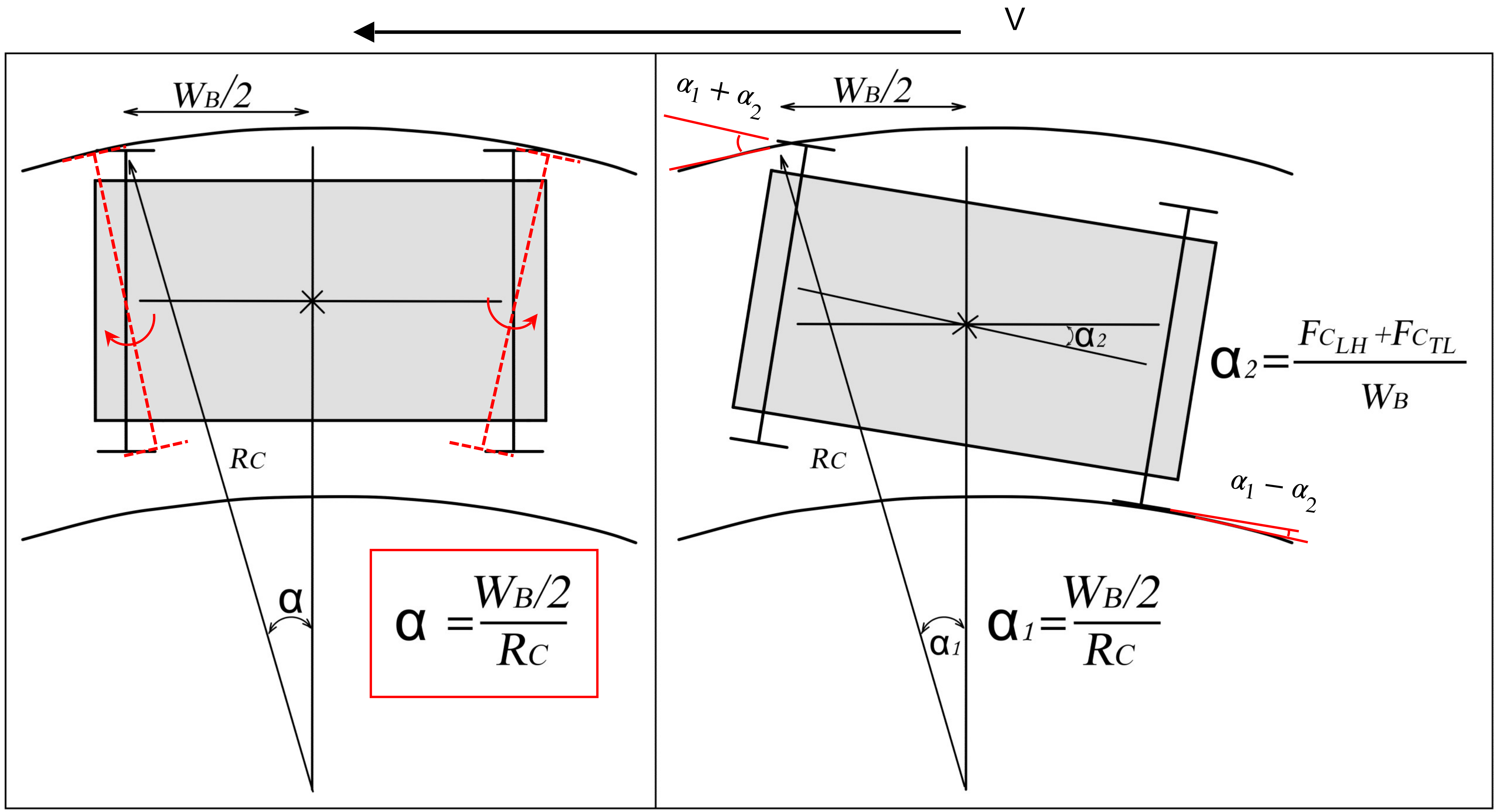
The Yaw Angle



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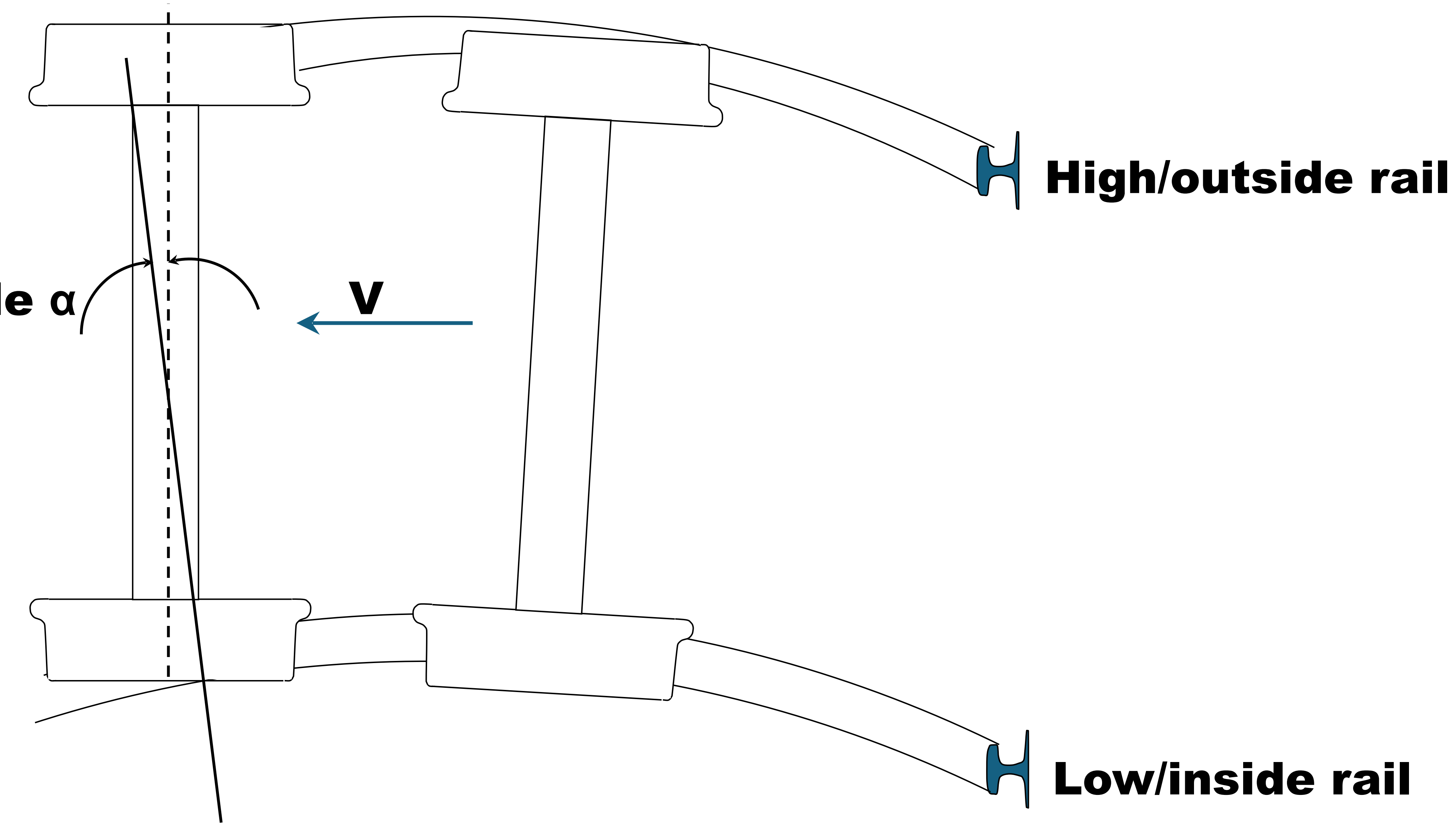
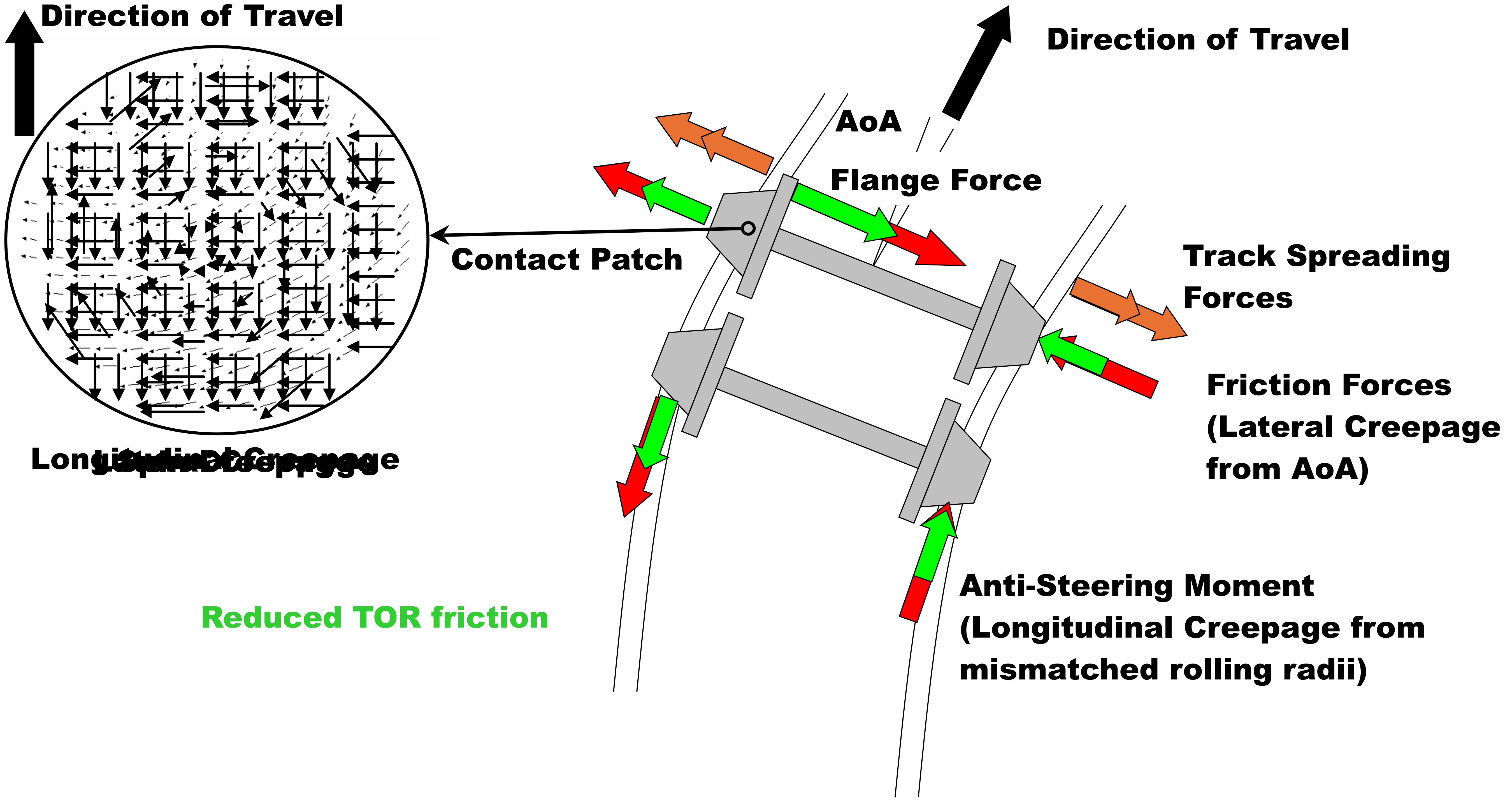
The Wheelset in a Curve

(Leading) wheelset shifts to outside of curve



Lateral Forces (Creep) in Curves



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WHEEL-RAIL PROFILE DESIGN AND PERFORMANCE

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Design of Engineered Rail Profiles

Rail design considers:

- Track curvature
- Worn wheel shapes
- Types of vehicle and speed (hunting)
- Dynamic rail rotation
- Rail hardness
- Grinding interval (profile deterioration between intervals)
- Static gage

Goals

- Control contact stress
- Inhibit hunting
- Minimize wear

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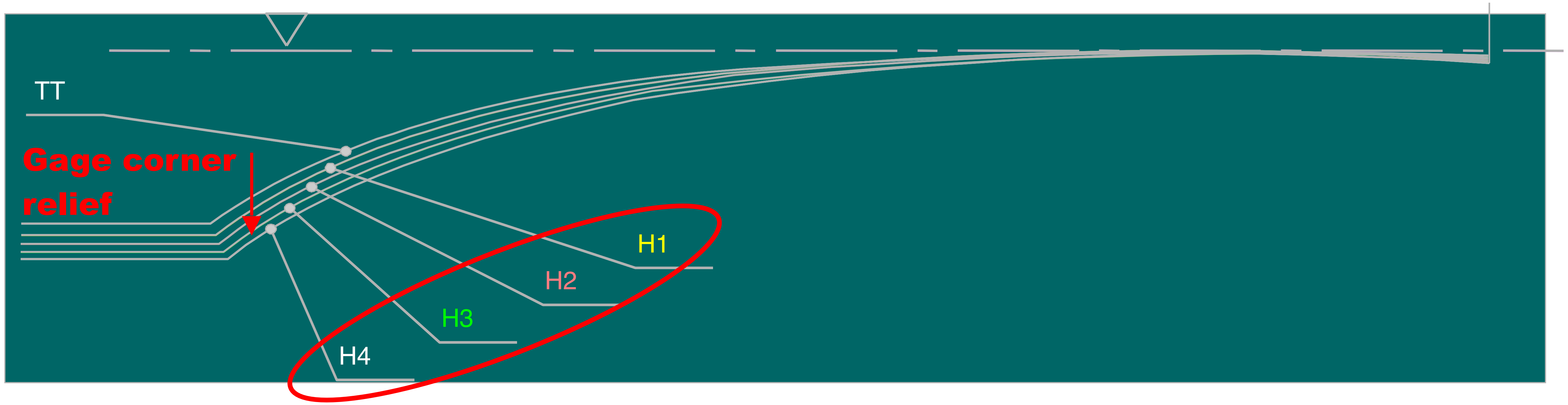
The NRC Family of Heavy Haul Rail Templates from the 1990s



Rail Profile Design Criteria

Goals are to reduce/control:

- Gauge face and TOR wear
- Rolling contact fatigue (RCF)
- Dynamic instability (hunting)
- Corrugation formation
- Wheel hollowing
- Easily or practically implemented by grinding

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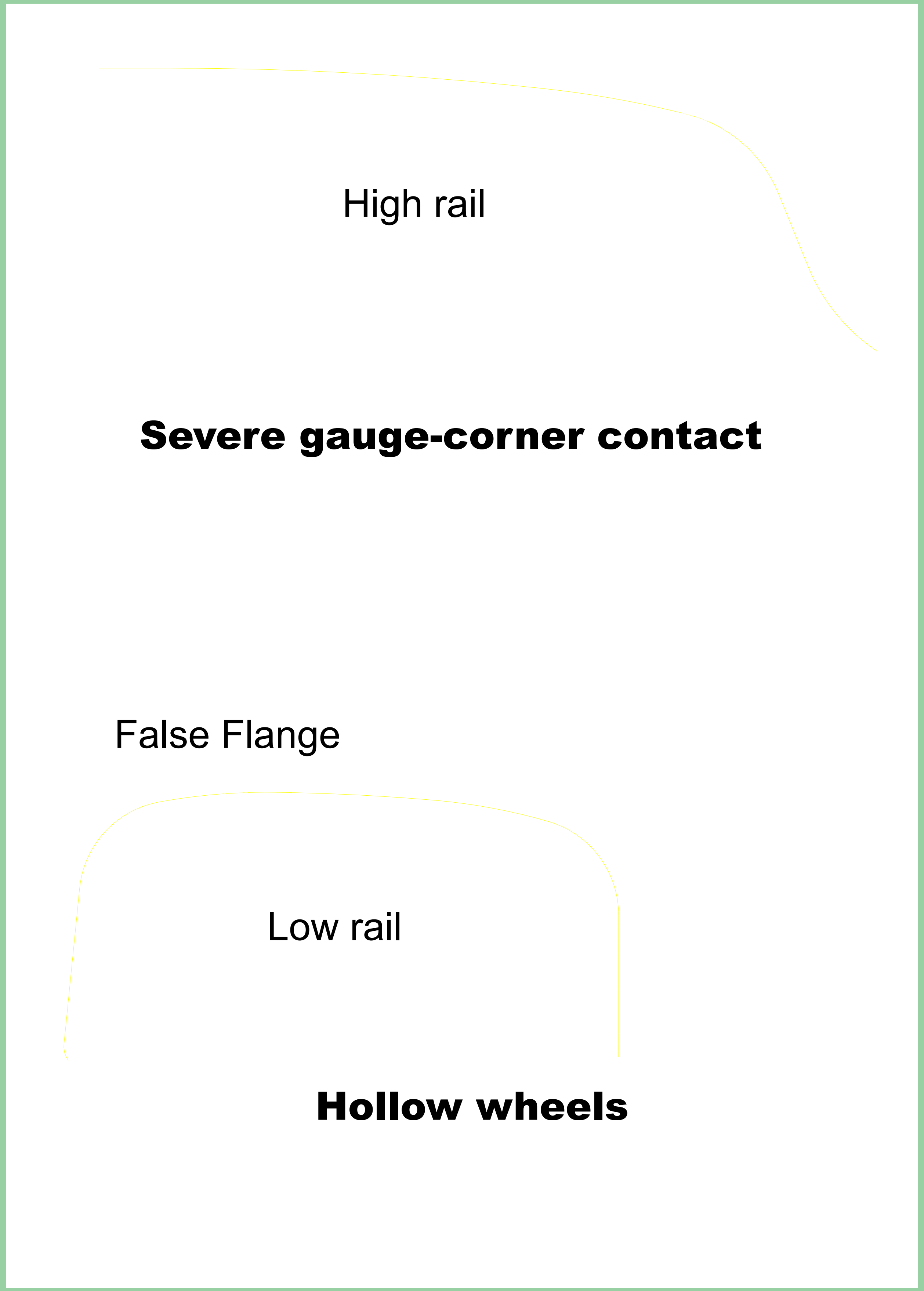
Wheel-Rail Contact Stresses

Stress and damage depend on:

- Wheel radius
- Wheel load
- Friction coefficient
- Wheel/rail profiles (contact geometry)



Wheel-Rail Conformality

- Closely conformal
  0.1 mm (0.004”) or less

- Conformal
  0.1 mm to 0.4mm
  (0.004” to 0.016”)

- Non-conformal
  0.4 mm (0.016”) or larger

Some Typical Issues Associated with Wheel-Rail Conformality

Closely conformal profiles

- Dynamic instability (hunting)
- Corrugation formation by spin creepage

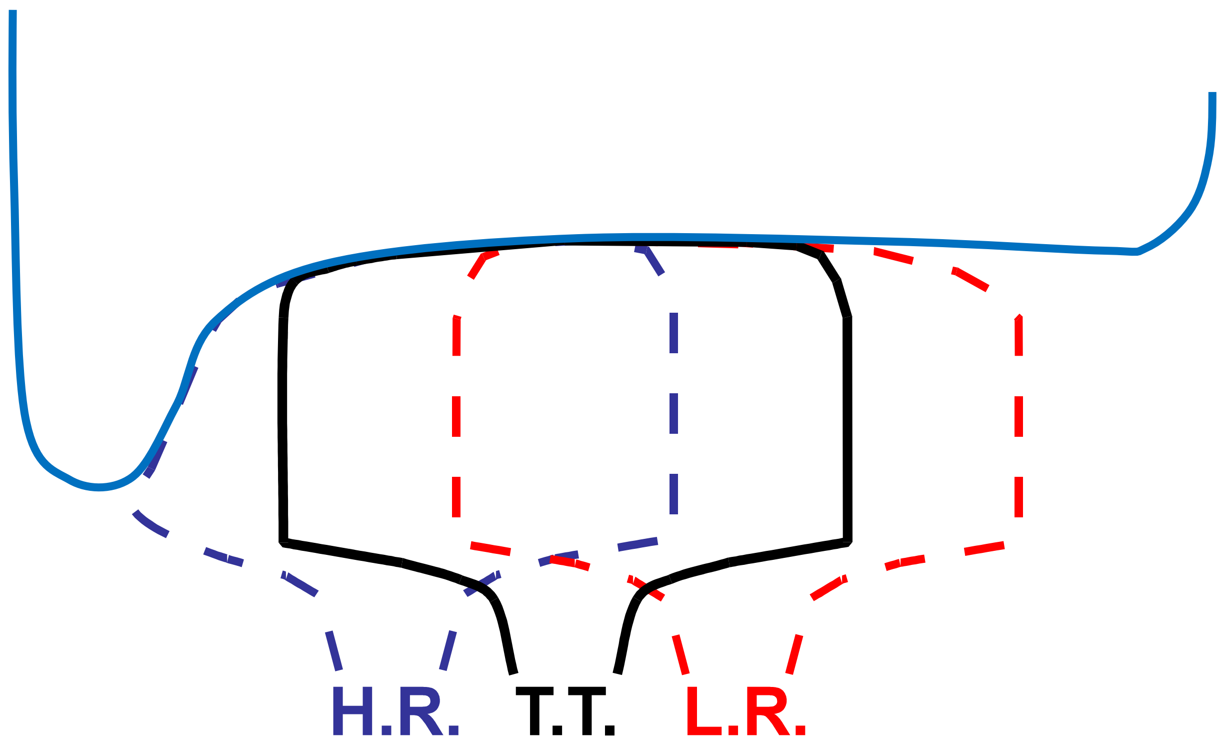
Conformal profiles

- Low stress state W/R interface
- Heavy haul = 2PT conformal (balance contact stress steering and wear)

Non-conformal profiles

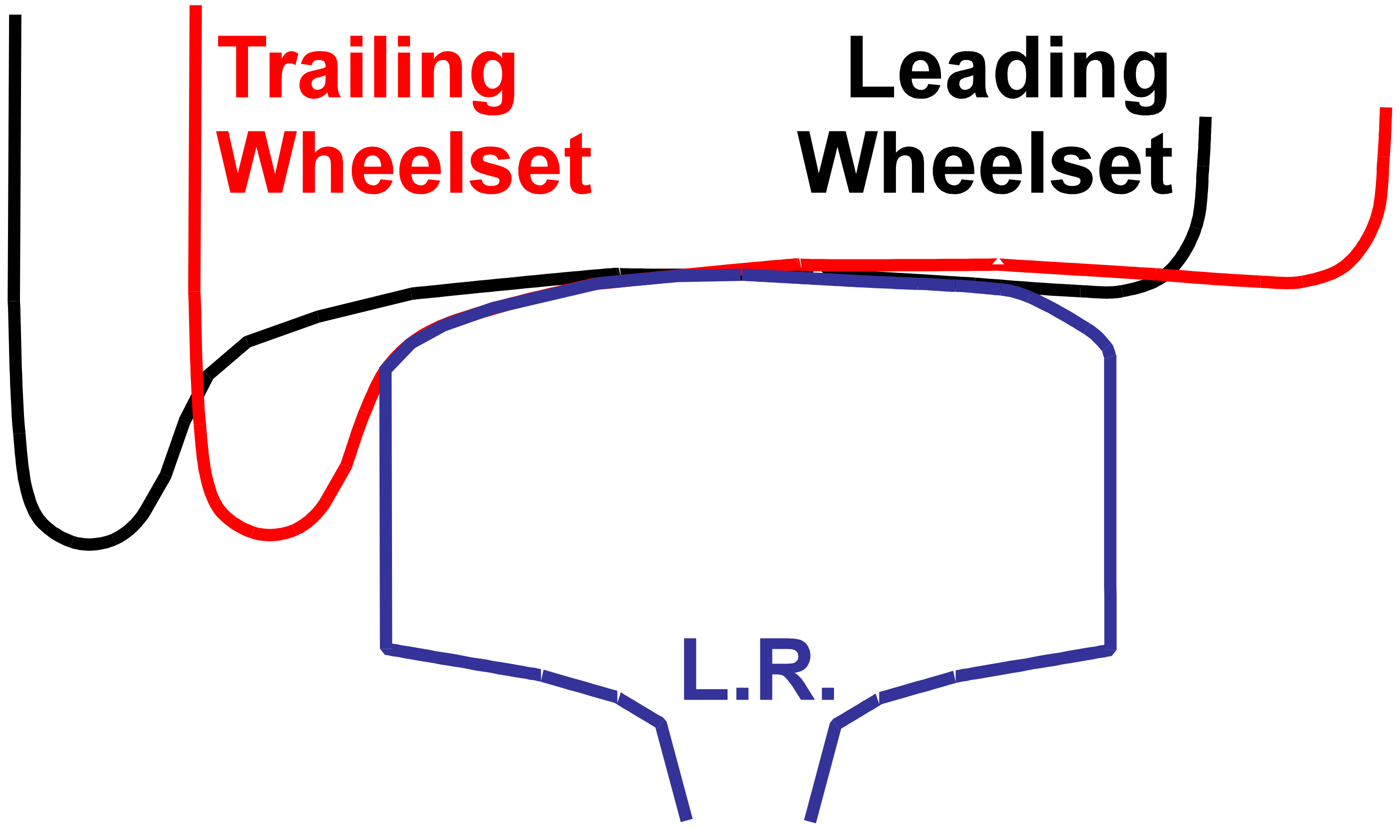
- High stress state W/R interface
- 1PT: cracks (RCF) at GC of HR and FS of LR
- 2PT: high gauge face wear in curves

Worn Wheel and Rail Profiles are Envelopes of Each Other



Worn wheel is an envelope of all rail profiles it encounters on a particular route

Worn rail is an envelope of all wheel profiles that pass over it



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Pummelling Analysis

Simulation

- Measured wheel profiles
- Vehicle characteristics (stiffness, wheelbase etc.)
- Rail hardness (for damage evaluation)
- Rail curvature, super-elevation, dynamic rail rotation etc.

Evaluate distributions of

- Contact stress
- Steering moments
- Effective conicity

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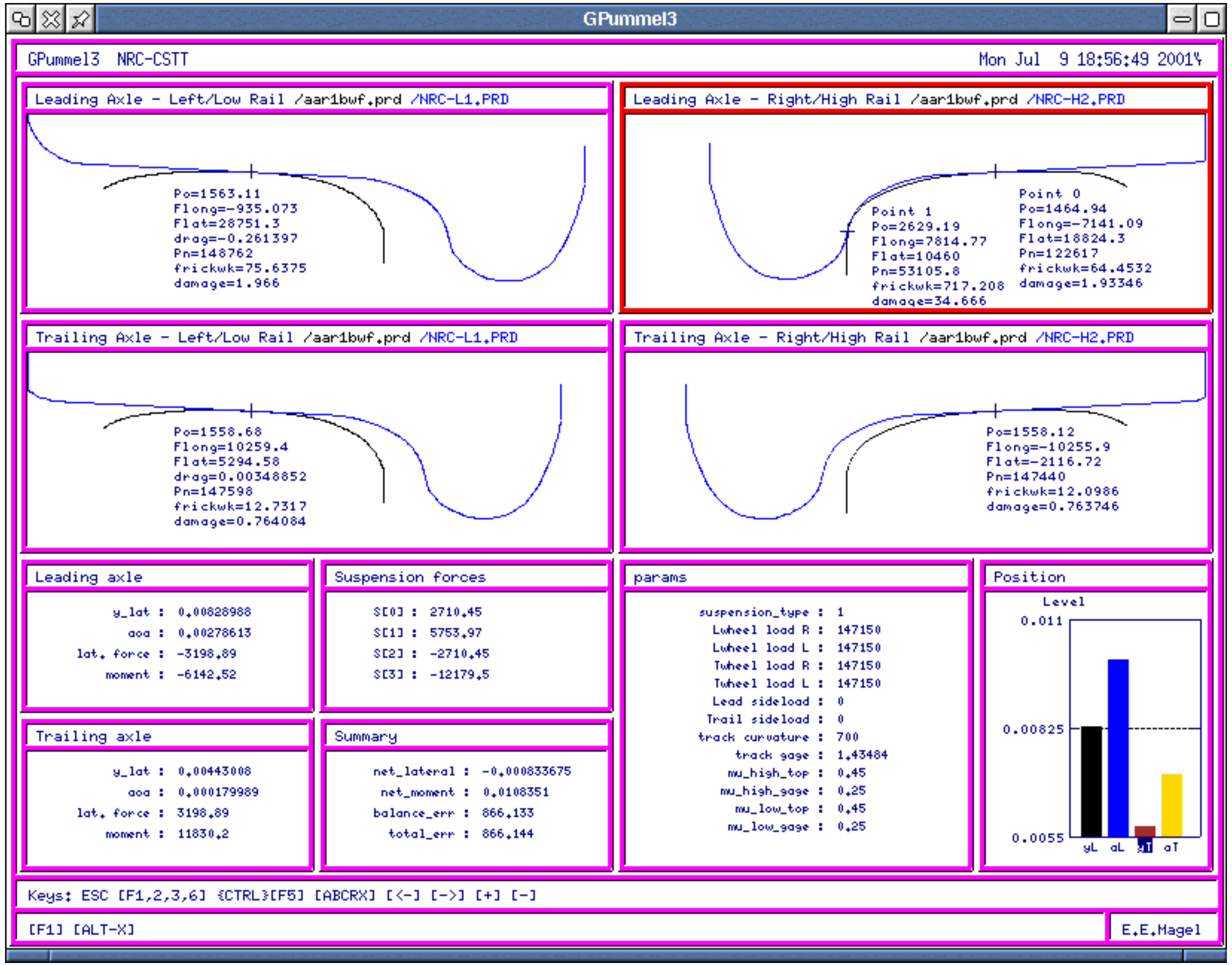
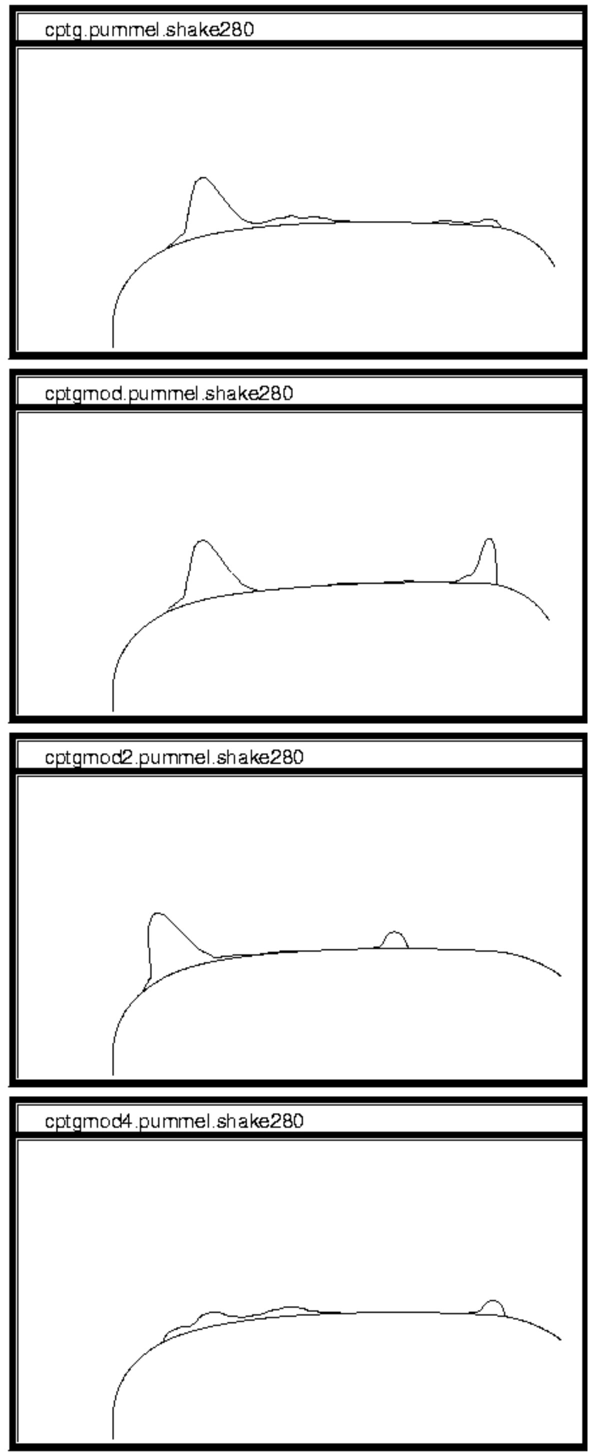
Pummelling: Design/Analysis Tool





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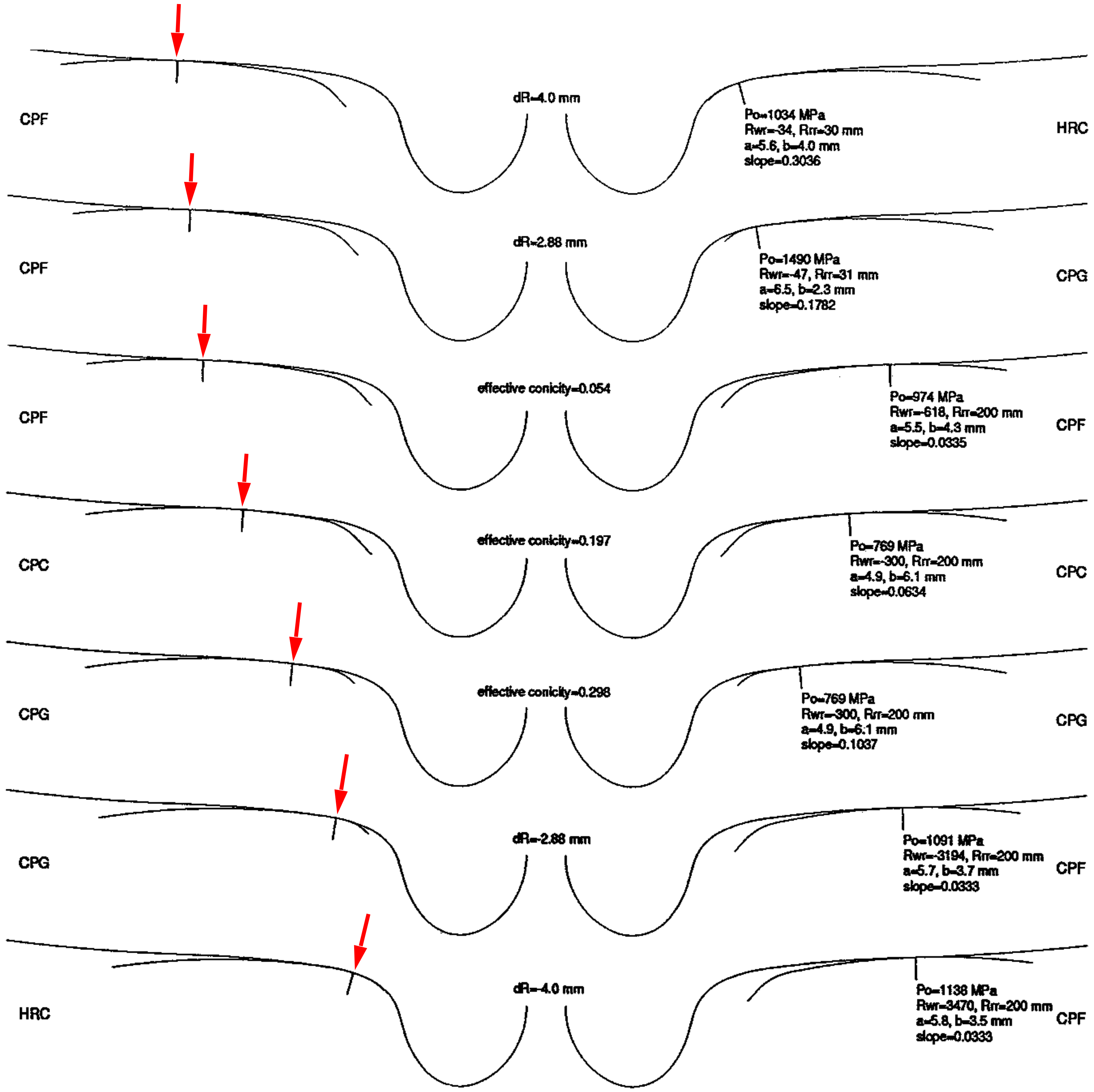
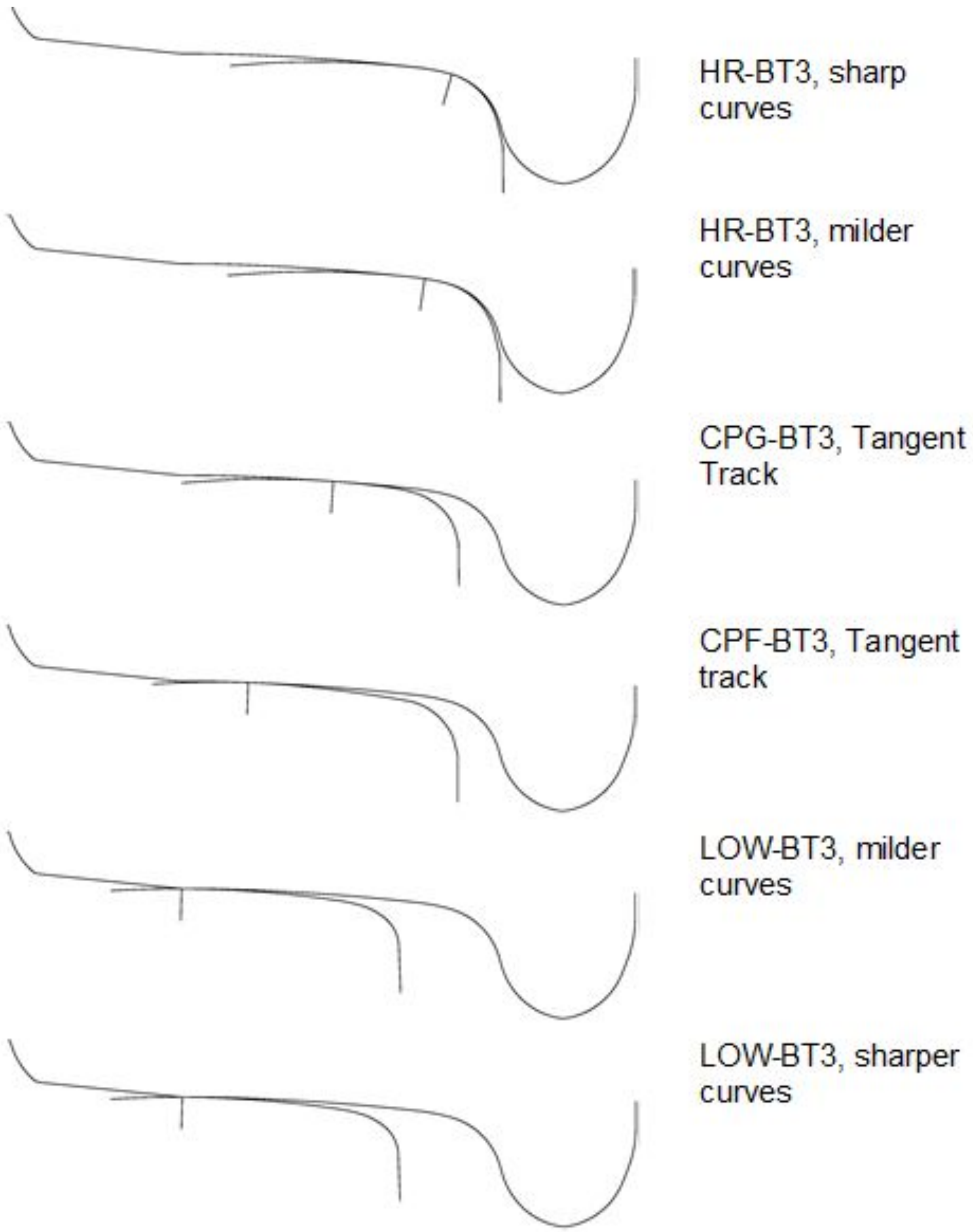
Families of Rail Profiles

Los Angeles



San Francisco



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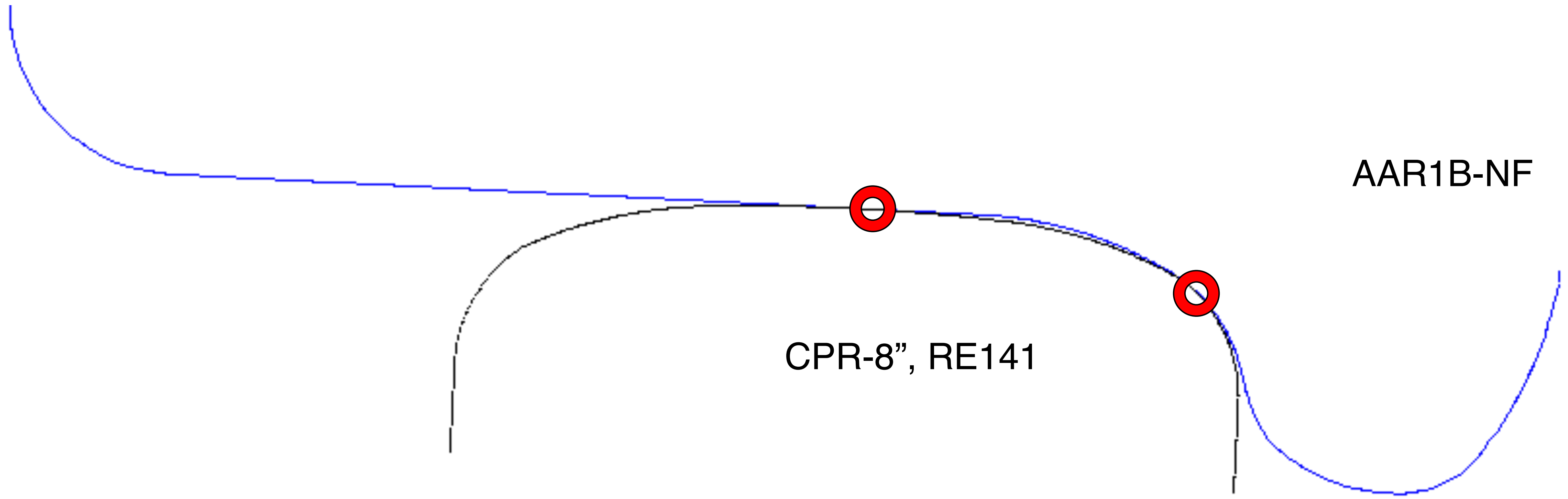
VEHICLE-TRACK DERAILMENT MECHANISMS AND RISK ASSESSMENT

WHEEL CLIMB

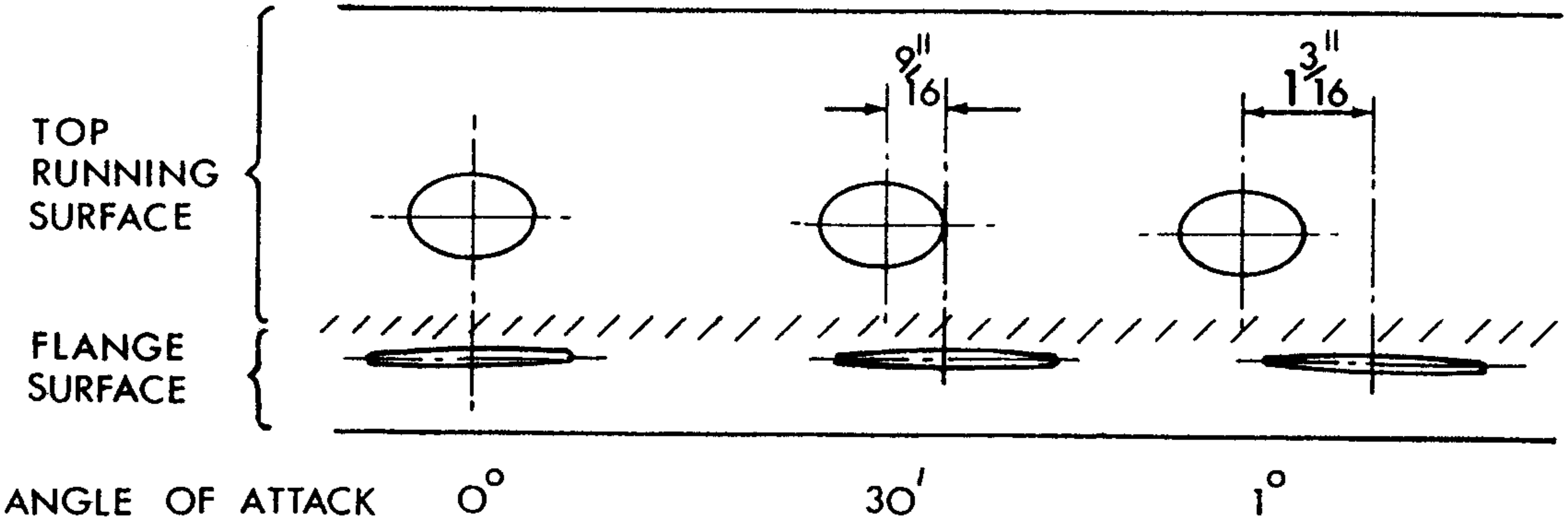
Wheel-Rail Contact

W/R contact often takes place at two points simultaneously (some new wheels especially)



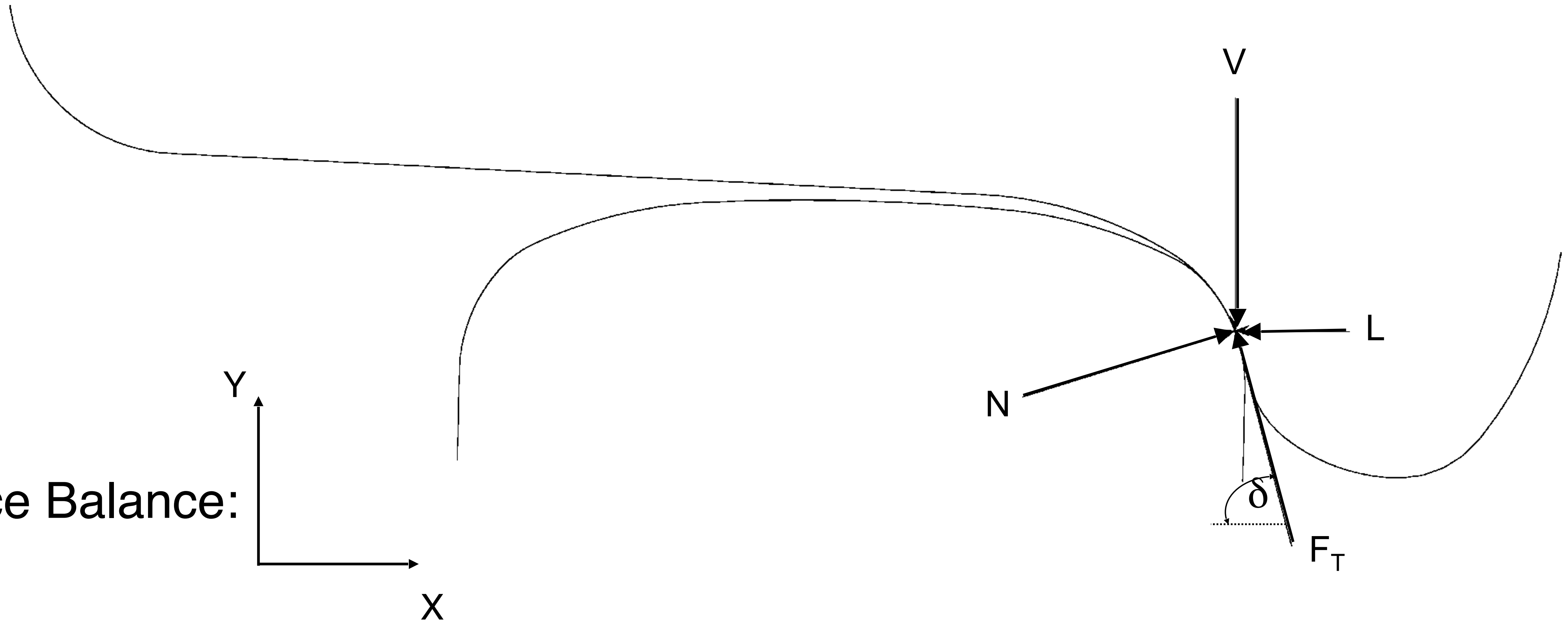
Wheel-Rail Contact (continued)

Plan view of contact ellipses on high rail for different angles of attack



Deriving Nadal

Force Balance:



$$\sum Fx = 0 \Rightarrow N\sin(\delta) - F_T\cos(\delta) - L = 0$$
$$\sum Fy = 0 \Rightarrow F_T\sin(\delta) + N\cos(\delta) - V = 0$$

$$\frac{L}{V} = \frac{\tan\delta - F_T / N}{1 + F_T \tan\delta / N}$$

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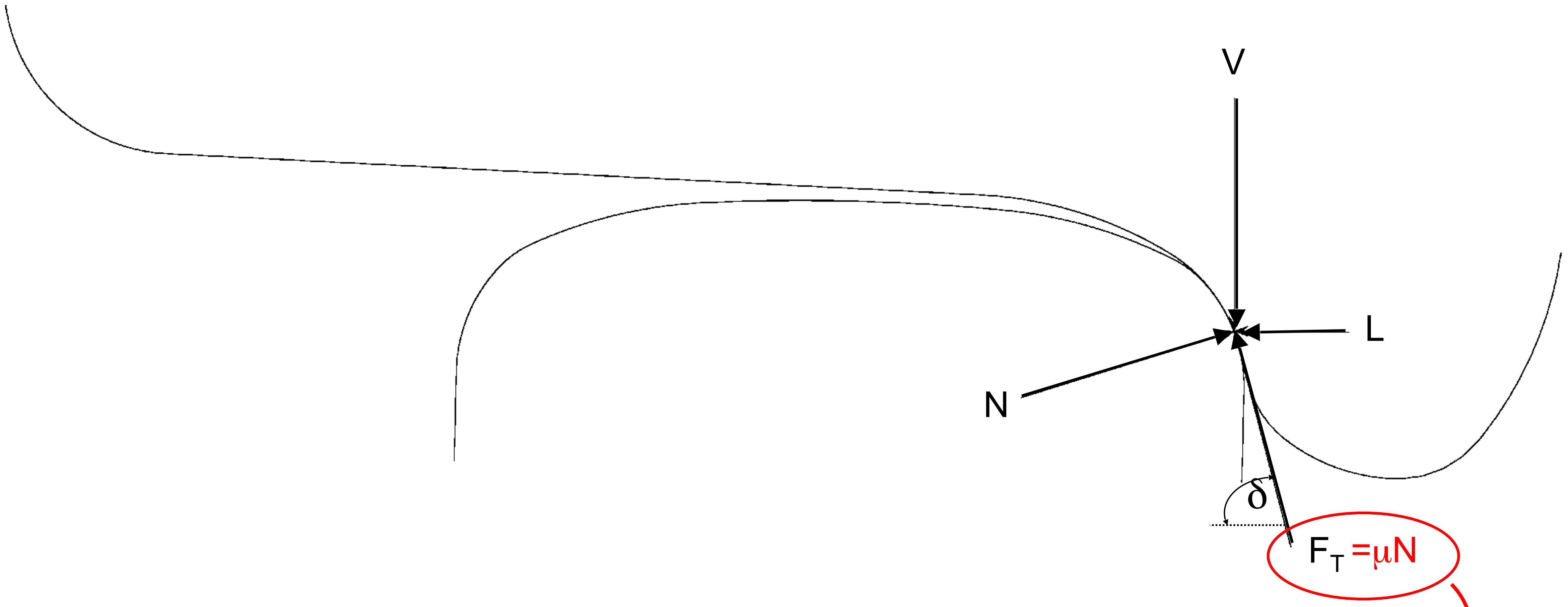
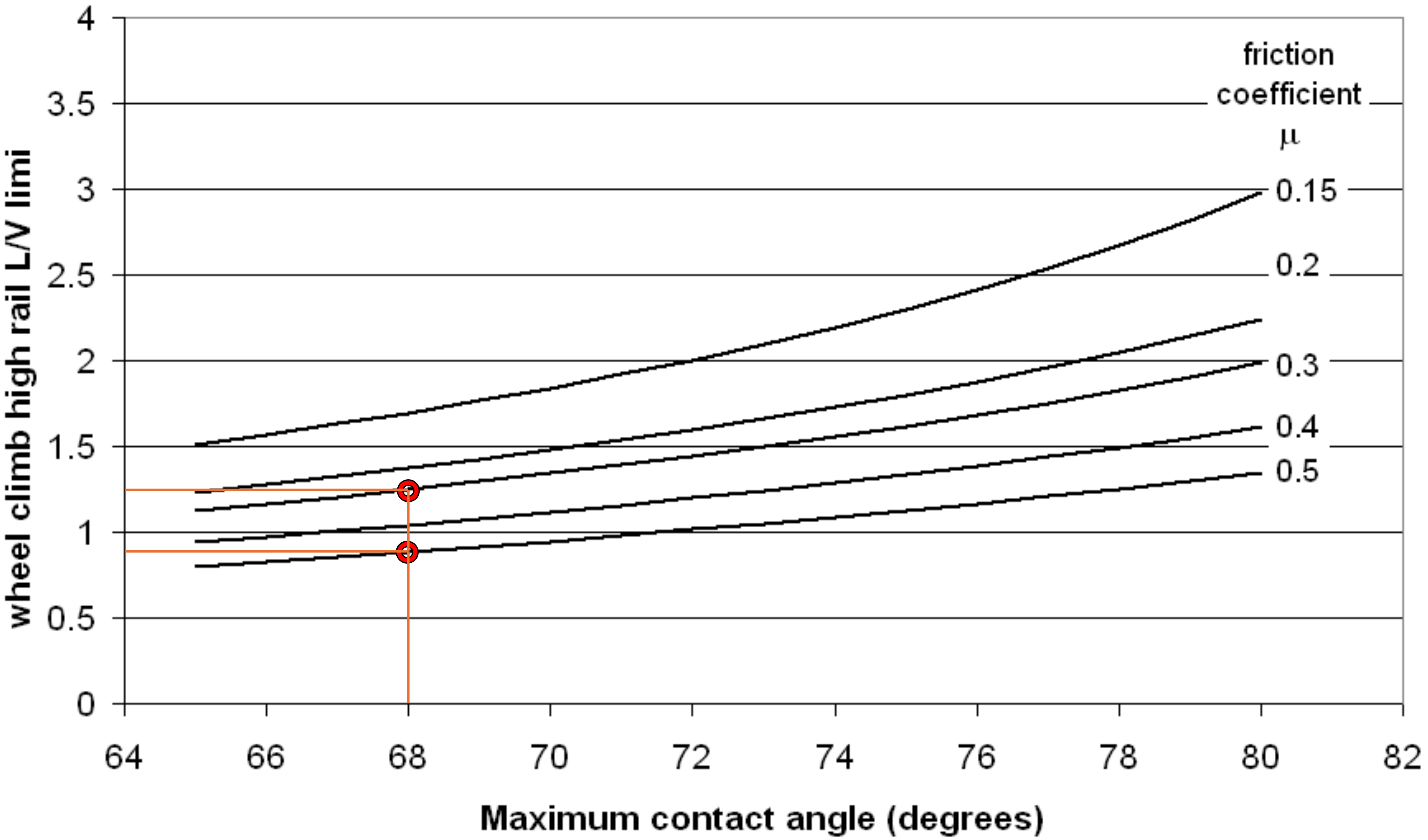
Nadal’s Relationship



$$\frac{L}{V} = \frac{\tan\delta - \mu}{1 + \mu \tan\delta}$$

$$\boxed{\frac{L}{V} = \frac{\tan\delta - F_T / N}{1 + F_T \tan\delta / N}}$$

Nadal Index (1908)



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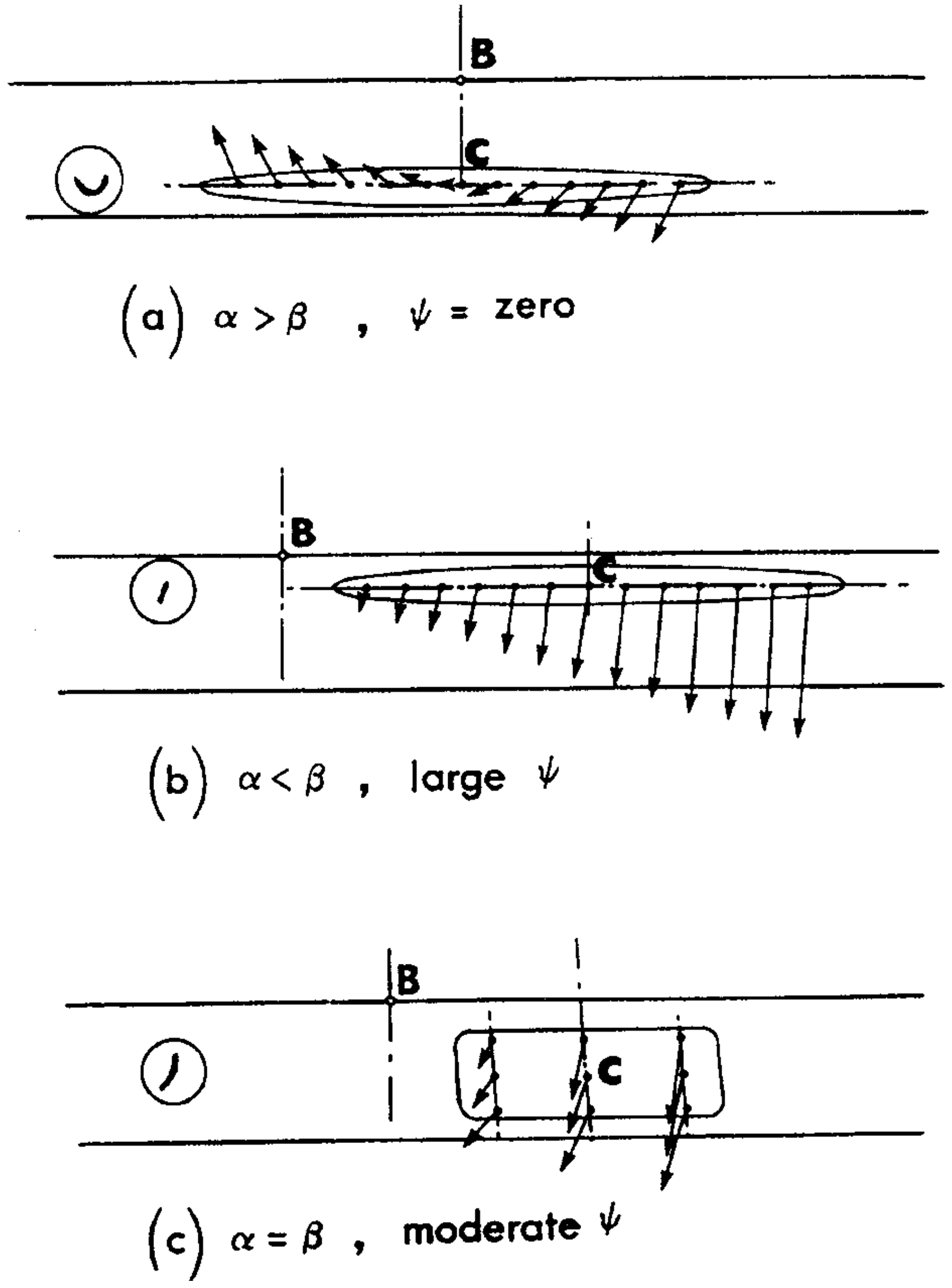
Slip Vectors at the Gage Face Contact

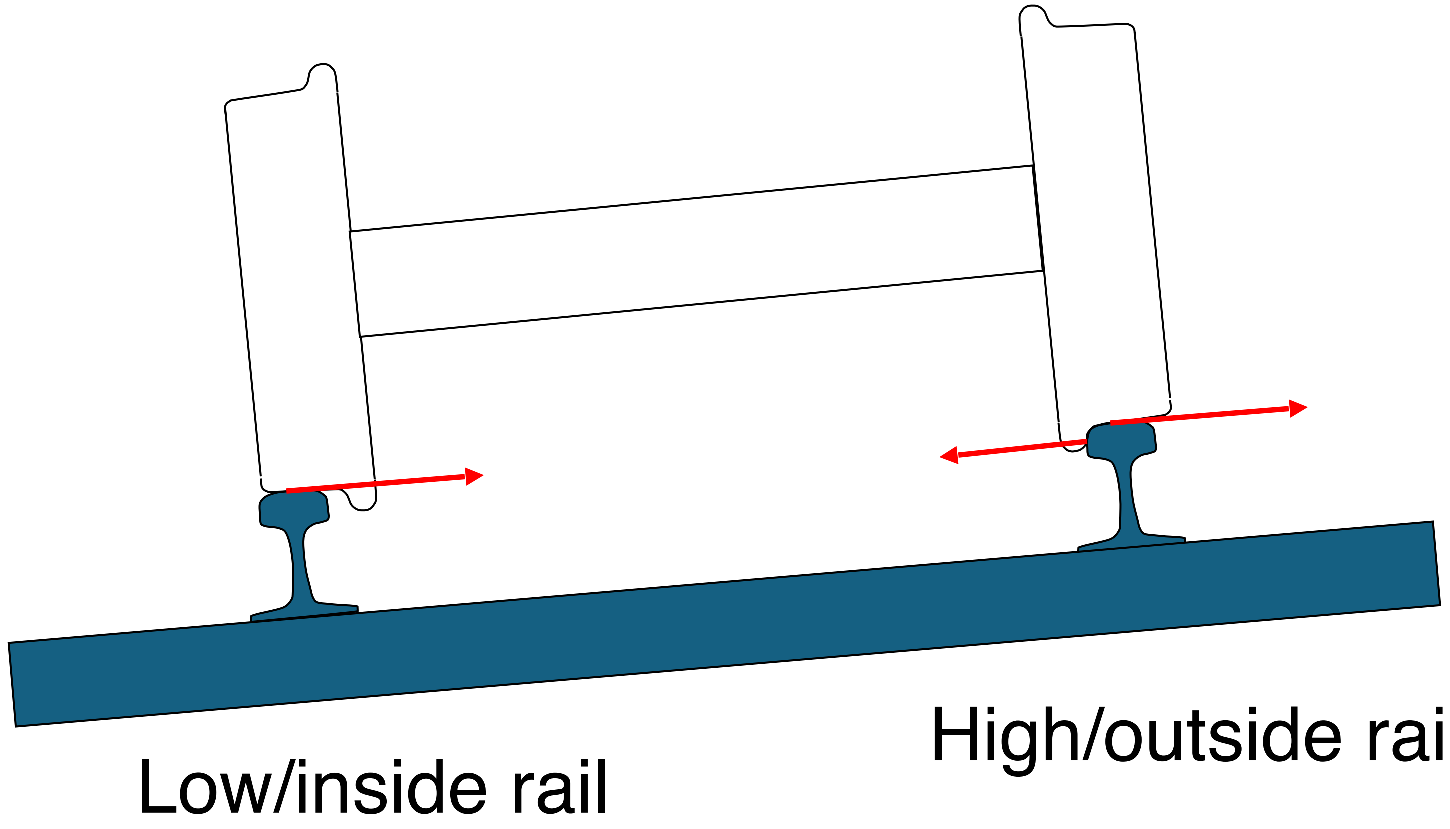


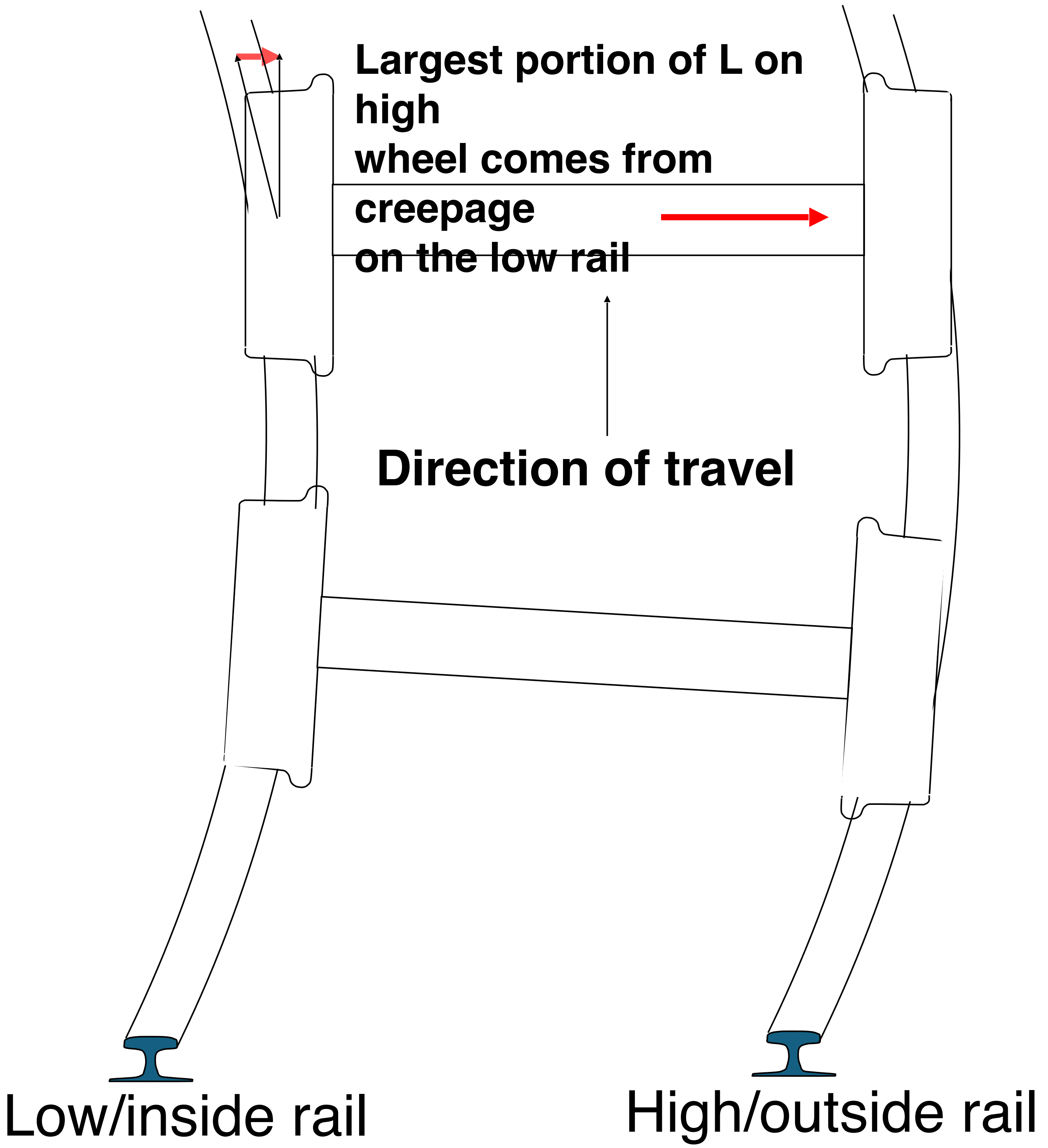
α = angle of attack

δ = wheel flange angle

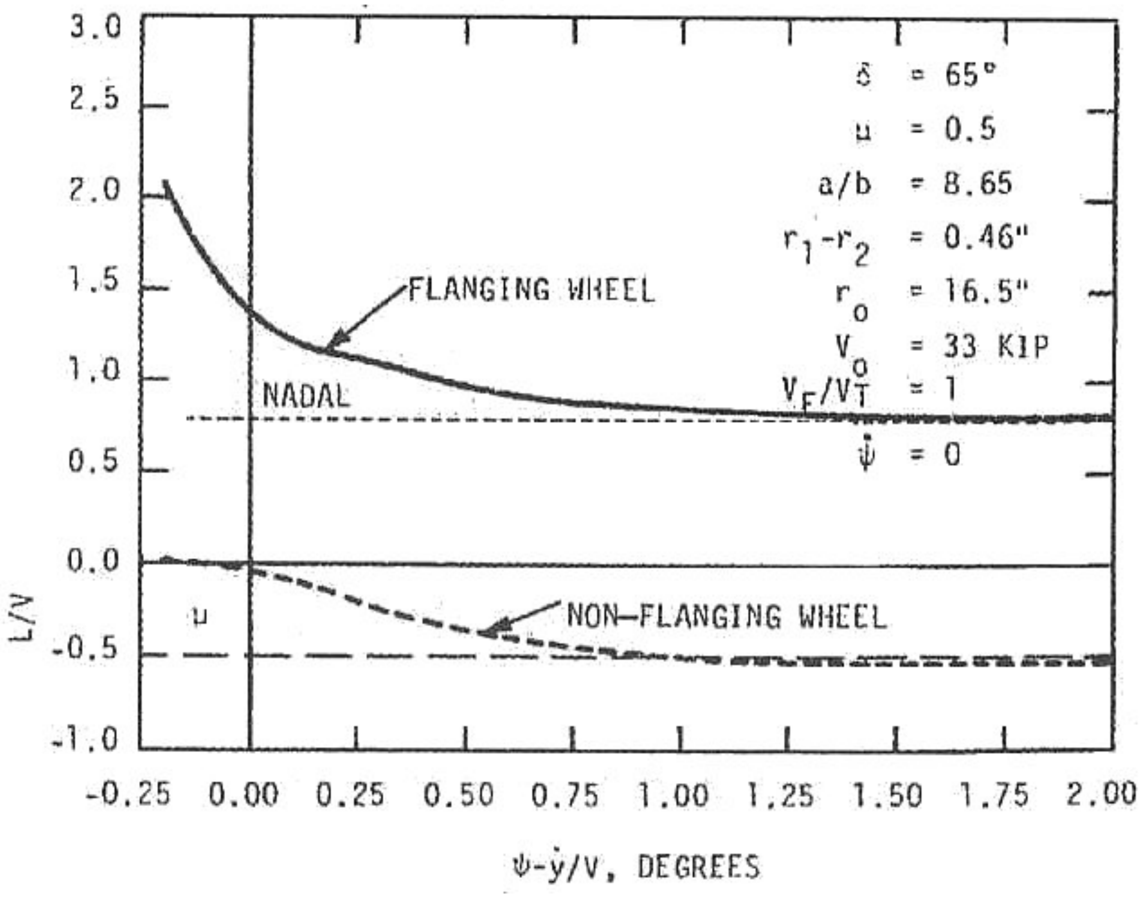
β = gage face angle

Lateral wheel/rail forces





Weinstock Derailment Criterion



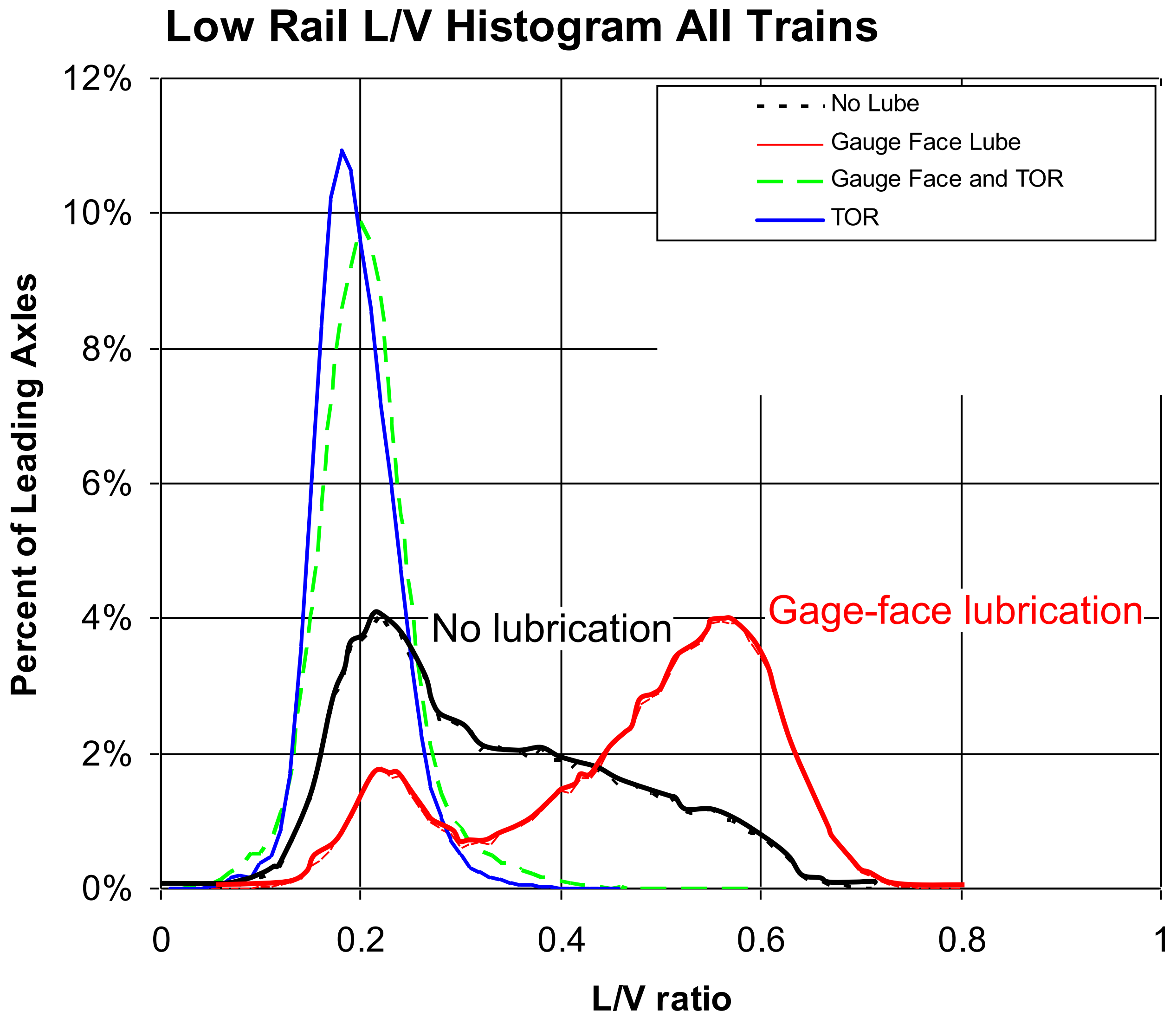
$$|L/V|_{flanging} + |L/V|_{non\_flanging} > (L/V_{NADAL} + m)$$

- Holds for all positive angles of attack,
- Less accurate for +ve cant deficiency

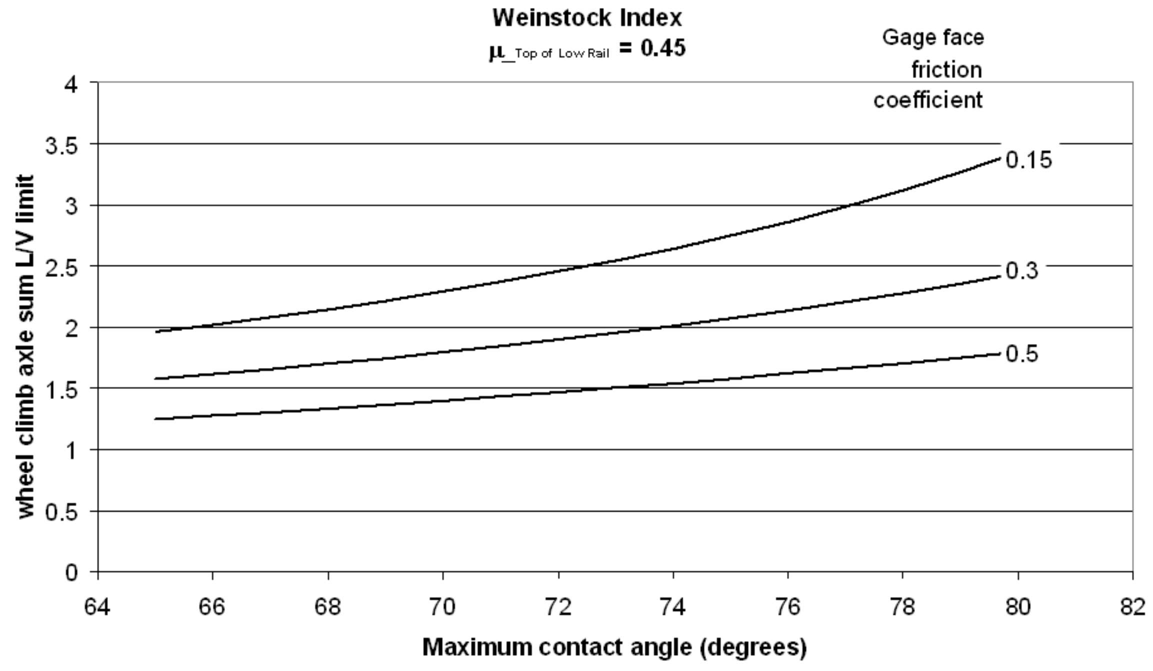
- At incipient wheel climb, the L/V values on the flanging and non-flanging wheels are, for positive angles of attack, separated by a roughly constant value equal to the Nadal limit plus the coefficient of friction on the top of the low rail

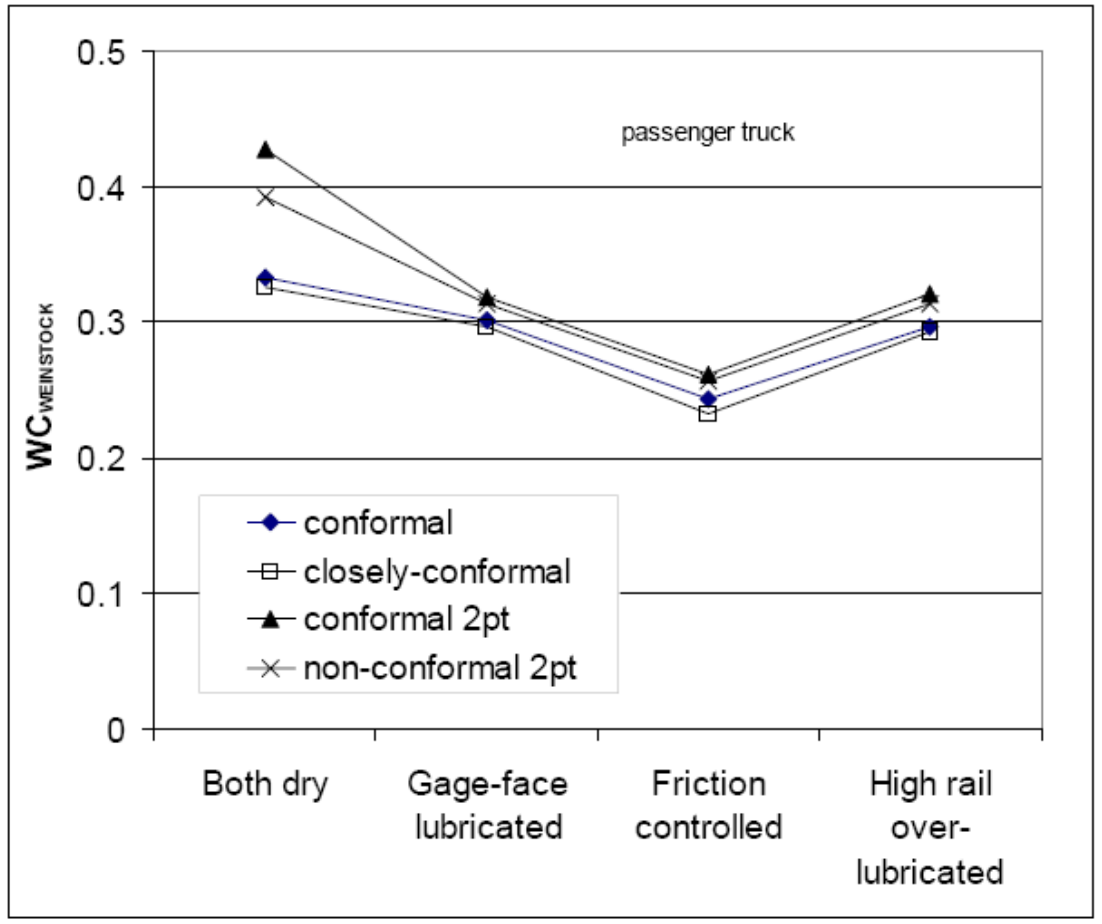
An Example

- Is lubrication a good thing?



L/V goes up, but Weinstock limit also.





Wheel Climb - Conclusions

- Nadal – provides a relationship between contact angle and friction coefficient
- Is based upon simplified view of the slip conditions
- Wheel climb threshold matches Nadal at most practical angles of attack, but not for low angles of attack.
- Weinstock rectifies that (for positive angles of attack) and includes explicitly the effect of friction on top of low rail.
- A safe L/V is some fraction of the (Nadal or Weinstock) threshold value, say 60-80%.
- These are static and quasi-static derivations.

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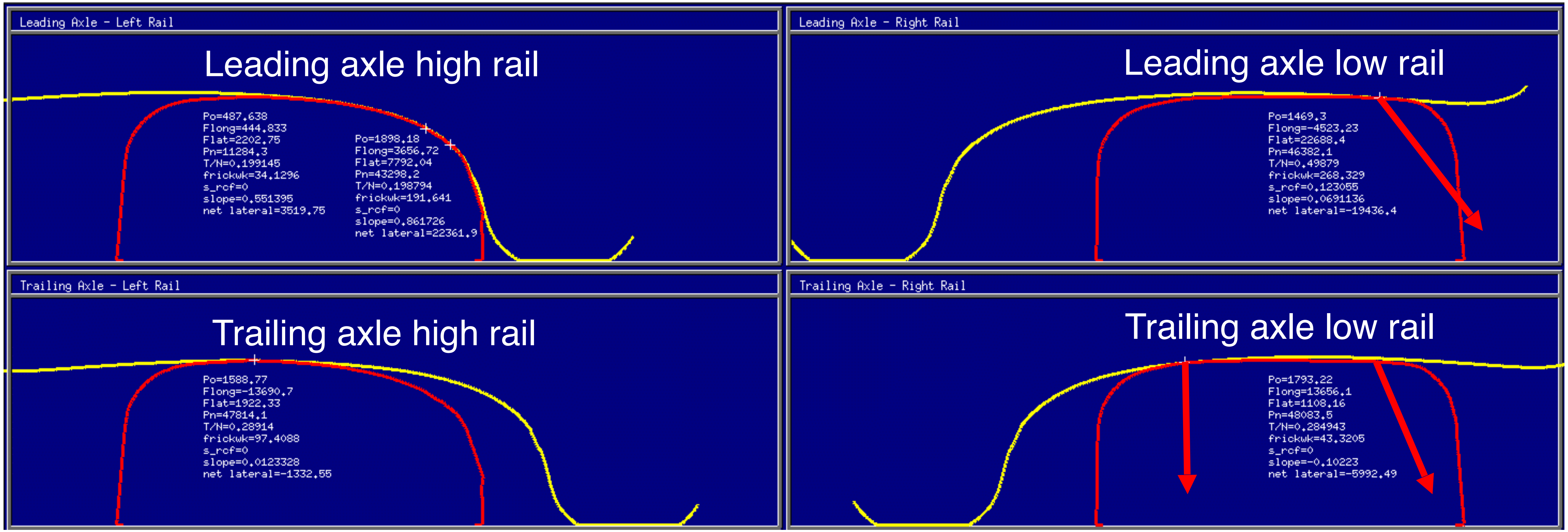
VEHICLE-TRACK DERAILMENT MECHANISMS AND RISK ASSESSMENT

RAIL ROLLOVER

Low Rail Rollover

- Wide gauge, hollow wheels, poor restraint, underbalanced running, high friction



Conclusions

Matching of wheel/rail profiles

- Rolling radius difference: stability and curving
- Strong impact on stress, curving forces, stability, surface damage, safety/derailment (with friction conditions, truck suspensions, track geometry etc.)
- Must consider both new and worn shapes (pummelling)

Nadal formula is adequate for most wheel climb analyses

- Wheel climb risks grow with a sustained increase in lateral force or decrease in vertical force.