Principles of wheel-rail interaction

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1. **Wheel-rail guidance mechanisms**
    a. **Vehicle hunting**
    b. **Vehicle curving**
2. **Creepages and creep forces**
3. **The conflict between running in curves and running on straight track**
4. **Designing a wheel-rail profile combination**

Wheelset guidance mechanisms

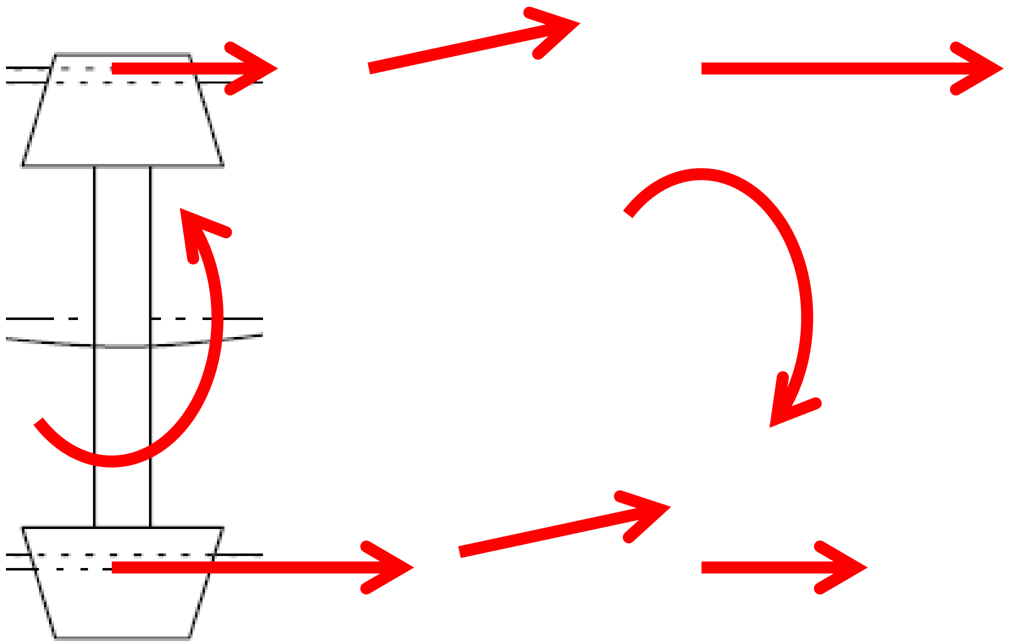
What is the main difference between the

→Two important Guidance mechanisms:

- Hunting motion on straight track
- Curving behaviour

Railway wheels have to have the same rotational speed

Wheelset hunting



Conicity and equivalent conicity

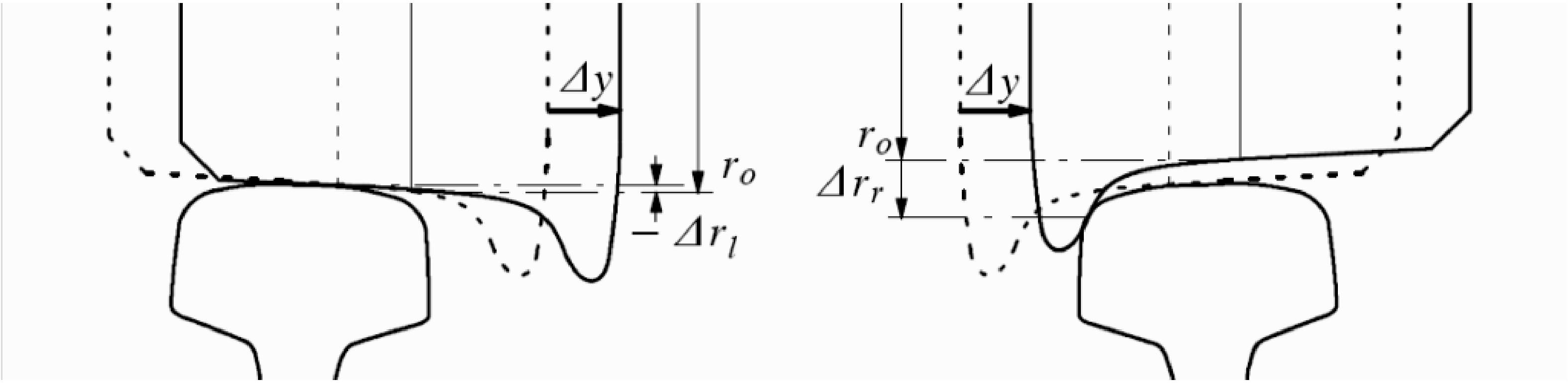
Conicity λ for a single wheel

$$\lambda = \frac{\Delta r}{\Delta y}$$

Equivalent conicity λ_{eq} for a wheelset

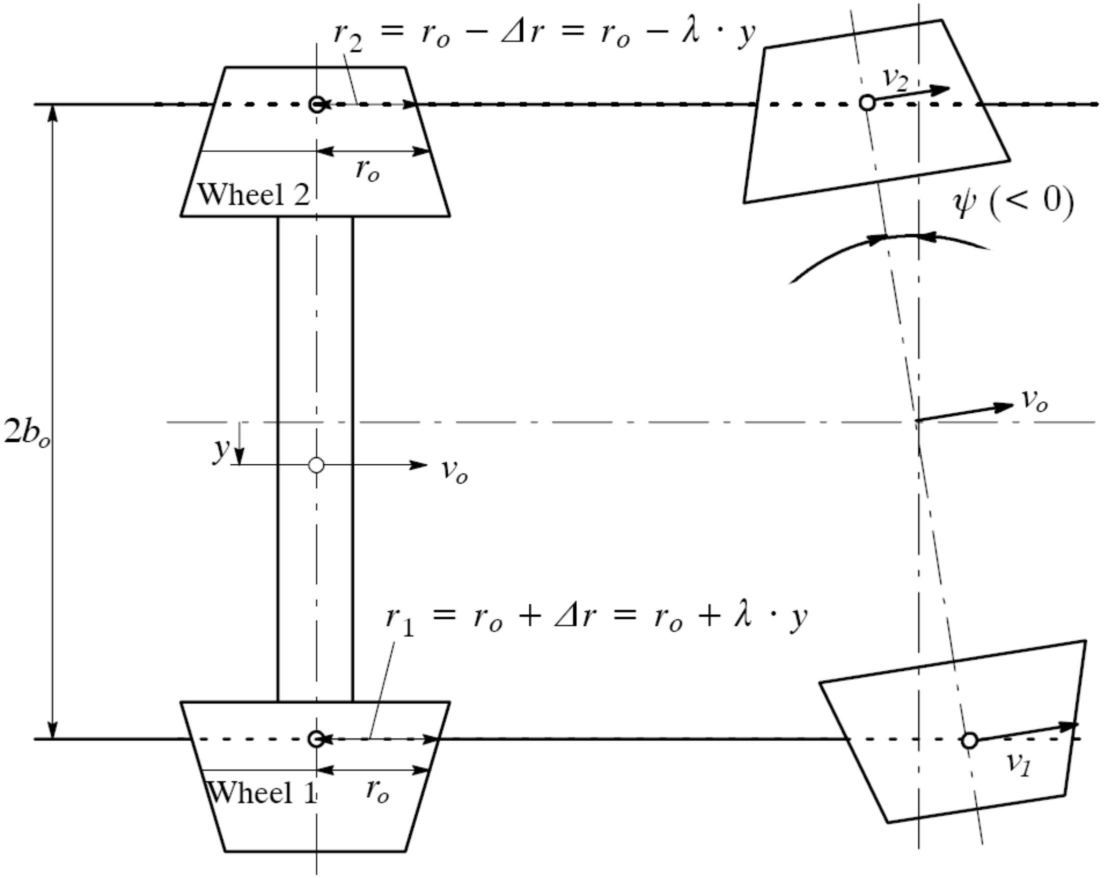
$$\lambda_{eq} = \frac{r_r - r_l}{2\,\Delta y} = \frac{\Delta r_r - \Delta r_l}{2\,\Delta y}$$

for a defined lateral offset Δy



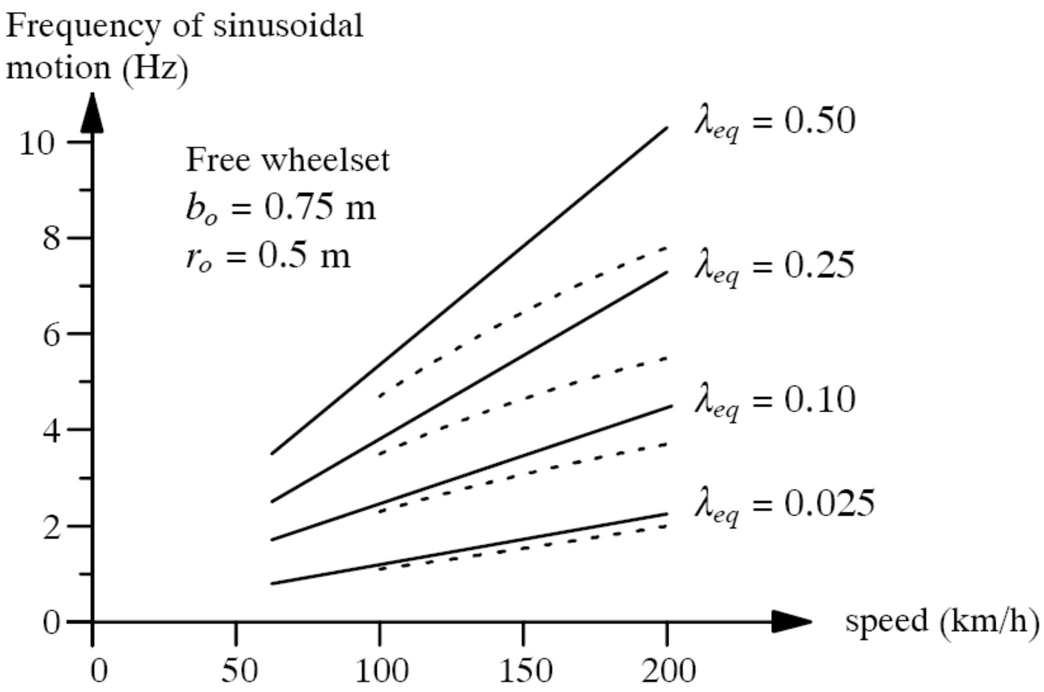
Klingel equation

for a free wheelset with conical wheels:



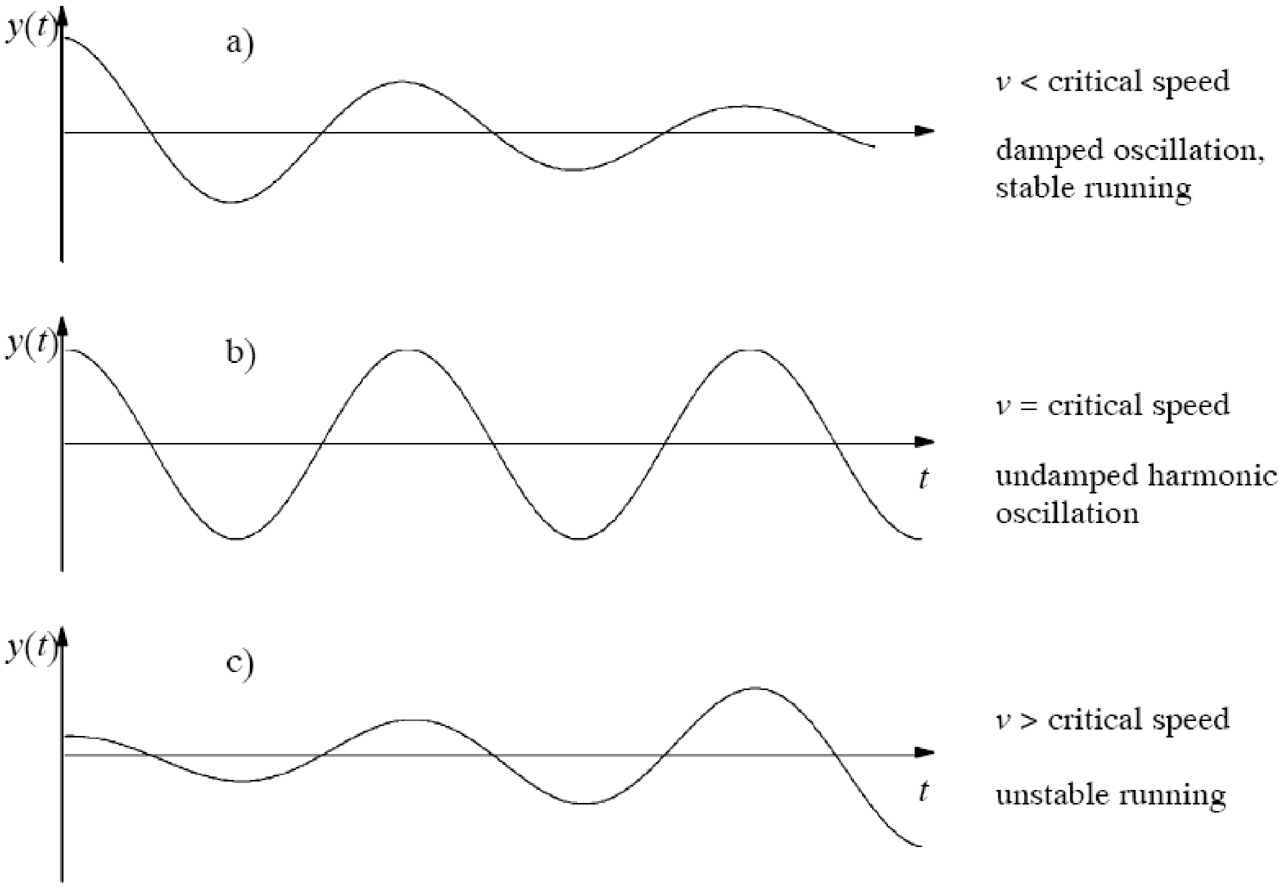
$$L_o = 2\pi \sqrt{\frac{b_0 r_0}{\lambda}}$$

Klingel equation



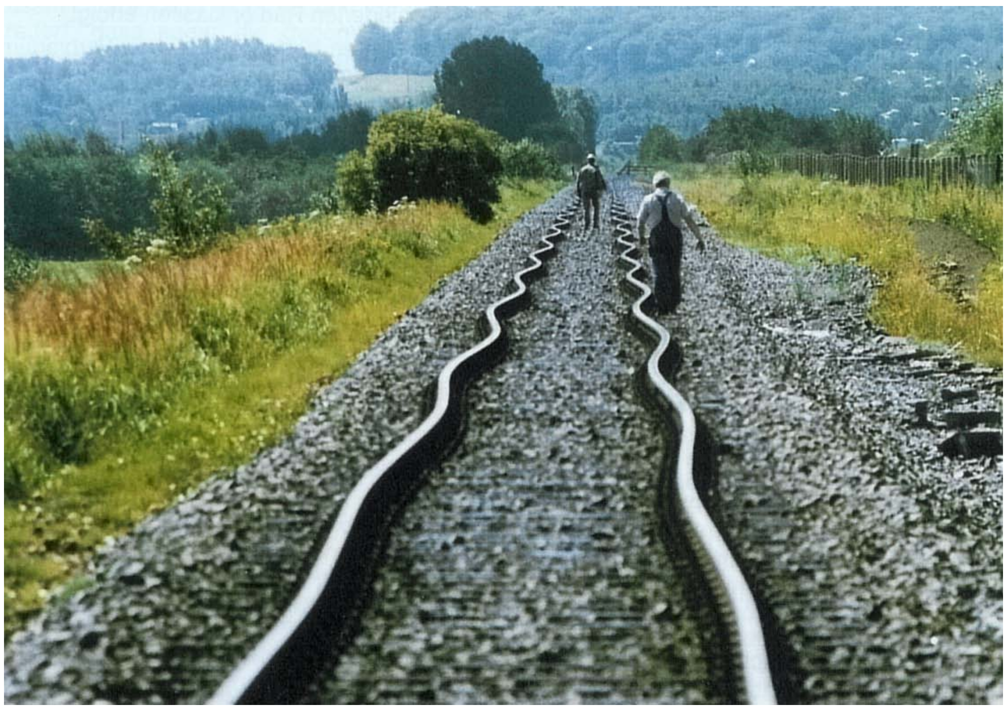
$$L_o = 2\pi \sqrt{\frac{b_0 r_0}{\lambda}}$$

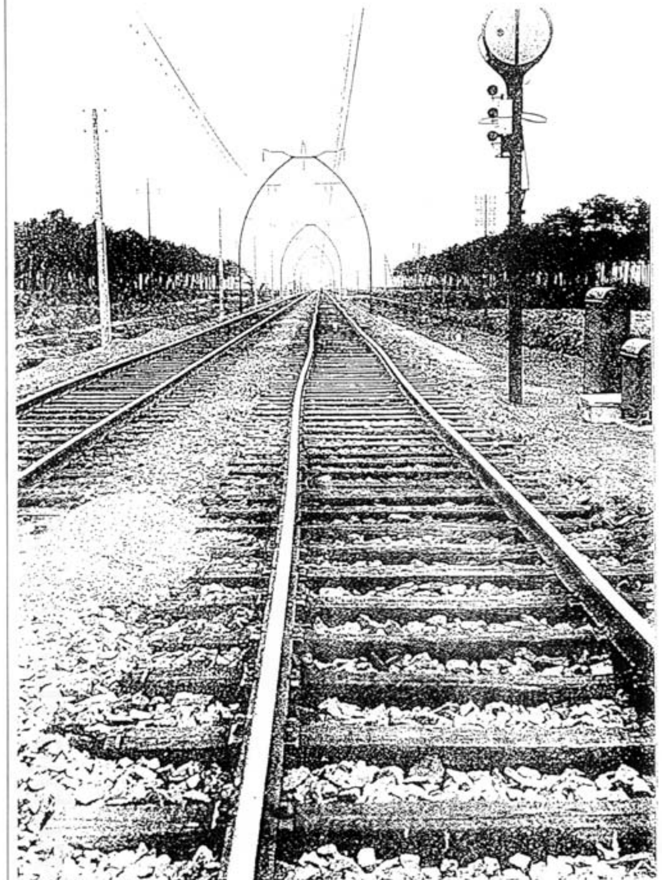
Critical speed



Critical speed

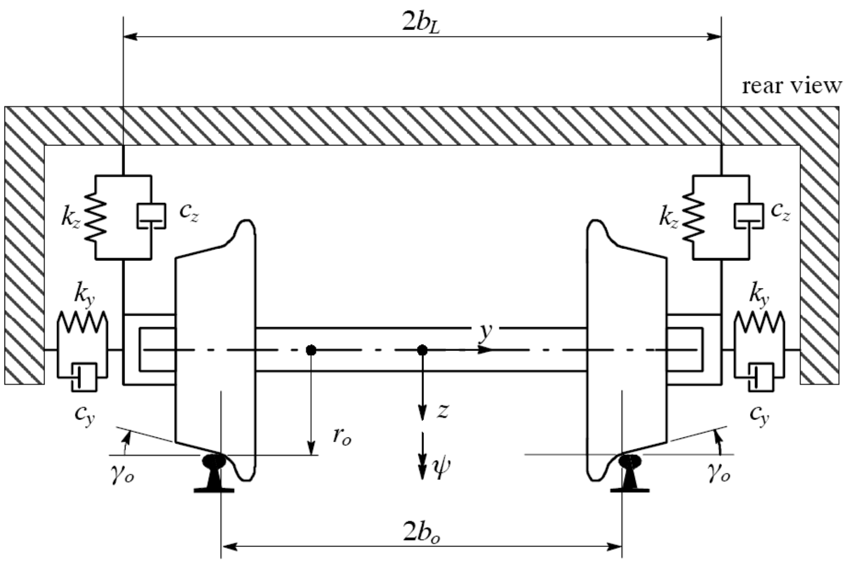
Track destroyed after severe bogie instability = ”hunting”

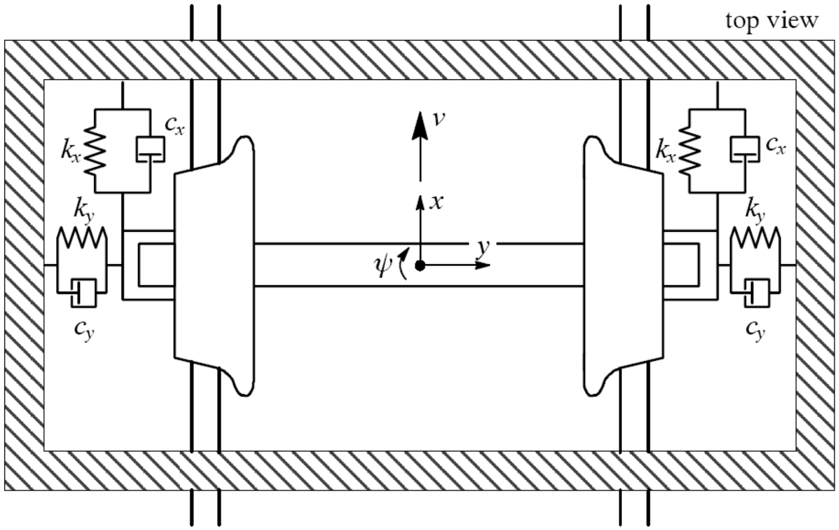




Close to disaster. Just how near the French BB9004 locomotive came to catastrophe when it achieved the 1955 world record of 331km/h was a closely guarded secret until this photograph – not published until 1981 – revealed the extent of track deformation. *La Vie du Rail*

Simplified wheelset model





r_o = nominal wheel radius

k_x, k_y, k_z = stiffnesses wheelset/frame

c_x, c_y, c_z = damper coefficients, dito

Critical speed

$$\begin{bmatrix} m & 0 \\ 0 & J \end{bmatrix}\begin{Bmatrix} \ddot{y} \\ \ddot{\psi} \end{Bmatrix} + \begin{bmatrix} 2c_y & 0 \\ 0 & 2b_L^2 c_x \end{bmatrix}\begin{Bmatrix} \dot{y} \\ \dot{\psi} \end{Bmatrix} + \frac{1}{v}\begin{bmatrix} 2\kappa_{22} & 2\kappa_{23} \\ 0 & 2b_o^2\kappa_{11} \end{bmatrix}\begin{Bmatrix} \dot{y} \\ \dot{\psi} \end{Bmatrix} +$$

$$+ \begin{bmatrix} 2k_y + 2\kappa\left(Q_o - \dfrac{\kappa_{23}}{r_o}\right) & -2\kappa_{22} \\ \dfrac{2b_o\kappa_{11}\lambda_{eq,a}}{r_o} & 2b_L^2 k_x \end{bmatrix}\begin{Bmatrix} y \\ \psi \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

What influences critical speed?

- Conicity
- Longitudinal stiffness bogie $\leftrightarrow$ wheelset
- Bogie wheelset distance
- Wheelset mass
- Bogie mass / inertia moment

Equivalent conicity
according to UIC 518 / EN14363

$\lambda_{eq} \leq 0.50$ for speeds up to 140 km/h

$\lambda_{eq} \leq 0.40$ for speeds above 140 km/h and up to 200 km/h

$\lambda_{eq} \leq 0.35$ for speeds above 200 km/h and up to 230 km/h

$\lambda_{eq} \leq 0.30$ for speeds above 230 km/h and up to 250 km/h

$\lambda_{eq} \leq 0.25$ for speeds above 250 km/h and up to 280 km/h

$\lambda_{eq} \leq 0.15$ for speeds above 280 km/h and up to 350 km/h

High conicity is usually the ”**worst case**”.

(Sometimes low conicity may also be a severe case.)

Influences on equivalent conicity

High conicity may be produced by

- Tight track gauge
- Low rail inclination
- Flat top of rail (=worn on tangent track)
- Wide wheel gauge
- Thick flanges
- Hollow wheel profiles (=worn)

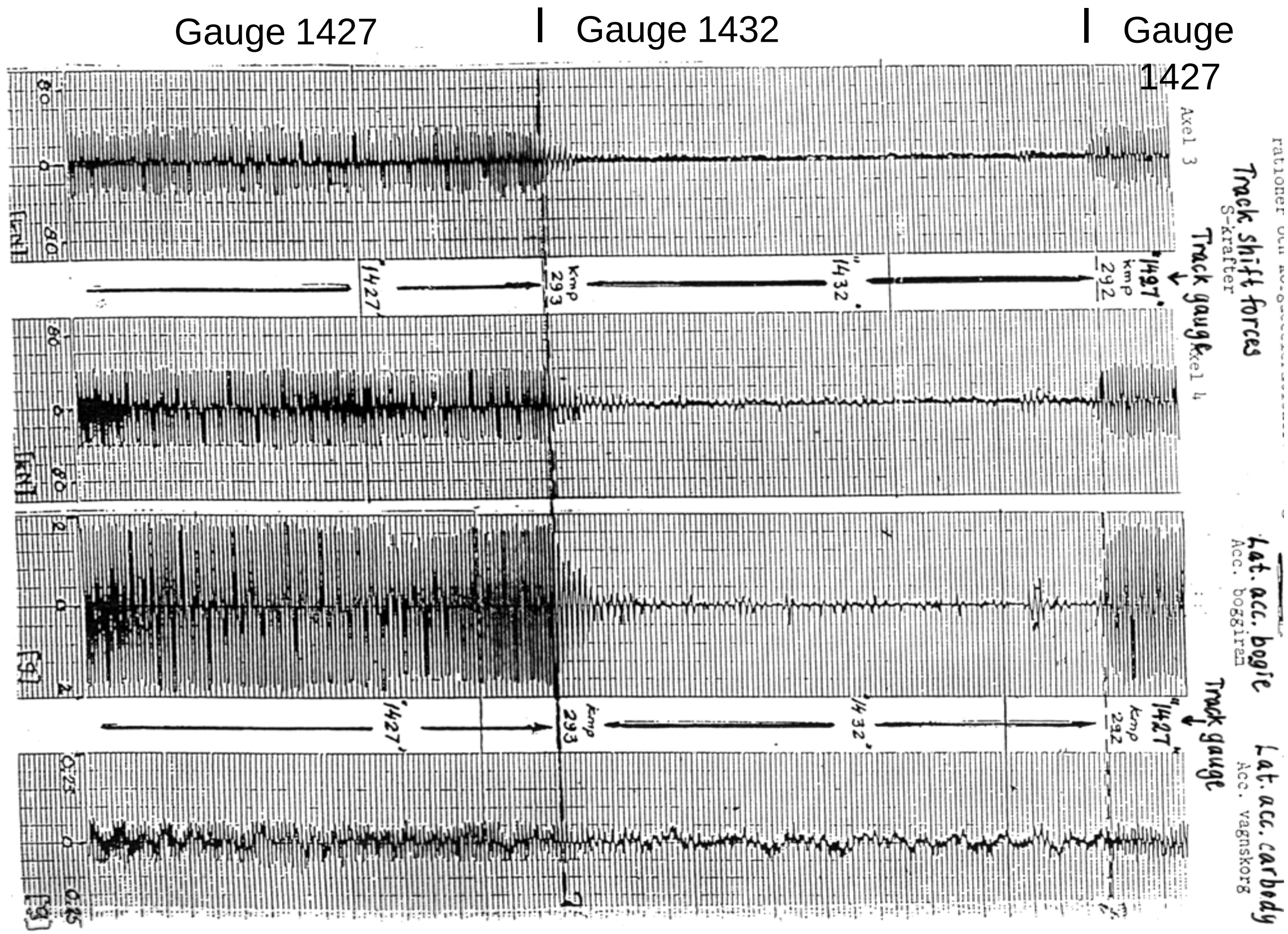
Example: Instability on narrow gauge

Lateral track shift force, wheelset 1 (kN)

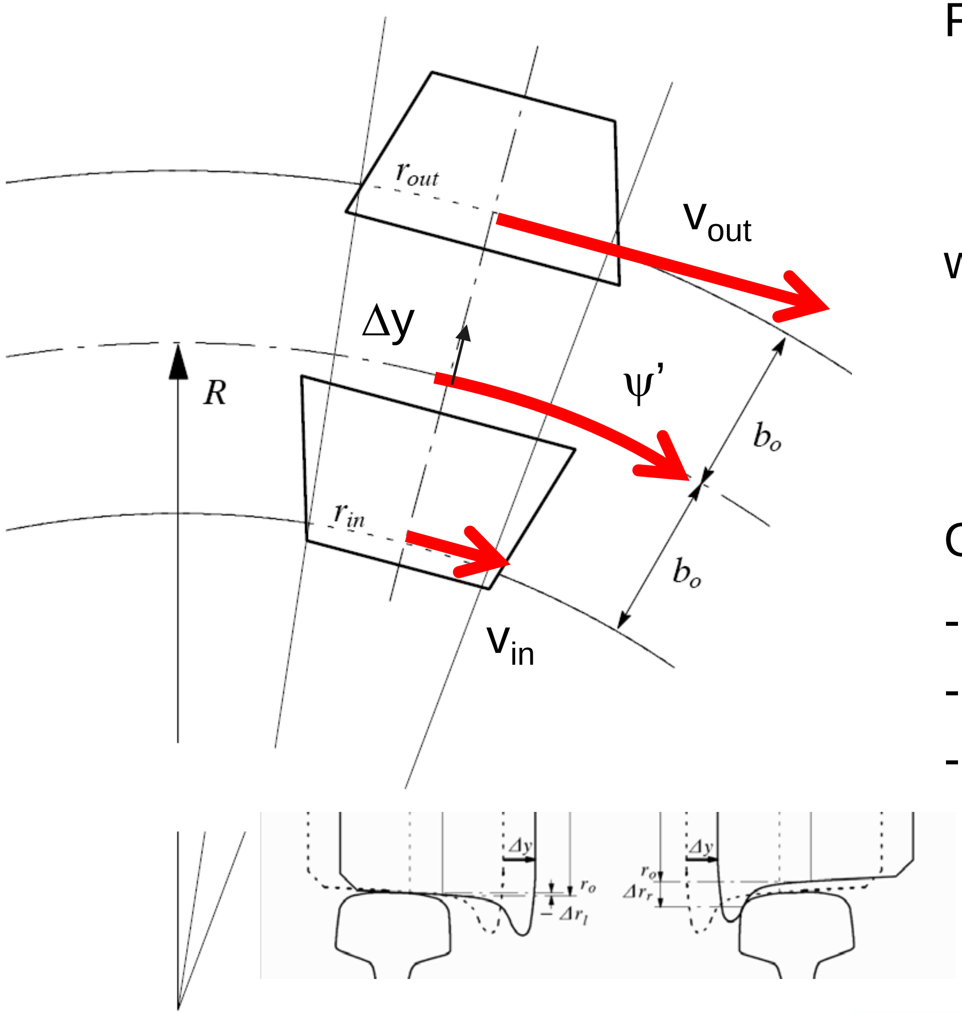
Lateral track shift force, wheelset 2 (kN)

Lateral acceleration bogie frame (g)

Lateral acceleration carbody (g)



Vehicle curving



For ideal curving:

$$\frac{r_{out}}{r_{in}} = \frac{R + b_o}{R - b_o}$$

which turns to

$$r_{out} - r_{in} = 2r_o \frac{b_o}{R}$$

Of advantage is:

- **High conicity**
- **High** w/r **friction**
- **Wheelset free** to take radial position

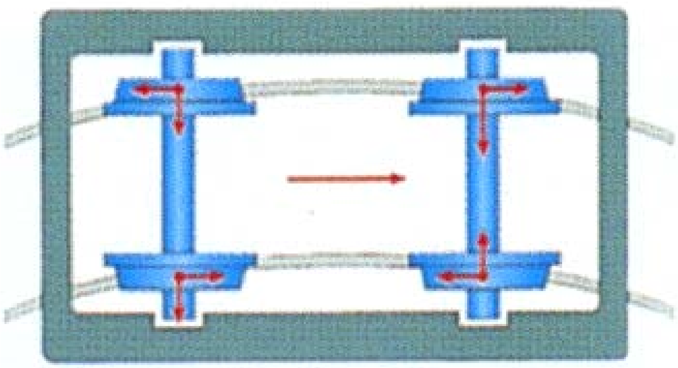
... it is not that simple

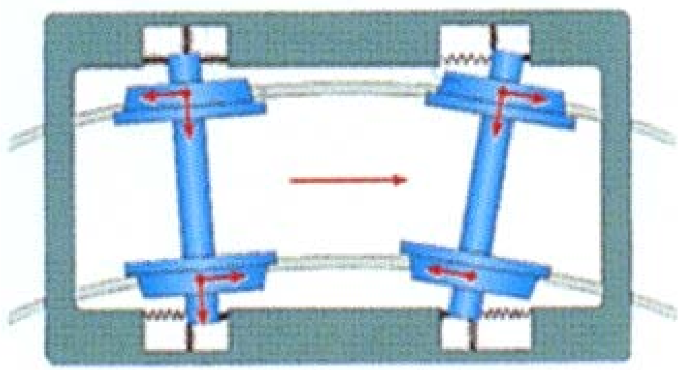
Wheelsets are usually
more or less contrained in a frame.

Forces are needed to turn around
the wheelset.

With very ”sfiff” constrains the
wheelset is never able to radial
self-steering.

With ”flexible” or ”soft” contrains the
wheelset is more or less able to
steer radially depending on friction,
curve radius, etc.



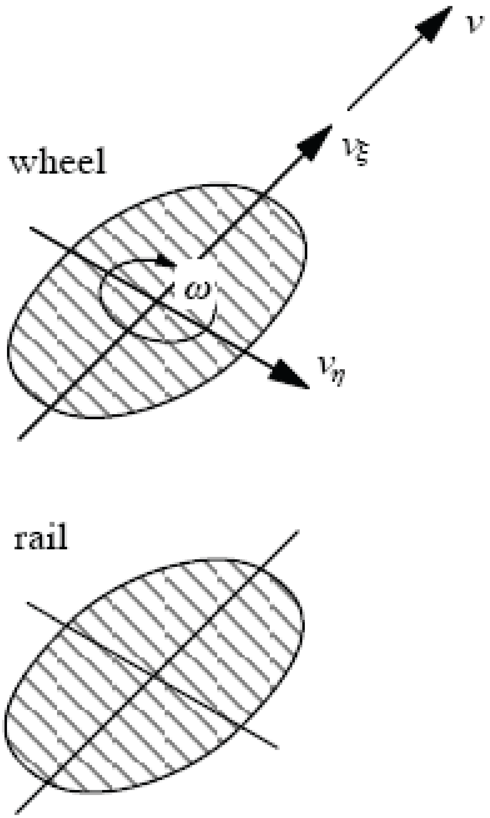


Friction and creep

Friction forces are usually acting in the wheel-rail interface.

Some "**sliding**" is necessary to generate these friction forces.

Sliding under simultaneous rolling is called creep.



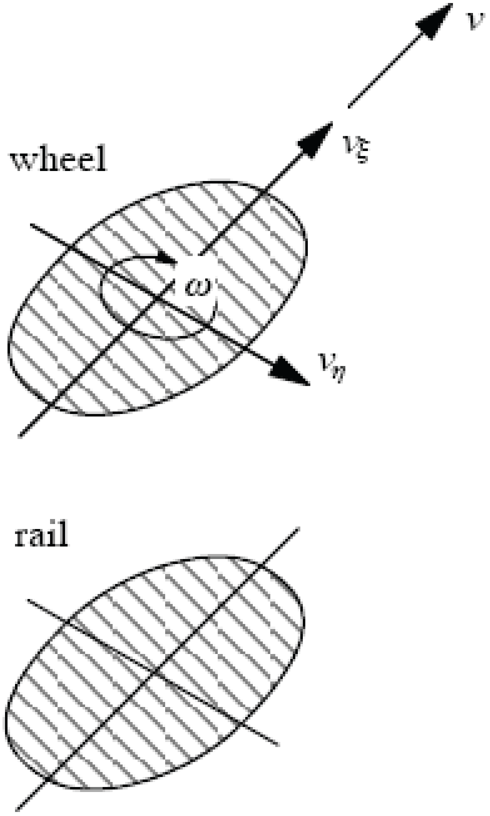
Creep -Definitions

v_ξ = longitudinal sliding speed wheel-rail (m/s)

v_η = lateral sliding speed wheel-rail (m/s)

ω = rotational sliding speed (spin) wheel-rail (rad/s)

v = forward speed (m/s)



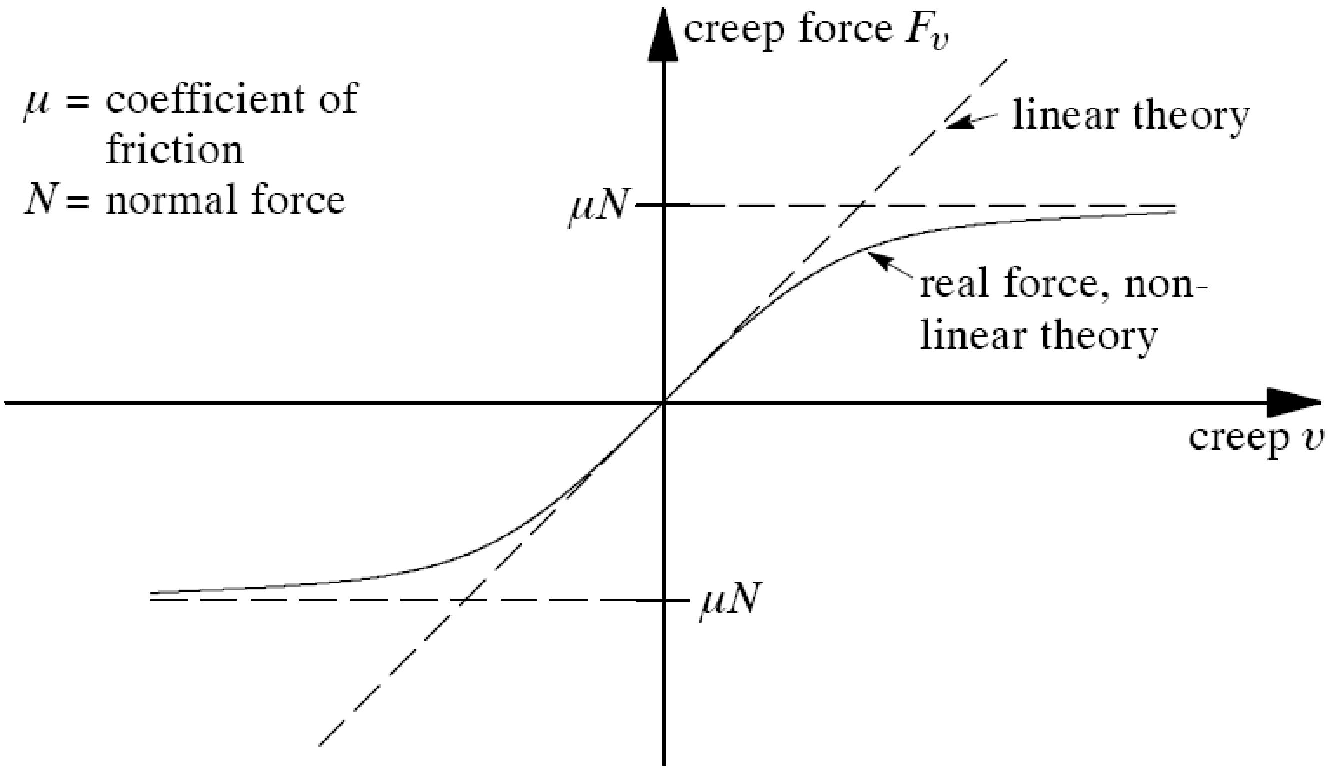
longitudinal creep $\upsilon_\xi = \dfrac{v_\xi}{v}$

lateral creep $\upsilon_\eta = \dfrac{v_\eta}{v}$

spin creep $\phi = \dfrac{\omega}{v}$

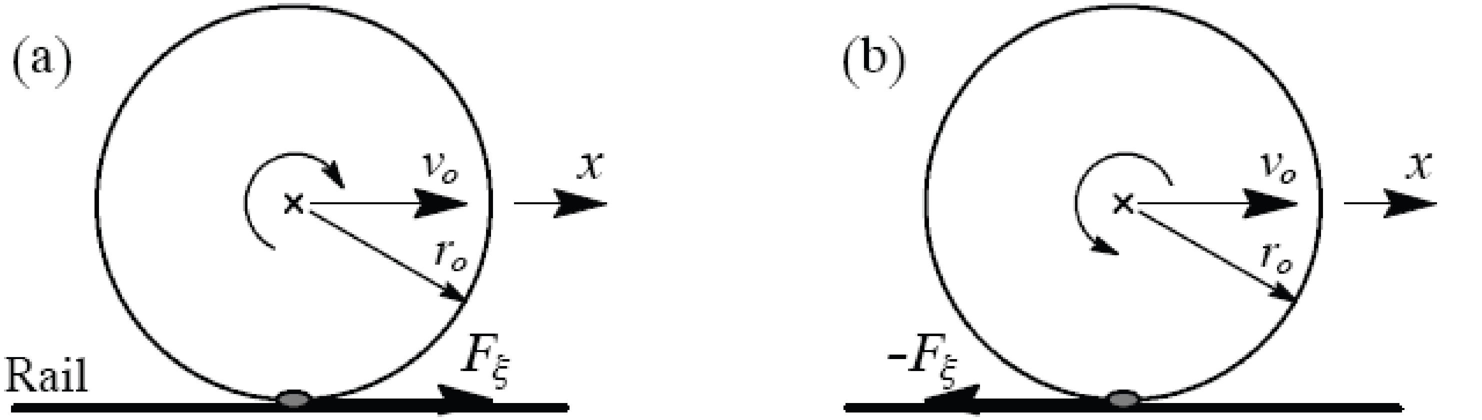
total creep $\upsilon = \sqrt{\upsilon_\xi^2 + \upsilon_\eta^2}$

Creep → Creep forces



Creep and creep forces

Example 1: Wheel in drivning or braking



$v_\xi < 0$

$F_\xi > 0$ (Driving)

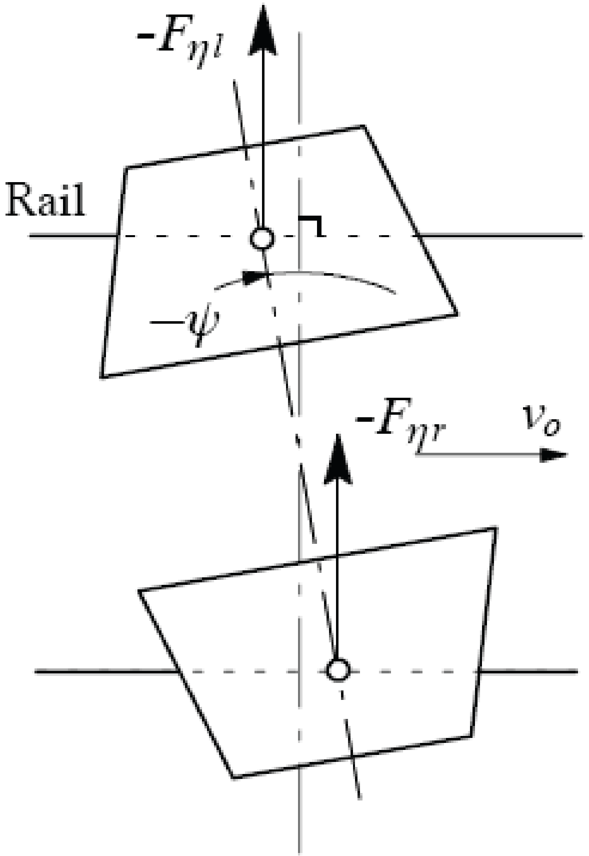
$v_\xi > 0$

$F_\xi < 0$ (Braking)

Creep and creep forces

Example 2: Wheel angle of attack

- There is a continuous ”sliding” (creep) in lateral direction;
  thus a steady lateral creep force is generated



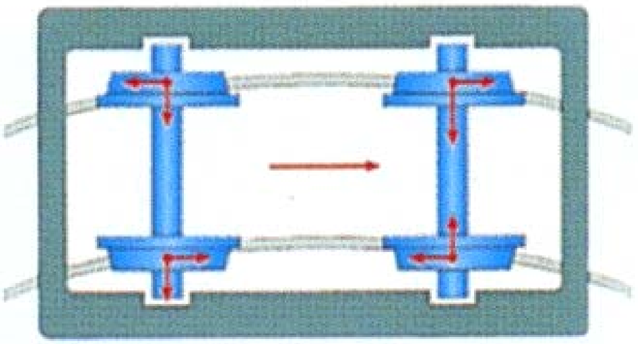
Vehicle curving again

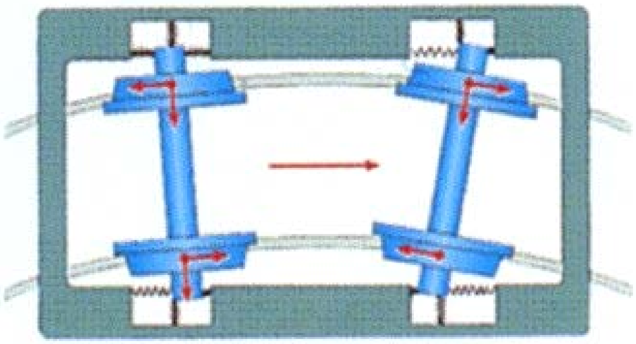
How will the wheelset behave

in reality?

- Radial steering or not?

- Which forces?





Vehicle curving

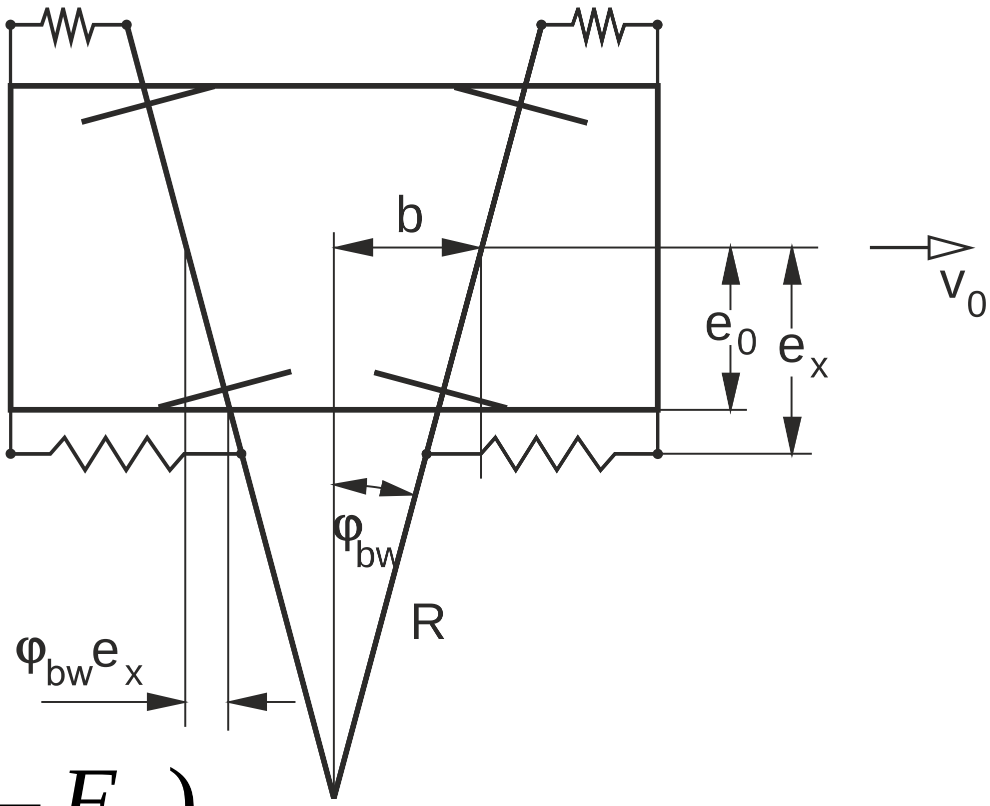
Force moment from longitudinal suspension:

$$2e_x^2 \cdot k_x \varphi_{bw} = ?$$

Balanced by

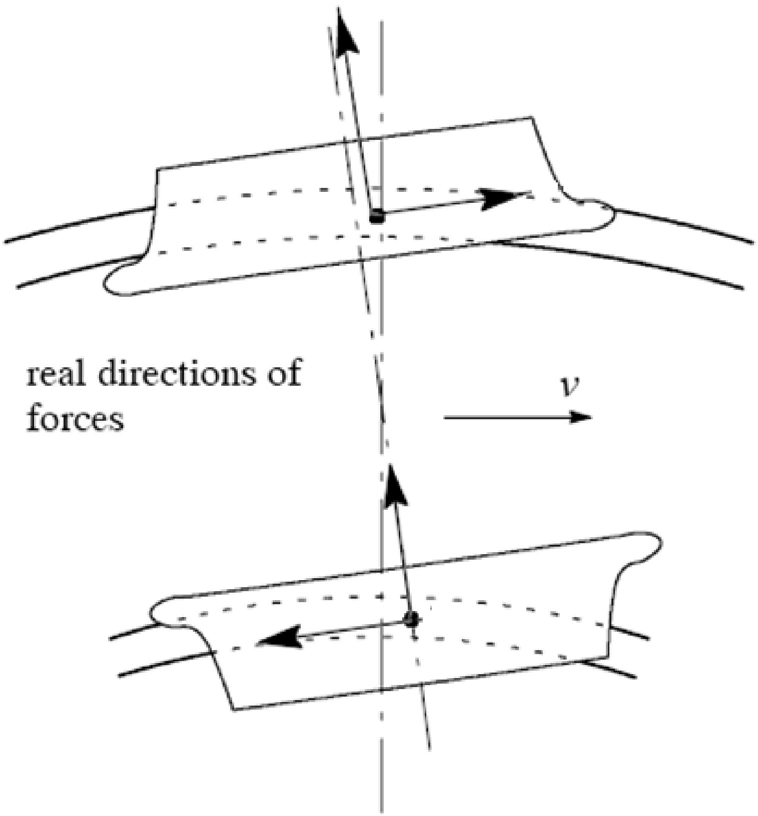
$$2e_x^2 \cdot k_x \varphi_{bw} = e_0 (F_{\xi l} - F_{\xi r})$$

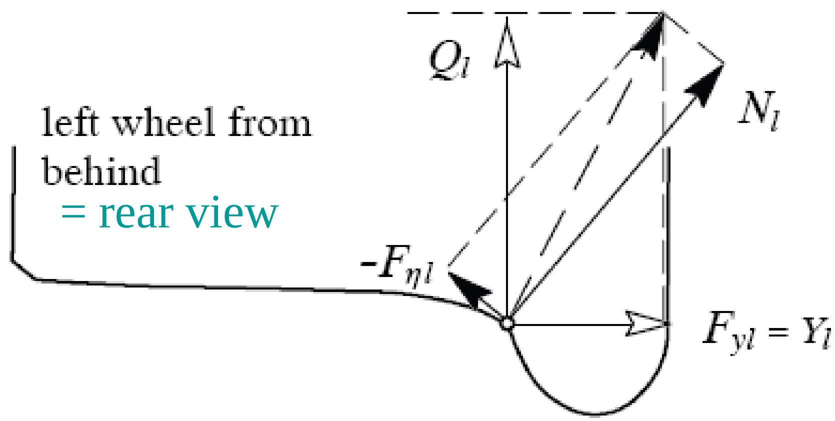
… the longitudinal creep forces



Forces on wheelset

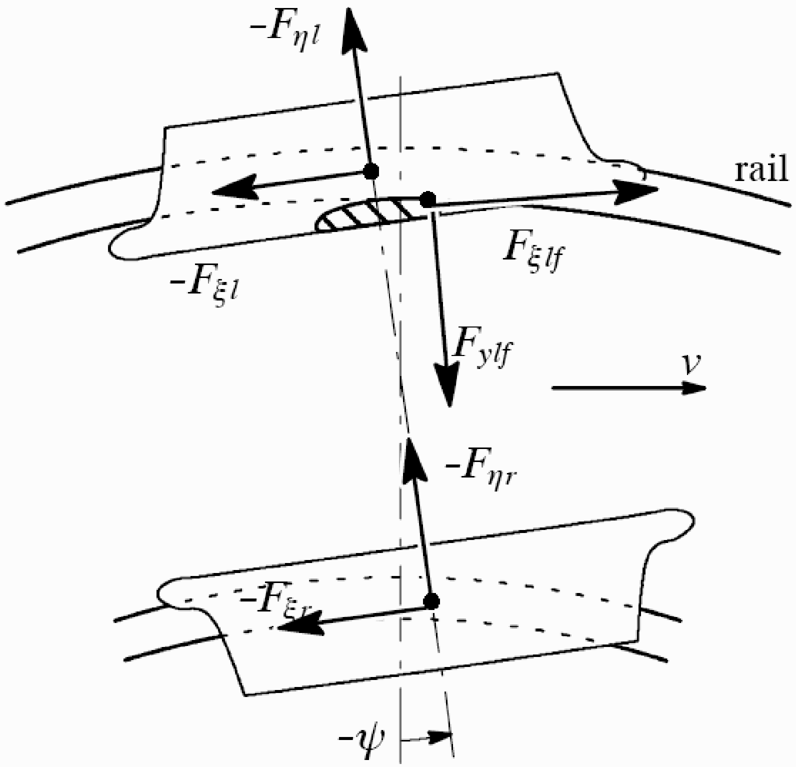
Case 1: One-point contact on outer wheel
= usually good; develop forces for radial steering





Forces on wheelset

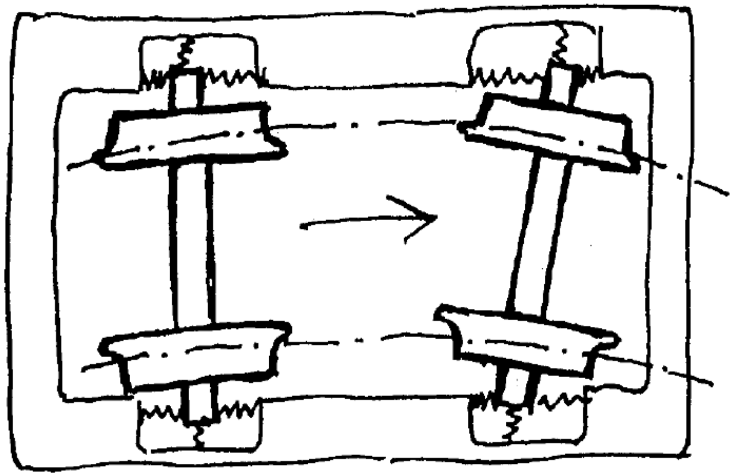
Case 2: Two point contact on outer wheel.
Will usually <u>not</u> develop forces for radial steering



(a) Top view of wheelset

Examples of forces in a curve

Flexible wheelset guidance (F)



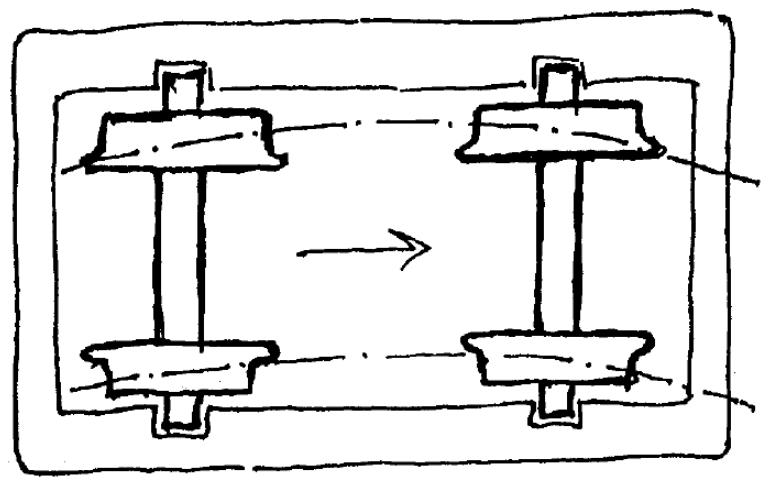
k_x = 4 000 kN/m per axle box

k_y = 1 000 kN/m per axle box

Stiff wheelset guidance (S)

k_x = 40 000 kN/m per axle box

k_y = 15 000 kN/m per axle box

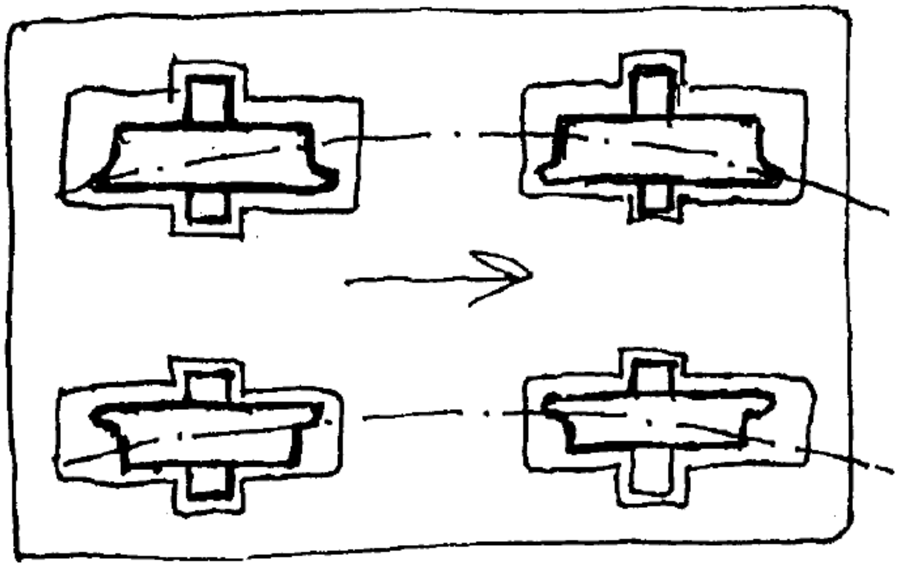


Examples of forces in a curve

Stiff wheelset guidance, independently rotating wheels (SI)

k_x = 40 000 kN/m per axle box

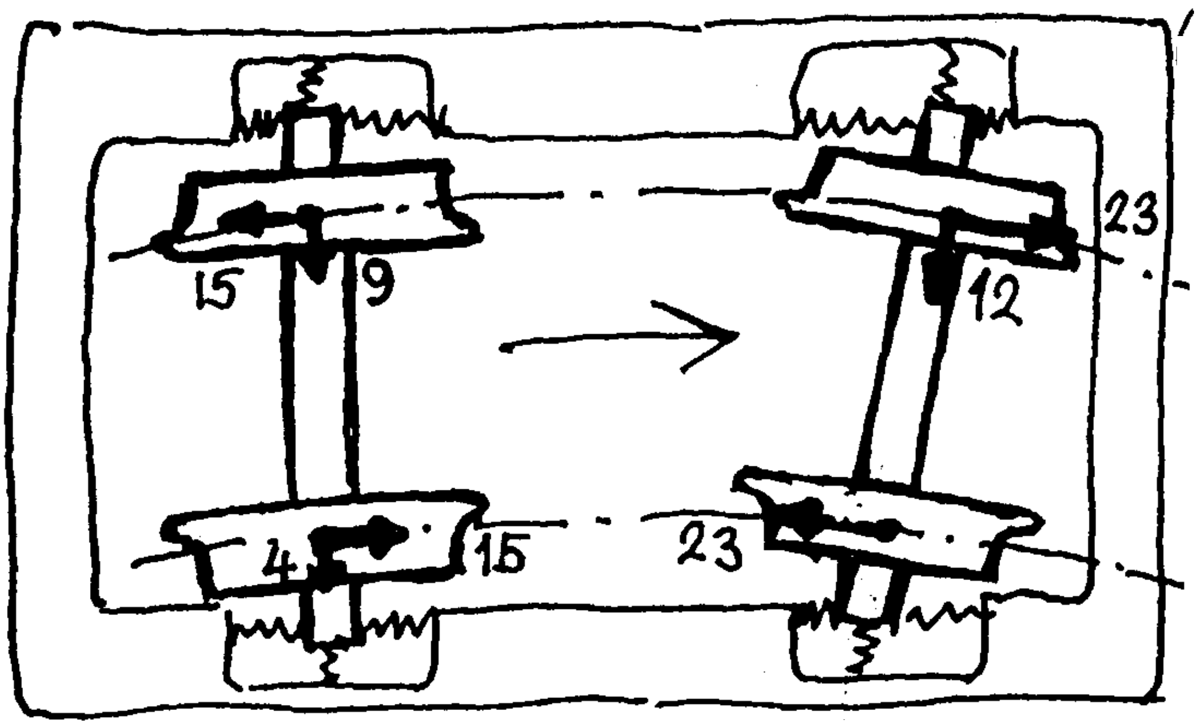
k_y = 15 000 kN/m per axle box



Examples of forces in a curve

R=400 m, h_t=145 mm, v=90 km/h: Soft bogie

Forces in kN, AoA α, roll radius increase Δr, Y/Q, energy diss. E



Δr = 4 mm
Y/Q = 0.10
E = 145 Nm/m

$\Delta r \approx 0$
E = 45 Nm/m

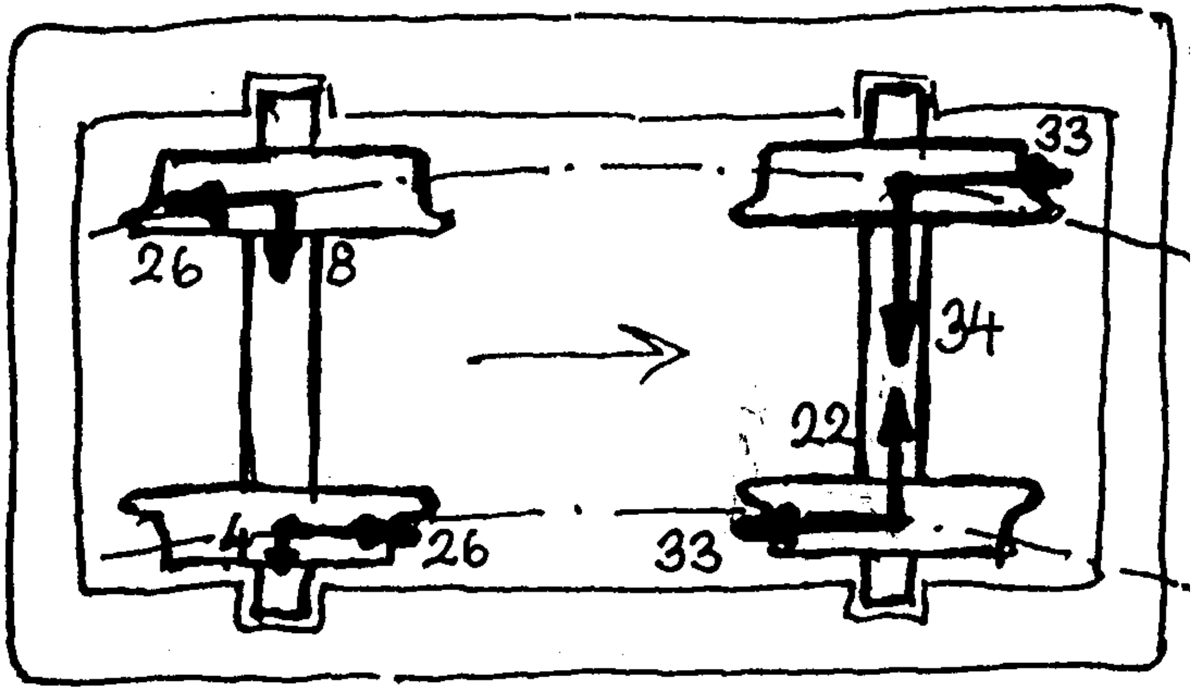
α = -0.5 mrad

$\alpha \approx 0$

Examples of forces in a curve

R=400 m, h_t=145 mm, v=90 km/h: Stiff bogie

Forces in kN, AoA α, roll radius increase Δr, Y/Q, energy diss. E



Δr = 10 mm
Y/Q = 0.29
E = 655 Nm/m

Δr = -0.5 mm
E = 436 Nm/m

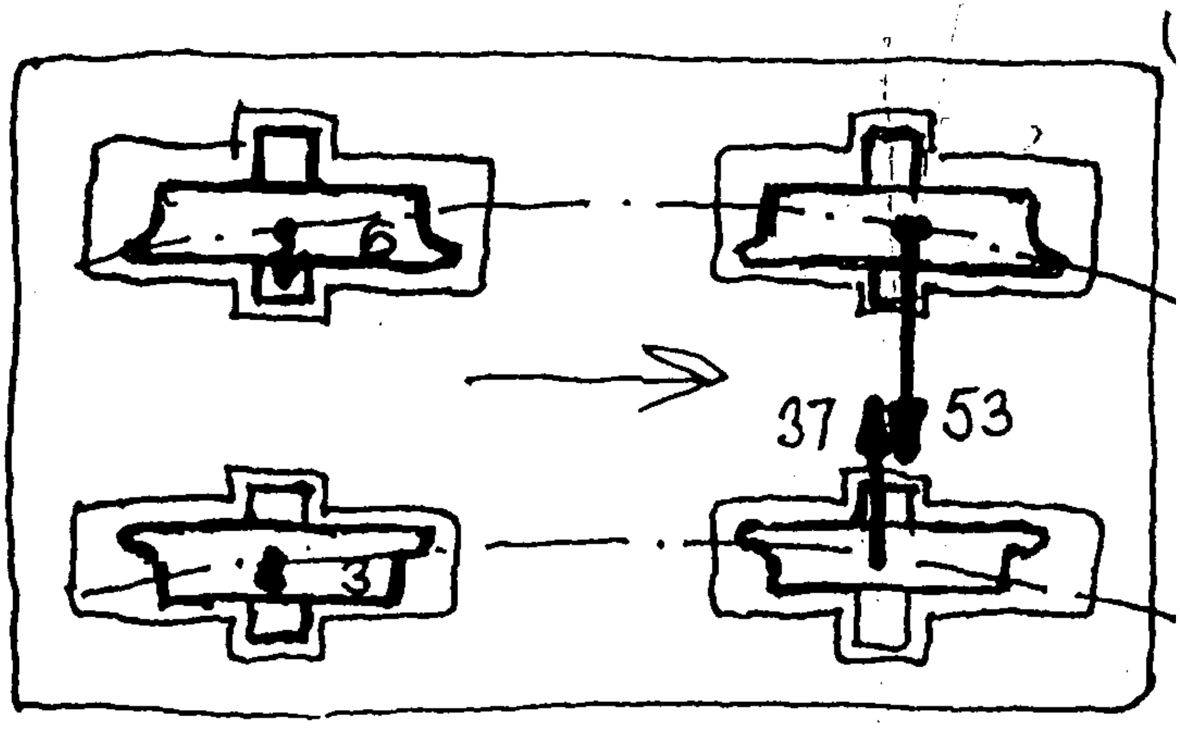
α = -0.5 mrad

α = 6 mrad

Examples of forces in a curve

R=400 m, h_t=145 mm, v=90 km/h: Stiff-indep

Forces in kN, AoA α, roll radius increase Δr, Y/Q, energy diss. E



Δr = 15 mm
Y/Q = 0.45
E = 606 Nm/m

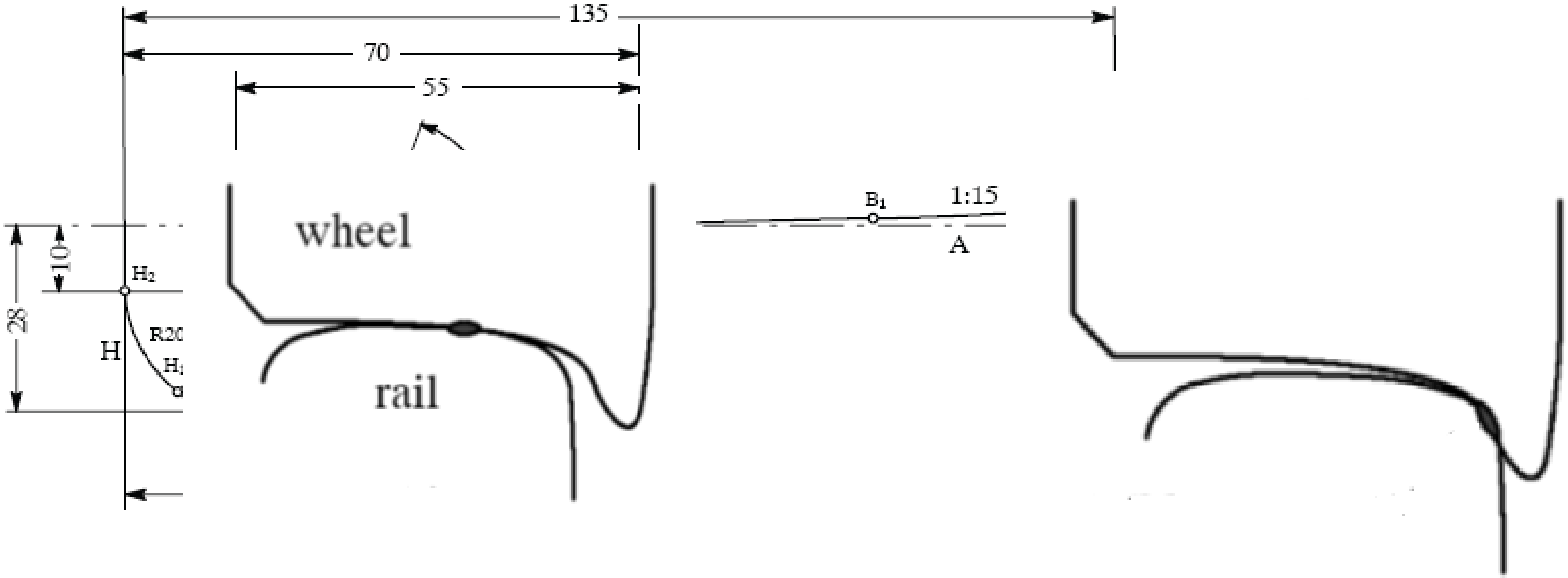
Δr = -1 mm
E = 266 Nm/m

α = -0.3 mrad

α = 7 mrad

How to solve the conflict between straight track and curving?

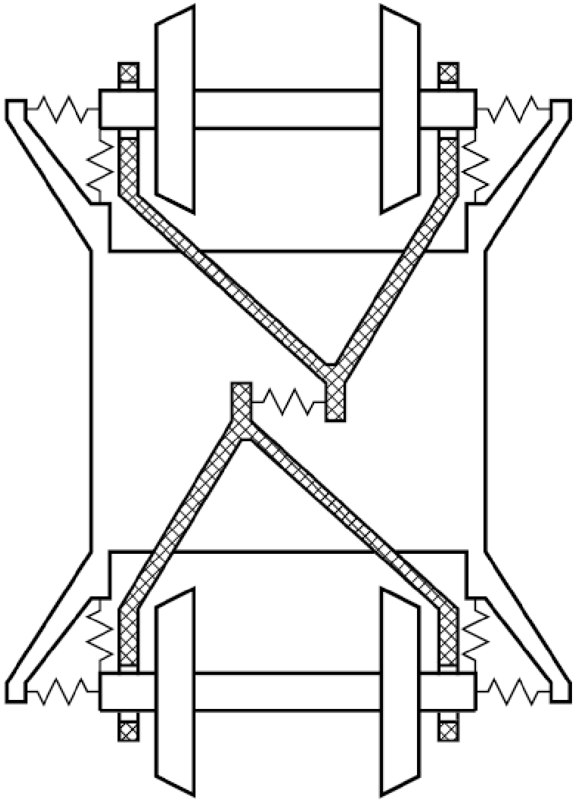
A real wheel profile is not a straight cone:



How to solve the conflict between straight track and curving?

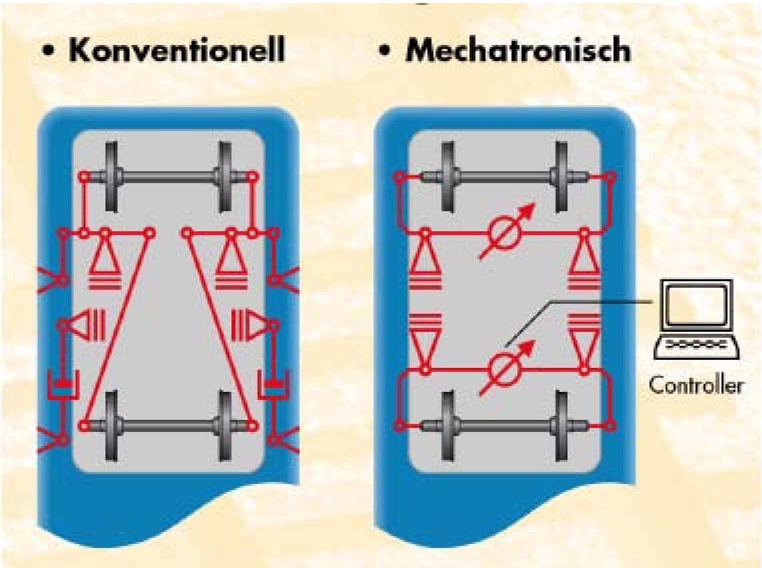
”Scheffel” bogie

- stiff in shear
- flexible in bending



How to solve the conflict between straight track and curving?

Active radial steering



Another conflict…

… The design of a wheel rail profile combination

Two tasks:

- Vehicle guidance (as described before)
- Transfer loads from wheel to rail

Contact pressure according to Hertz

Rail: UIC 60 or similar

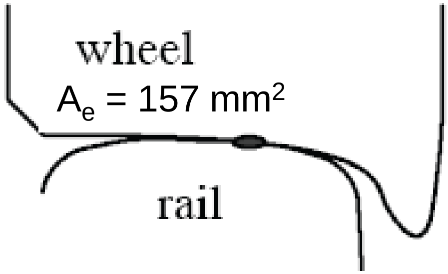
Wheel: r_0 = 0.46 m (Ø 920 mm)

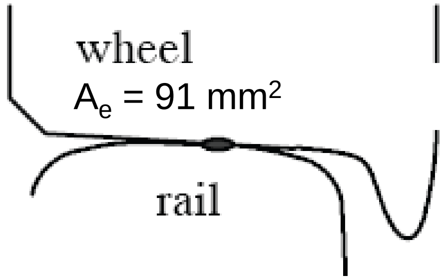
Normal force Q = 60 kN

Calculated contact pressure

1) Wheel UIC S1002 => σ_{max}= 573 Mpa

2) Straight conical wheel => σ_{max}= 990 Mpa



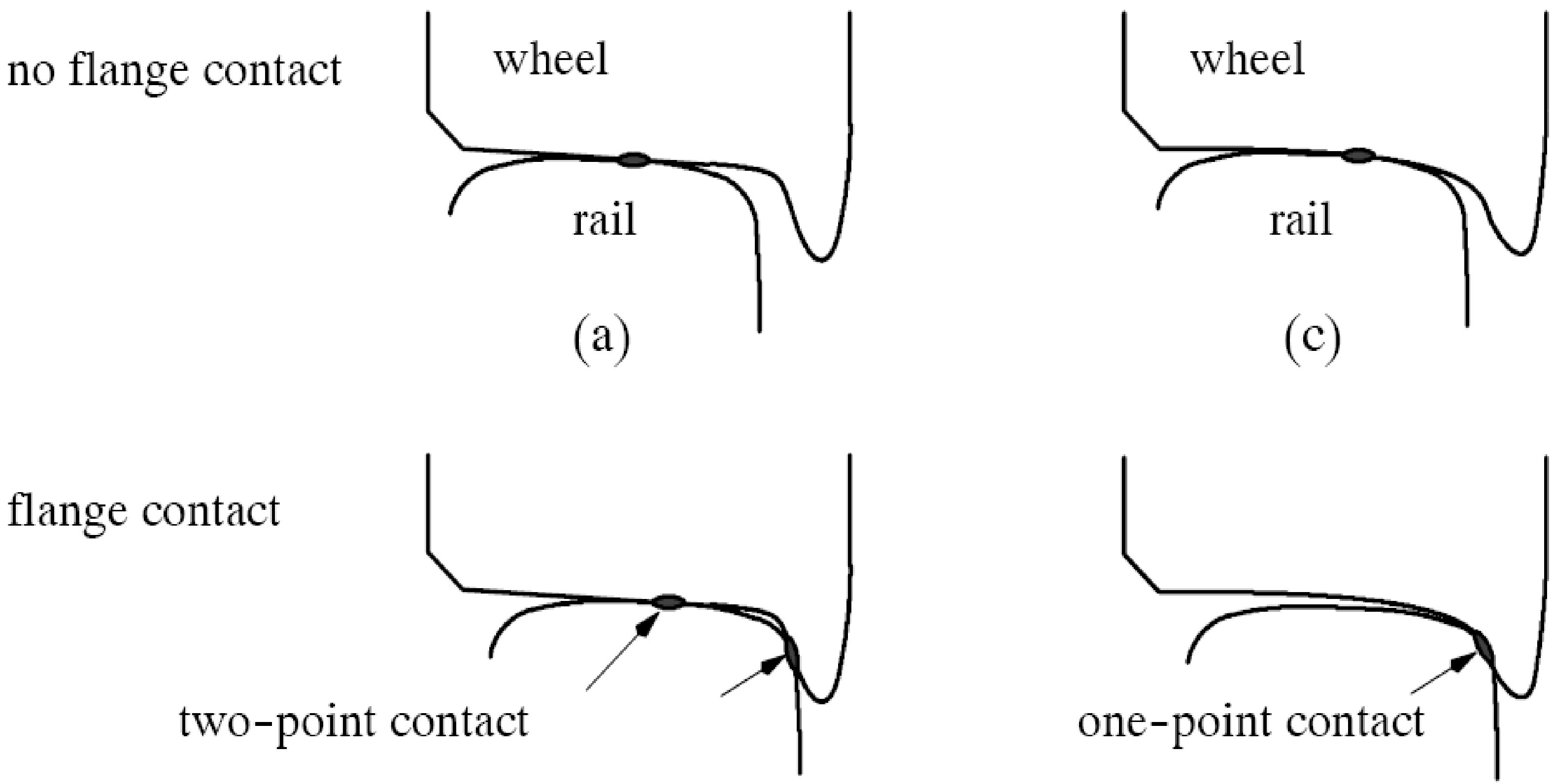


Steel material is often stressed above its yield limit!

Types of contact

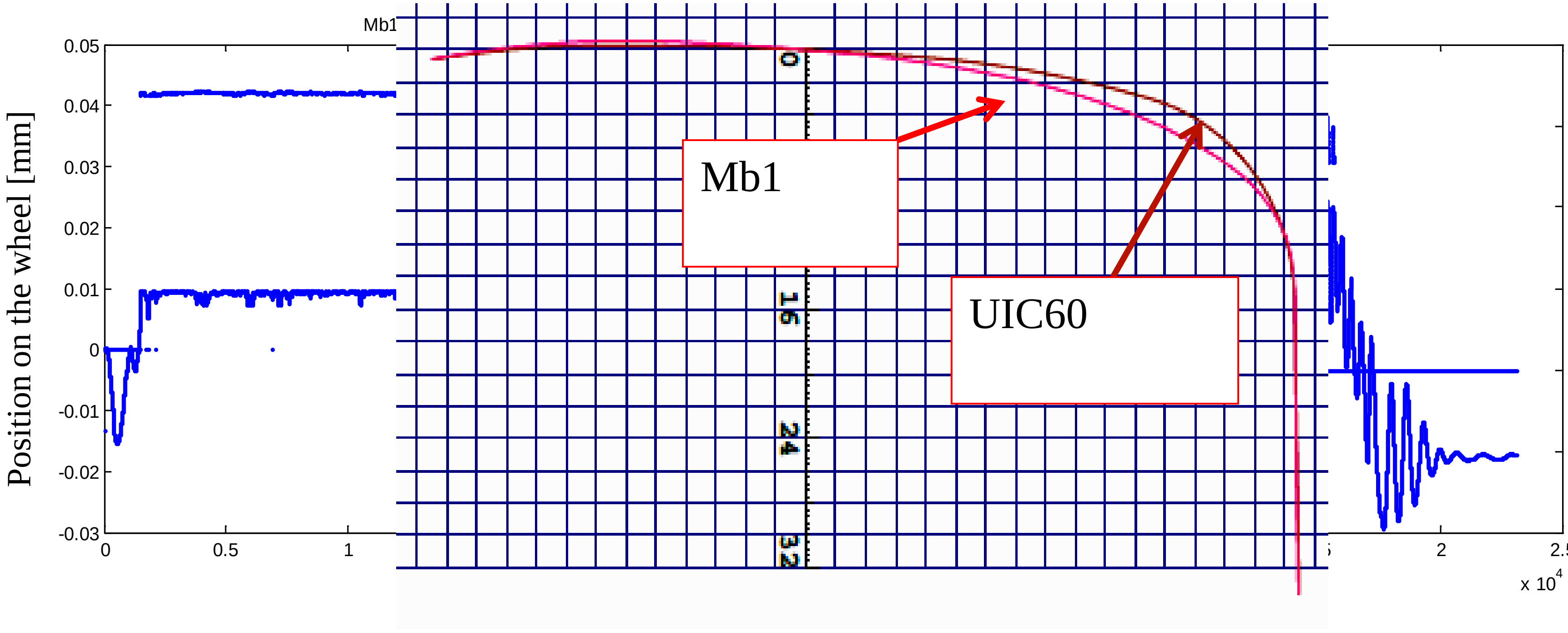
Straight conical wheel profile

Wear-adapted wheel profile



Types of contact

Example iron ore line in Northern Sweden



Types of contact

Wheel S1002
Rail UIC 60

1:20

1:30

1:40