Friction control in wheel-rail contacts

Alejandro Roda

Head Accredited Laboratory HOM

25.11.2024

MATISA Matériel Industriel SA

MATISA Matériel Industriel SA
Crissier SUISSE

On Track Machines (OTM) development and construction

Website: https://www.matisa.ch/fr/index.php

Videos
P95 - Renewal train (7min) https://youtu.be/o41wJwnJJAY
B66UC - Tamping machine (4min) https://youtu.be/W-7QjMeGcrk

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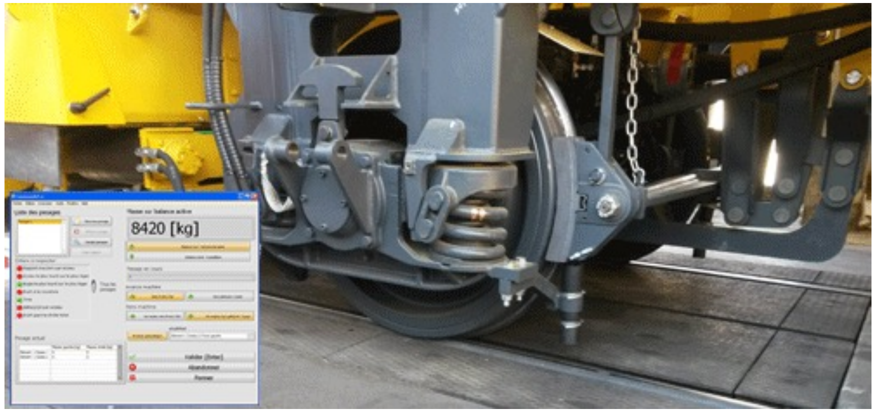
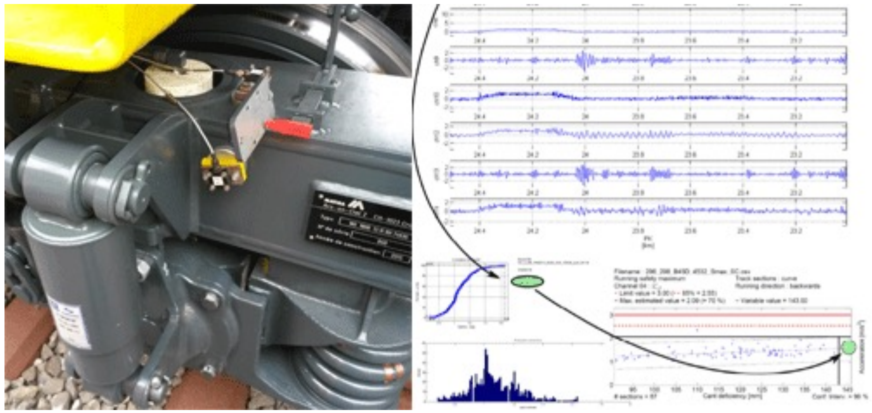
Website: https://www.matisa.ch/en/matisa-testing_laboratory%20.php

Weighing wheel by wheel
EN 15654-2



Running behaviour
EN 14363 §7



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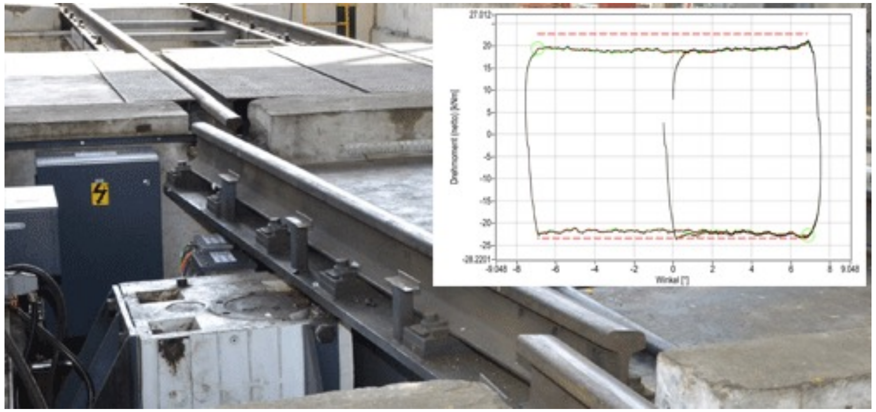
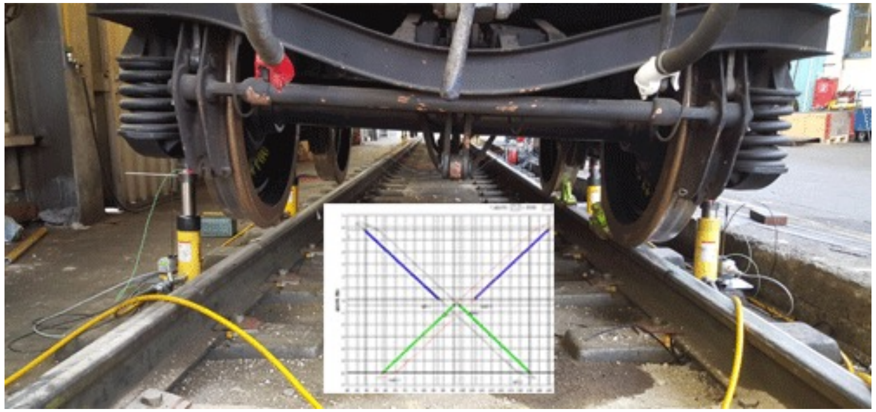
Website: https://www.matisa.ch/en/matisa-testing_laboratory%20.php

Resistance against bogie rotation
EN 14363 §6

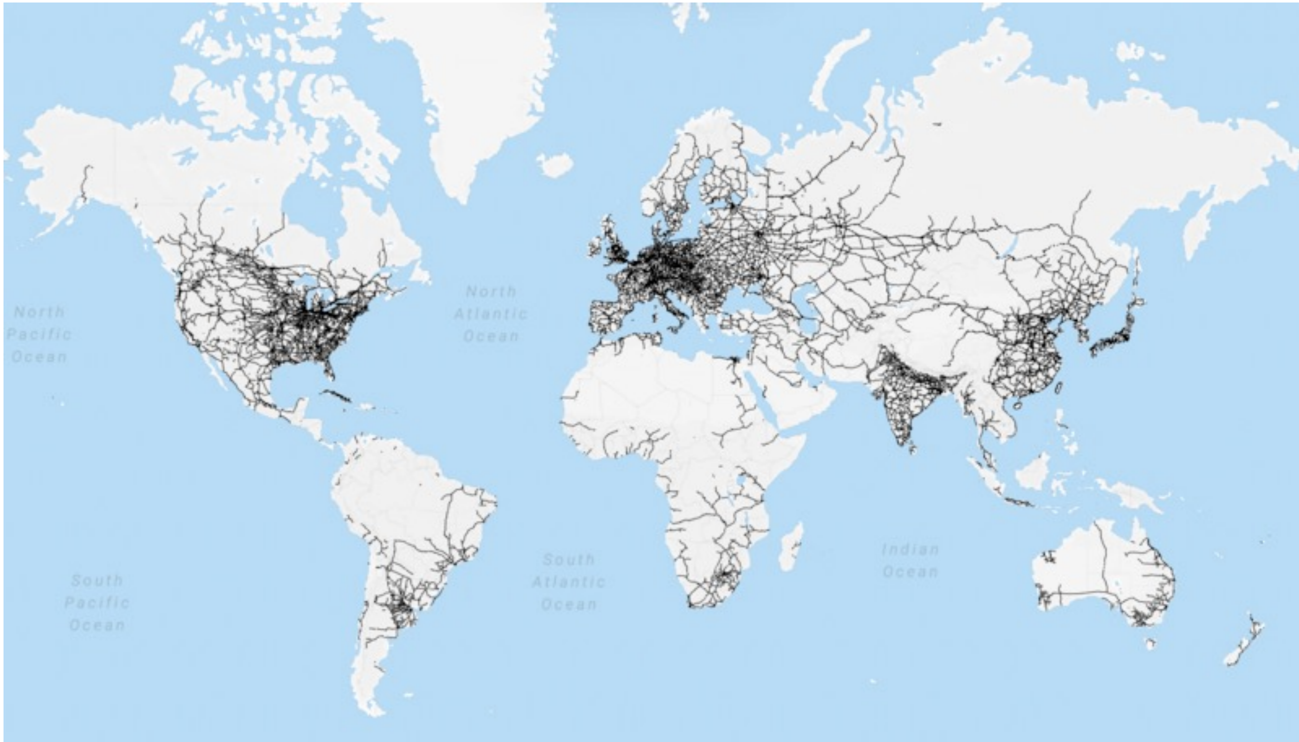


Safety against derailment on
twisted track - EN 14363 §6



Railway transport network

Country / Area	km
World	1,374,000
USA	220,000
China	159,000
EU-28	211,400
Switzerland	5,300



Modal transport volume

Passenger transport volume
EU-28 (2015)

Mode	Billion p-km	%
Sea	22	0.3
Road	5 388	81.6
Rail	544	8.2
Air	649	9.8
Total	**6 603**	**100.0**

eea.europa.eu

Freight transport volume
Worldwide (2015)

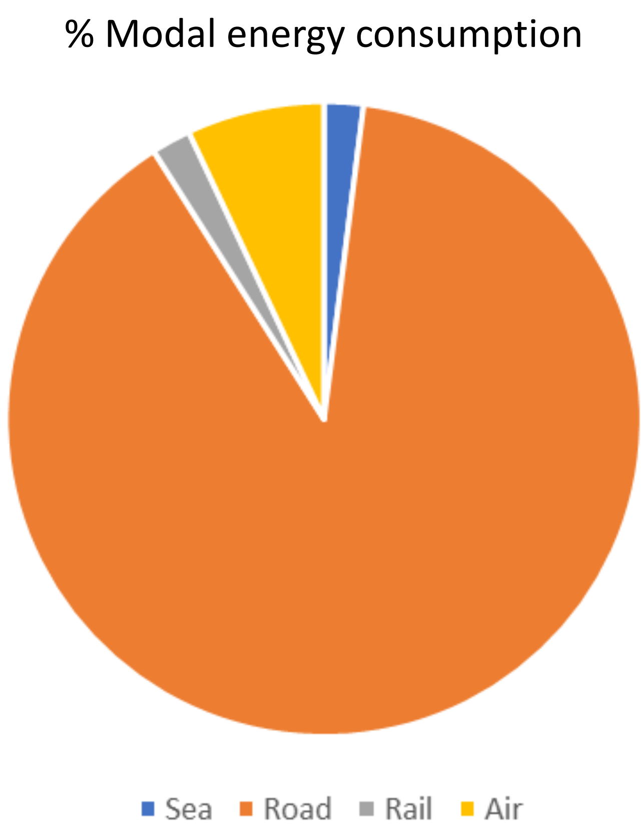
Mode	Trillion t-km	%
Sea	78.0	72.2
Road	19.8	18.3
Rail	10.0	9.3
Air	0.2	0.2
Total	**108.0**	**100.0**

"Global Freight Demand to Triple by 2050". The Maritime Executive. May 27, 2019

Modal transport energy consumption

Energy consumption in transport
IEA countries (2018)

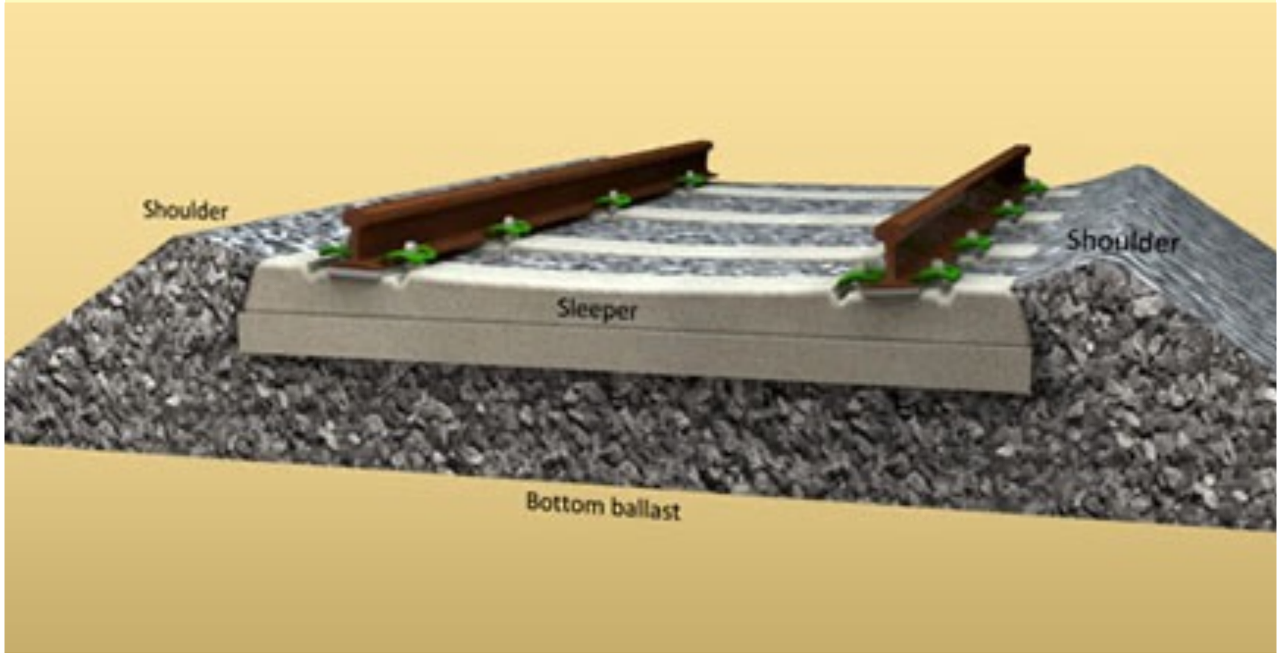
Mode	Trillion MJ	%
Sea	2.1	2.0
Road	93.9	89.0
Rail	2.1	2.0
Air	7.4	7.0
Total	**105.5**	**100.0**

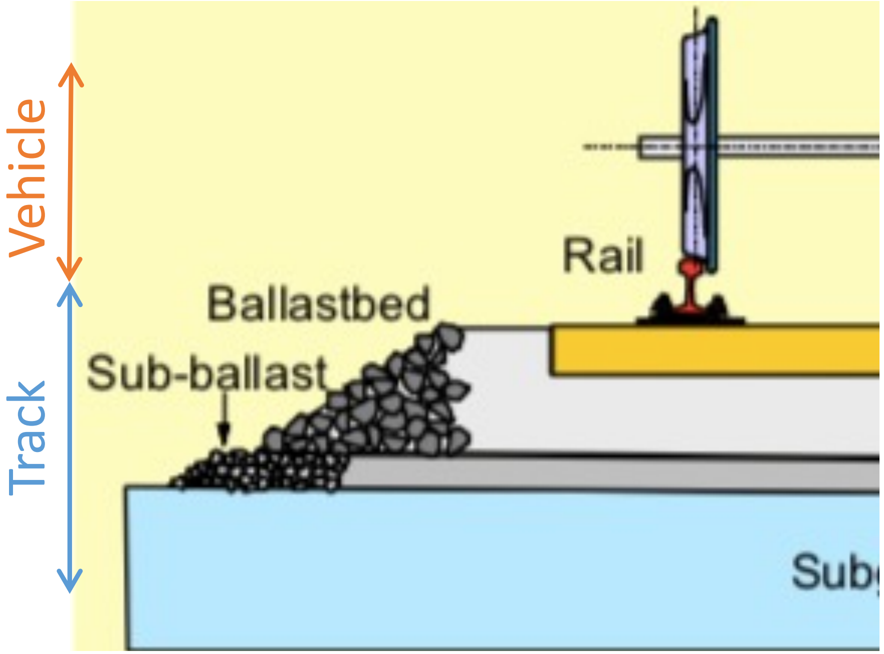


Why the rail transport system?

What does happen in the wheel-rail contact?

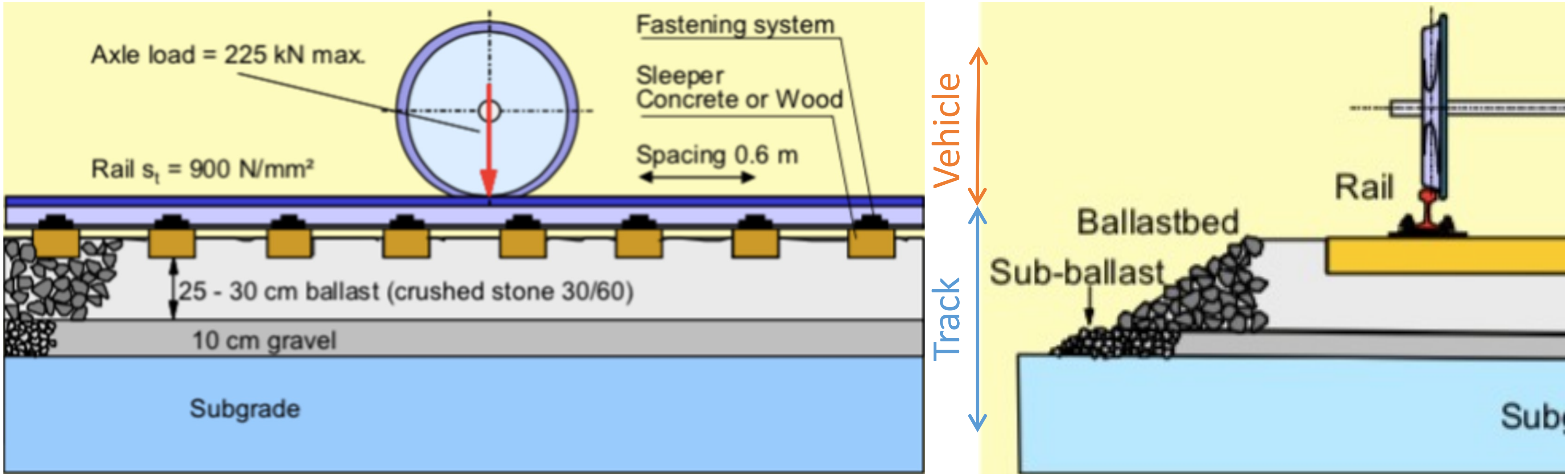
Railway (conventional) track structure and wheelset





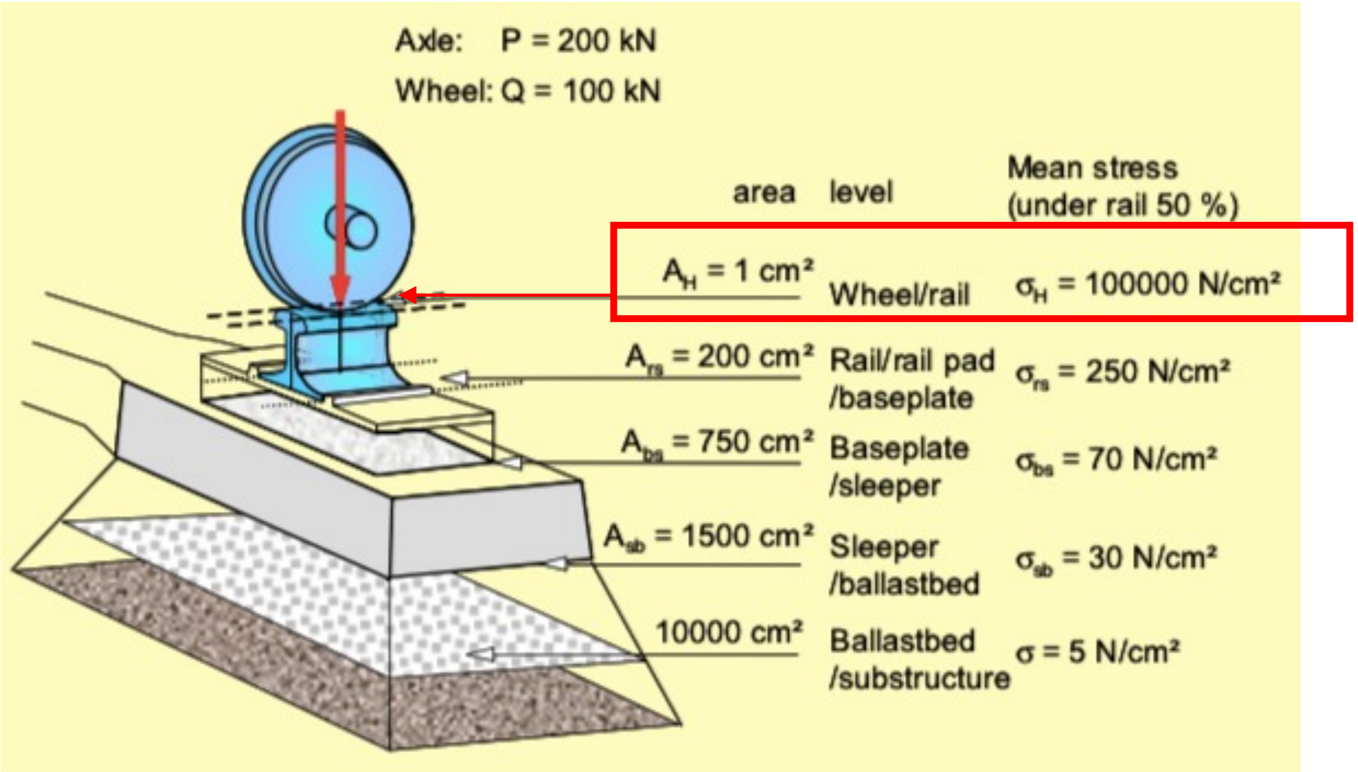
Esveld, C. (2001) Modern Railway Track.
2nd Edition, MRT-Productions

Railway (conventional) track structure and wheelset



Esveld, C. (2001) Modern Railway Track.
2nd Edition, MRT-Productions

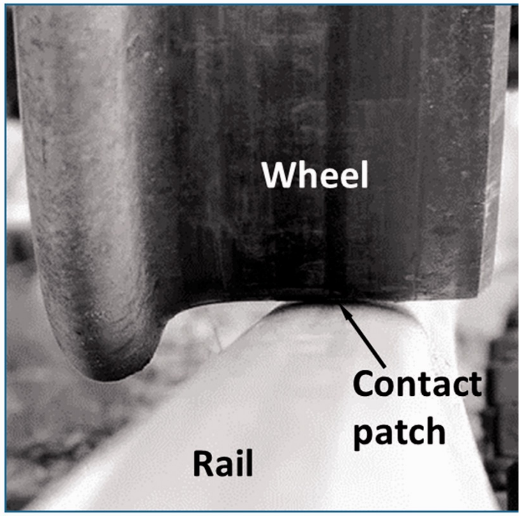
Load bearing function of the track (conventional)



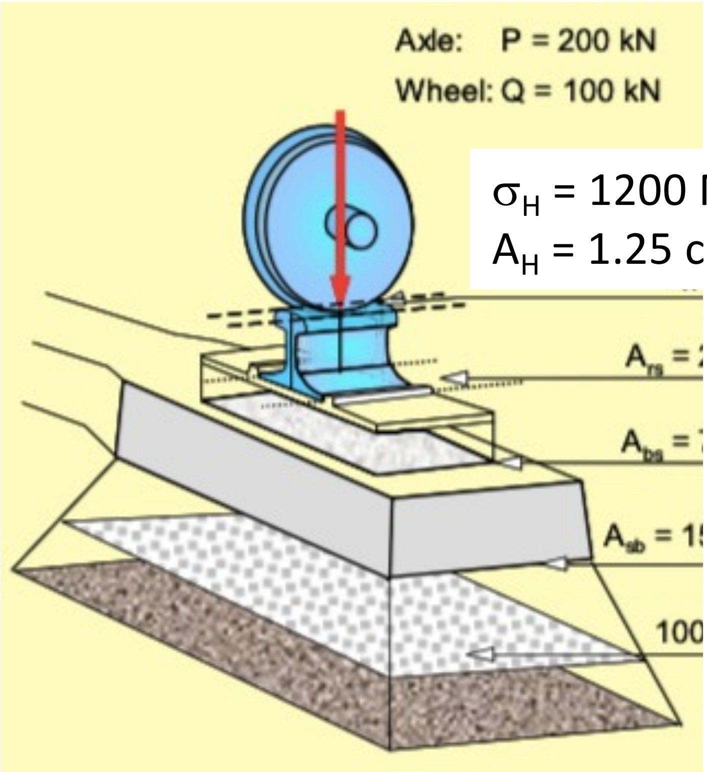
Esveld, C. (2001) Modern Railway Track.
2nd Edition, MRT-Productions

Rail transport advantages

- High Loads σ_H = 1000 MPa
- Low rolling friction (~0.0004)



Load bearing function of the track (conventional)



σ_H = 1200 MPa
A_H = 1.25 cm^2

Esveld, C. (2001) Modern Railway Track.
2nd Edition, MRT-Productions

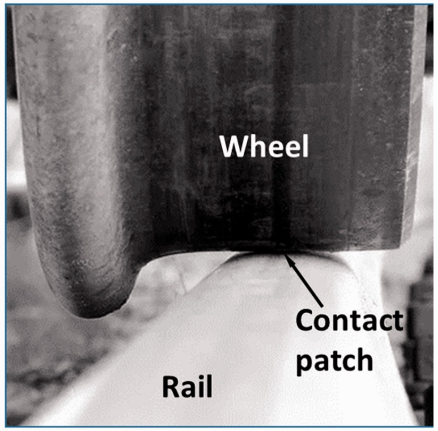
Wheel rail contact

Non-conformal contact

R_w = 500 mm (y) R_r = 300 mm (x)

Steel on steel E = 210 GPa ν = 0.3

Normal load F_n = 100 kN



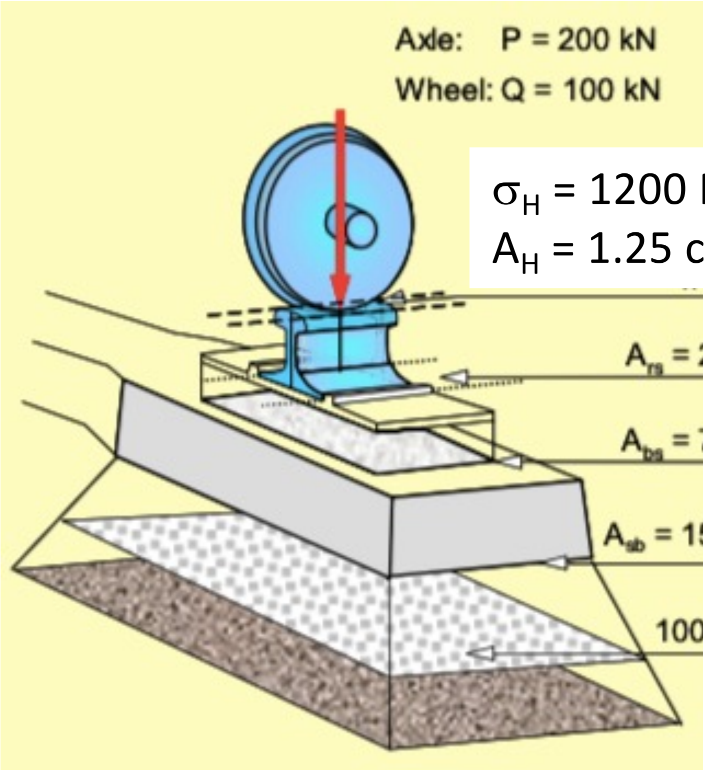
Hertz theory

E^* = 230.77 GPa R^* = 187.43 mm

Contact ellipse a / b = 7.557 / 5.282 mm

P_{avg} = 798 MPa / P_{max} = 1200 MPa

Load bearing function of the track (conventional)



σ_H = 1200 MPa
A_H = 1.25 cm^2

Esveld, C. (2001) Modern Railway Track.
2nd Edition, MRT-Productions

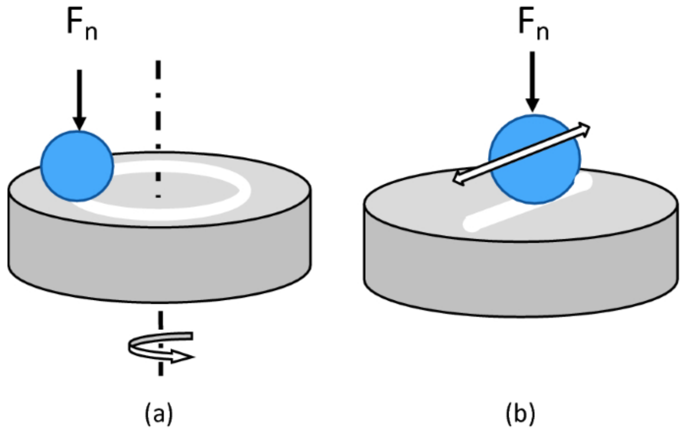
Laboratory setups

Ball on flat contact

Alumina ball ϕ = 3 mm

Steel sample

Normal load F_n = 5 N

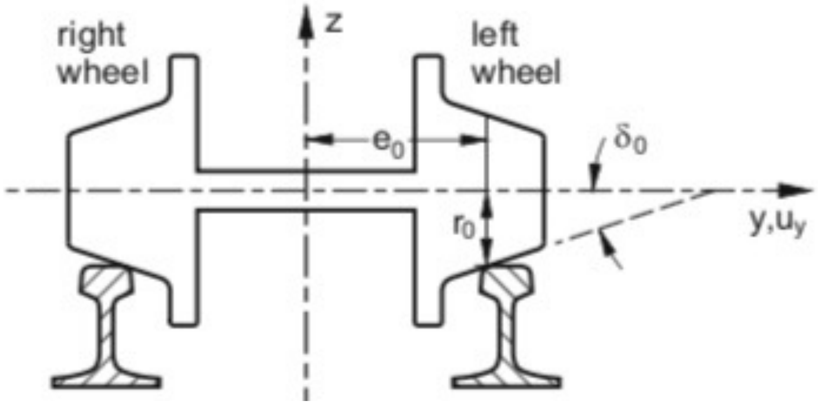


Hertz theory

Contact ellipse a,b = 0.0442 mm Area = 0.0061 mm2

P_{avg} = 816 MPa / P_{max} = 1225 MPa

Guiding function: Hunting motion

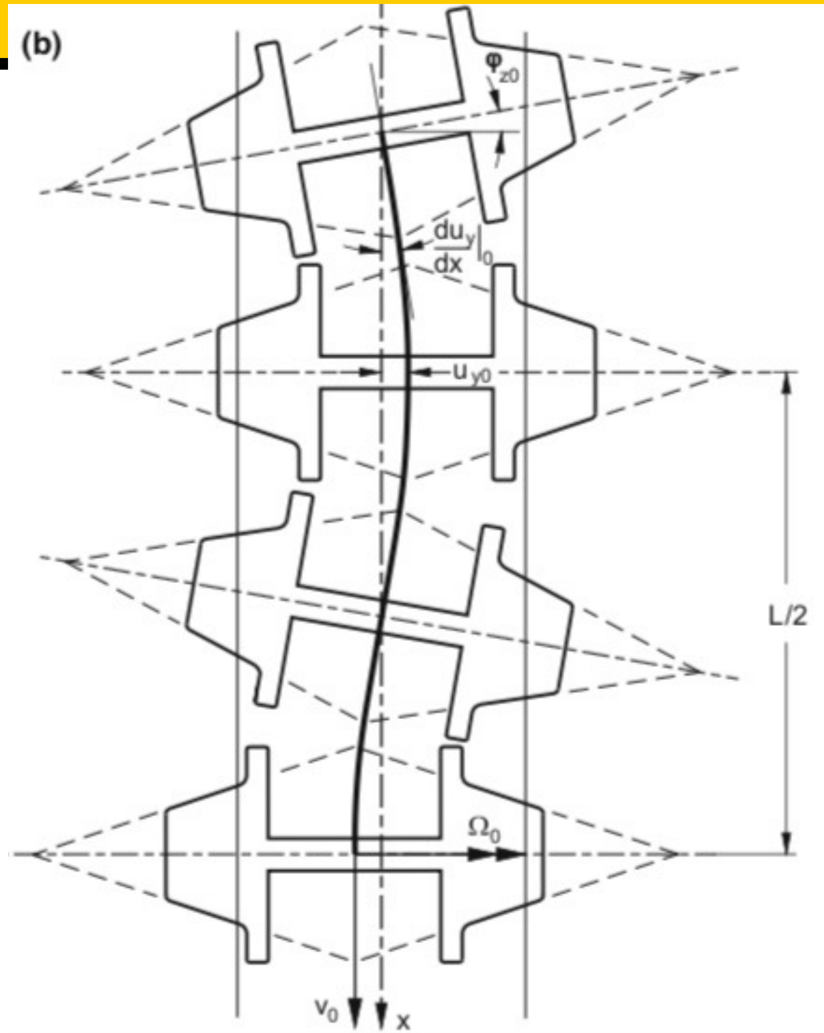


r_0 : rolling radius (nominal)
$2e_0$: contact points lateral distance
δ_0 : conicity (cone angle)

$$L = 2\pi\sqrt{\frac{e_0 r_0}{\delta_0}}$$

v_0 : wheelset longitudinal speed
Ω_0 : wheelset rotational speed

$$v_0 = \Omega_0 r_0 \qquad f = v_0/L$$



Videos
Guidance (2min) https://www.youtube.com/watch?v=vkzgcJGdUnA

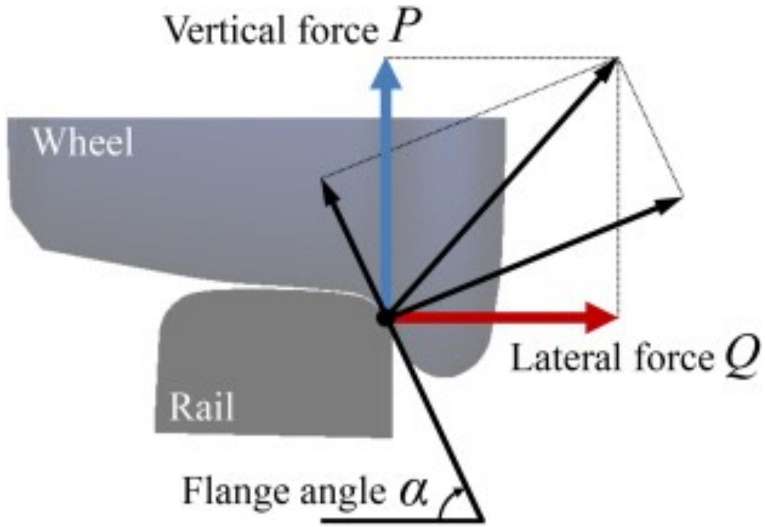
Knothe, K. (2017) "Rail Vehicle Dynamics"
Springer

Guiding function problems

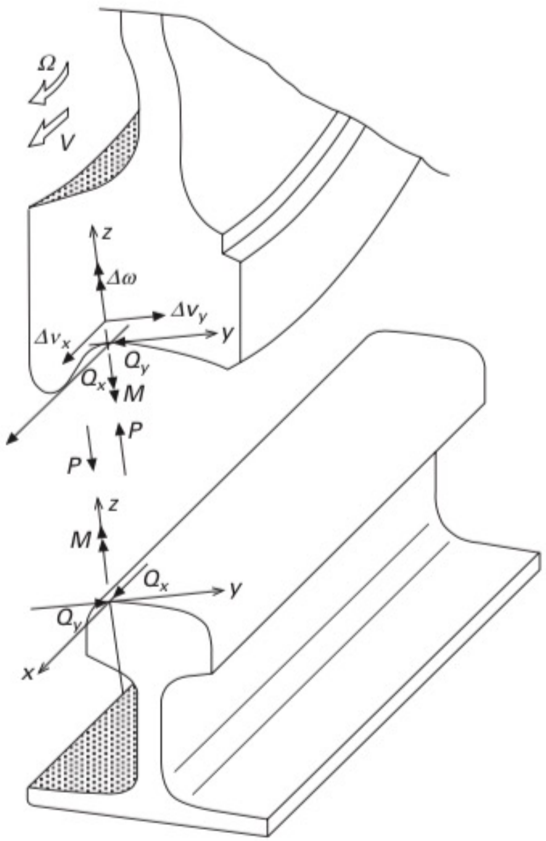
Instability

Track displacement after high-speed test of SNCF 1955

Flange-climb derailment



Wheel-rail contact parameters



Lewis, R. (2009) "Wheel-Rail Interaction Handbook" Elsevier

Running parameters

R = wheel rolling radius / rail radius
V = wheel travelling speed
Ω = wheel rotational speed
P = normal force

Contact forces

Q_x = longitudinal creep force T_ξ
Q_y = lateral creep force T_η
M = spin moment M_ζ

Δv_i = relative in-plane translation velocity between contacting bodies, $i \in \{x, y\}$
$\Delta\omega$ = relative rotation velocity between contacting bodies

Geometric and kinematic contact parameters

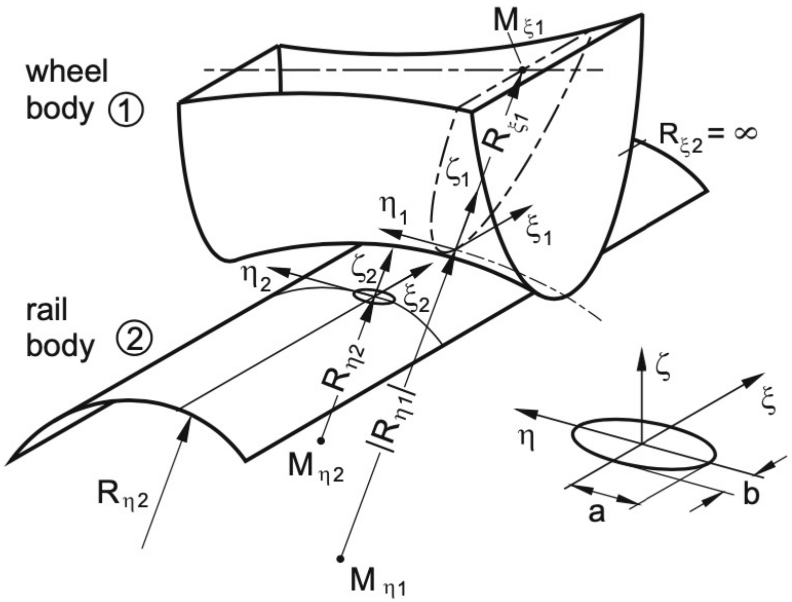
a = longitudinal contact ellipse semi-axis
b = lateral contact ellipse semi-axis
t = time
υ_x = longitudinal creep ratio ν_ξ
υ_y = lateral creep ratio ν_η
φ = spin ratio ν_ζ

Contact pressure distributions

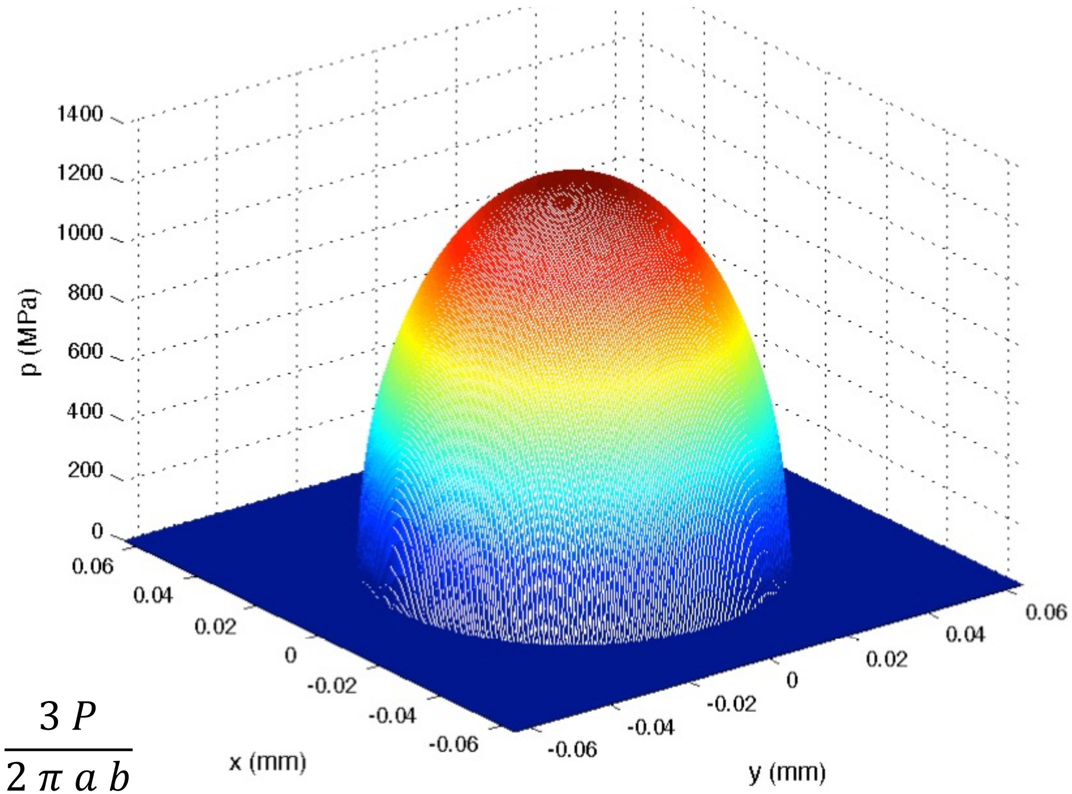
p = contact pressure
q_x = tangential stress component in longitudinal direction
q_y = tangential stress component in lateral direction

$\boxed{\mu = \text{coefficient of friction}}$
α = traction coefficient

Wheel-rail normal contact: Hetzian distribution



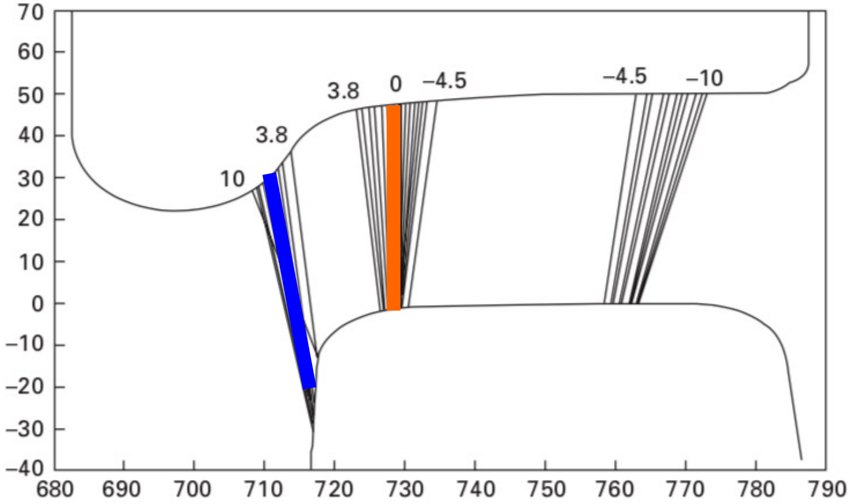
Contact pressure distribution p(x,y)

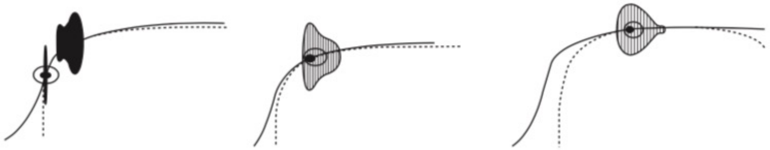


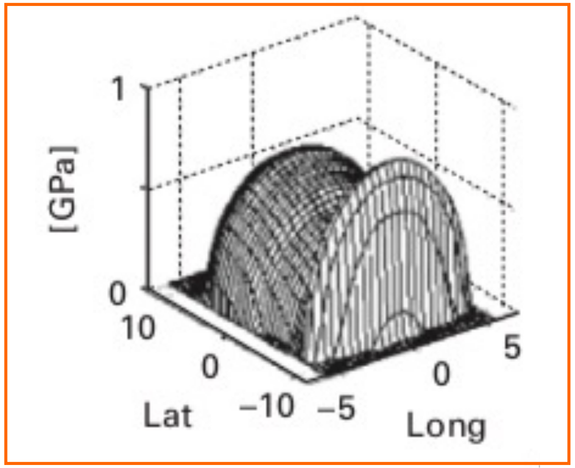
$$p_0 = \frac{3\,P}{2\,\pi\,a\,b}$$

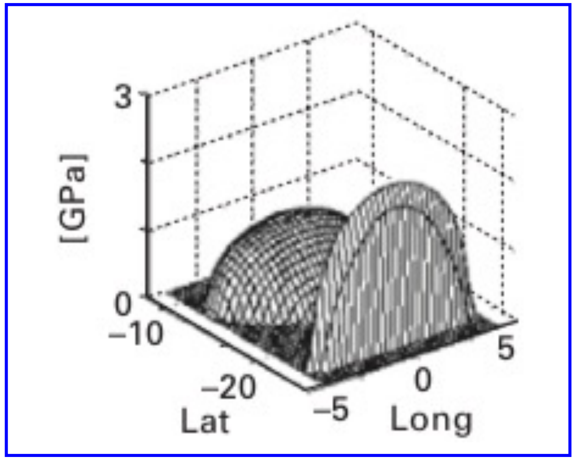
$$p(\xi,\eta) = p_0\sqrt{1-(\eta/a)^2-(\xi/b)^2}$$

Wheel-rail normal contact: non-Hertzian distributions



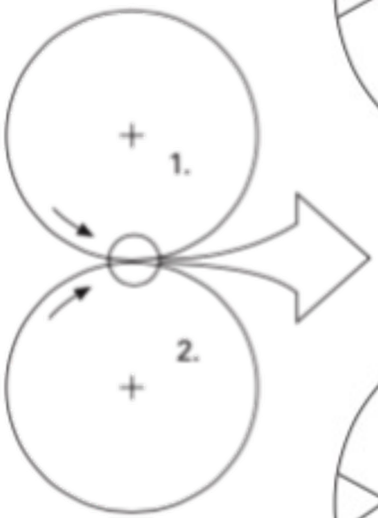


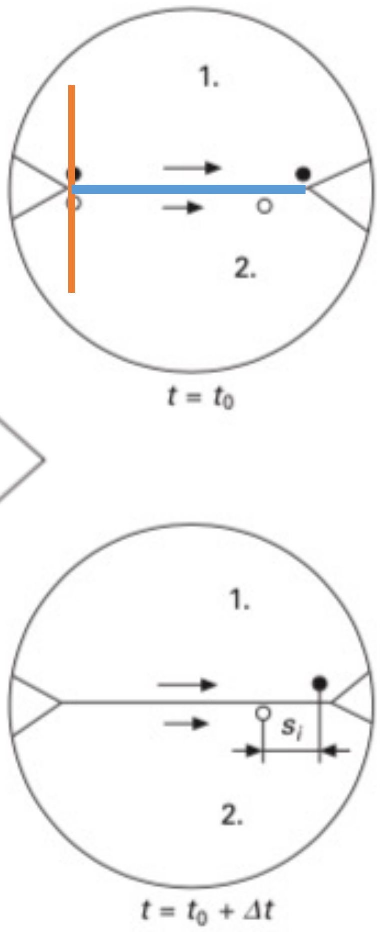




Lewis, R. (2009) "Wheel-Rail Interaction Handbook" Elsevier

Wheel-rail tangential contact: slip, creep and adhesion





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2D problem
Tangential distribution

$$q_1(\xi) = \frac{\mu\, p_0}{a}\sqrt{a^2 - \xi^2}$$

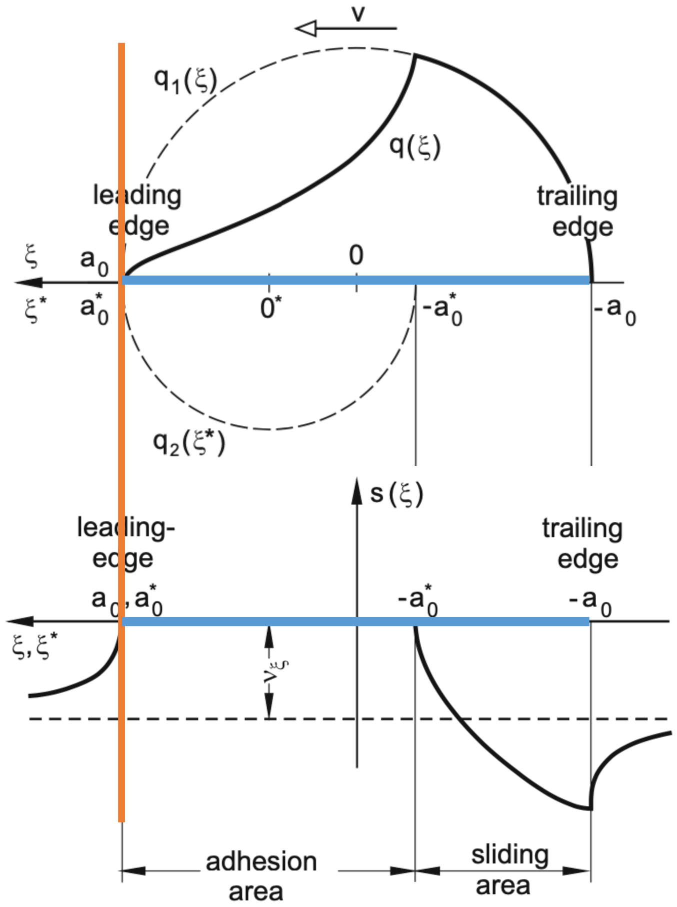
$$q_2(\xi^*) = -\frac{\mu\, p_0}{a^*}\sqrt{{a^*}^2 - {\xi^*}^2}$$

slip s

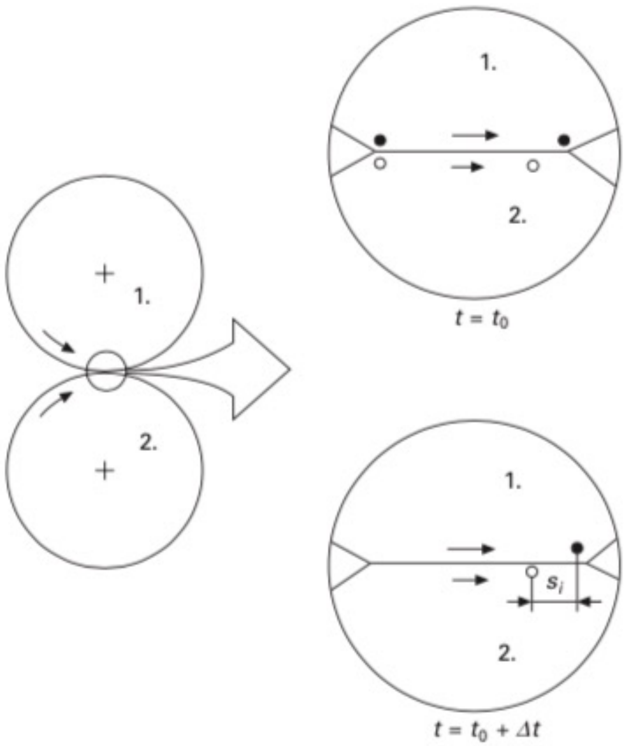
creep $v_x = (s/\Delta t)/V$

Local creepage

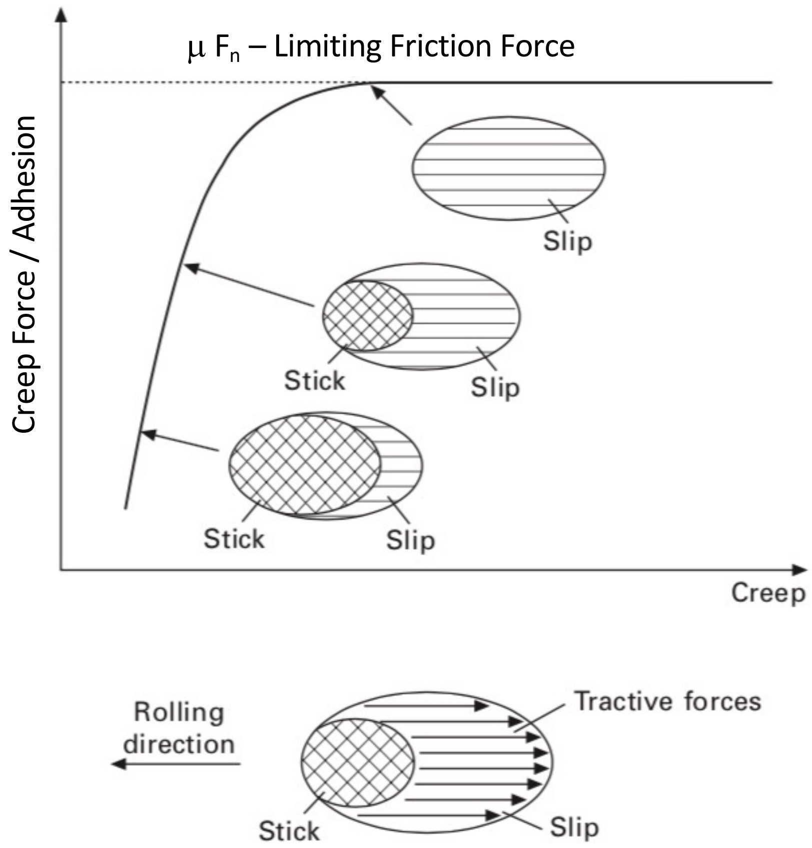
Carter (1926) Proc.R. Soc. L. A 112



Wheel-rail tangential contact: slip, creep and adhesion



Slip	s
Creep	$v_x = (s/\Delta t)/V$
Creep force	Q_x
Adhesion	$\alpha = Q_x/F_n$



Creep influence in wheel-rail contact conditions

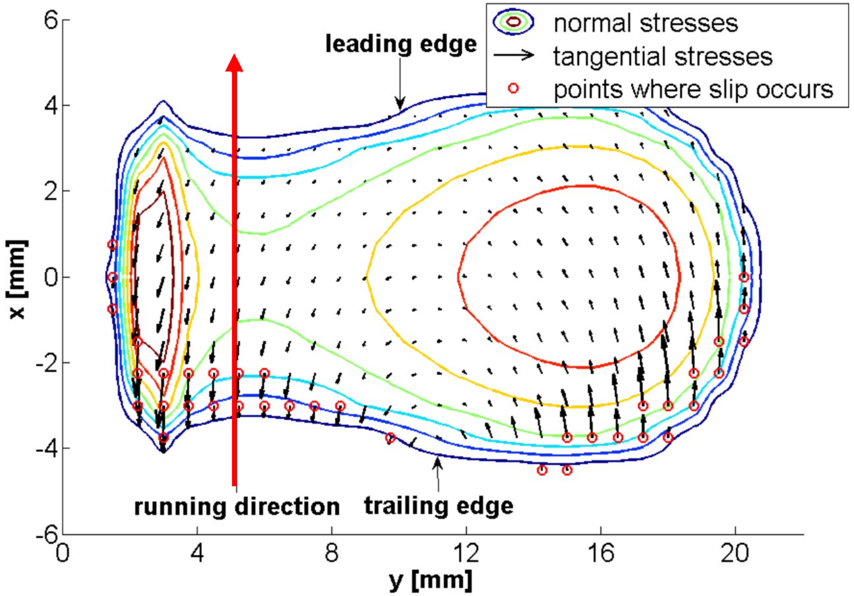
Types of creep:

1) Longitudinal creepage (ν_ξ): spinning and skidding in running direction
2) Lateral creepage (ν_η): the angle of attack or skew
3) Spin creepage (ν_ζ): the contact plane inclination and steering

3D tangential contact

$$\left\{\begin{matrix} T_\xi \\ T_\eta \\ M_\zeta \end{matrix}\right\}_{\text{lin}} = Gab \begin{bmatrix} C_{11} & 0 & 0 \\ 0 & C_{22} & \sqrt{ab}\, C_{23} \\ 0 & -\sqrt{ab}\, C_{23} & ab\, C_{33} \end{bmatrix} \left\{\begin{matrix} \nu_\xi \\ \nu_\eta \\ \nu_\zeta \end{matrix}\right\}.$$

$T_{\xi,\eta}, M_\zeta$: Creep forces
C_{ij} : Kalker's coefficients
$\nu_{\xi,\eta,\zeta}$: Creepages



Railway steel on steel contacts:

- Free running (no creep) → small rolling resistance
- Creep motion → higher friction

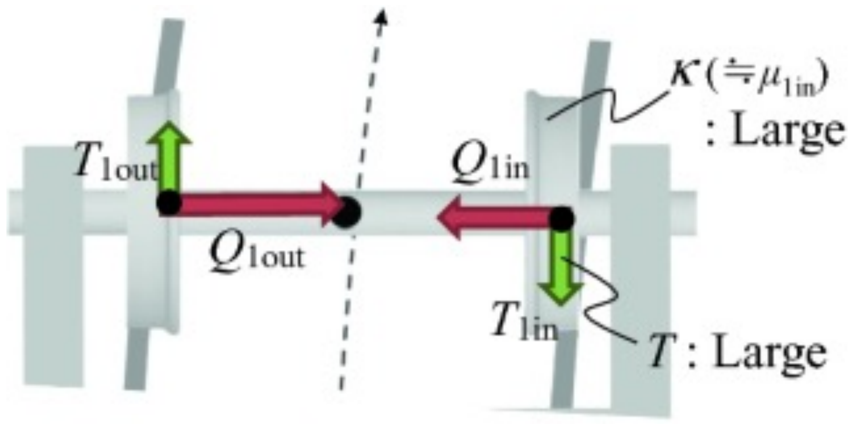
Key role of creep forces in vehicle-track interaction

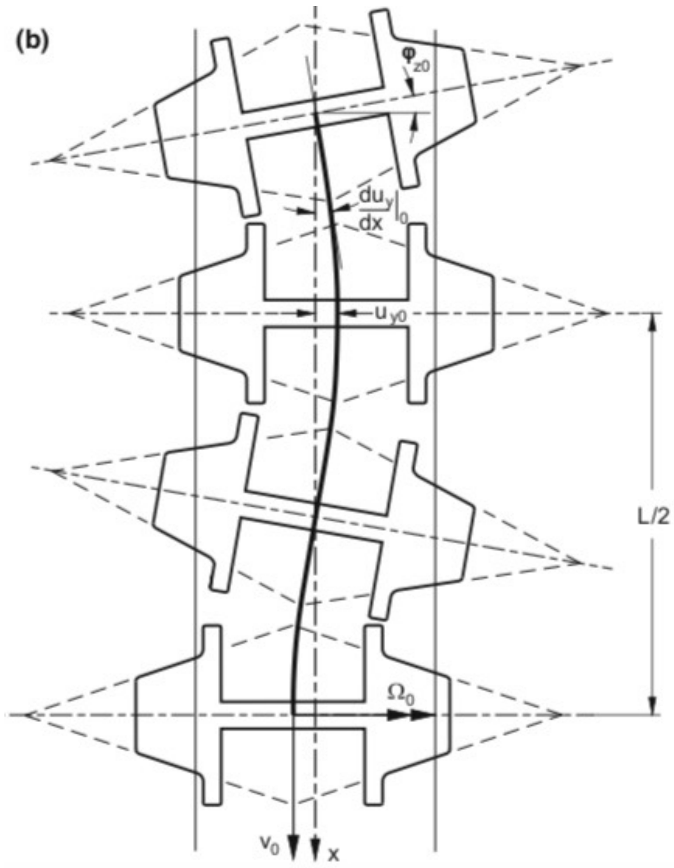
- Traction and braking
- Stability (hunting), oscillation behavior
- Safety against derailment, wheel-rail forces, track loading in curves
- Wear
- Rolling contact fatigue (RCF)
- Squeal noise

Key role of creep forces in vehicle-track interaction

Pure rolling

- Stability (hunting), oscillation behavior





Creep forces

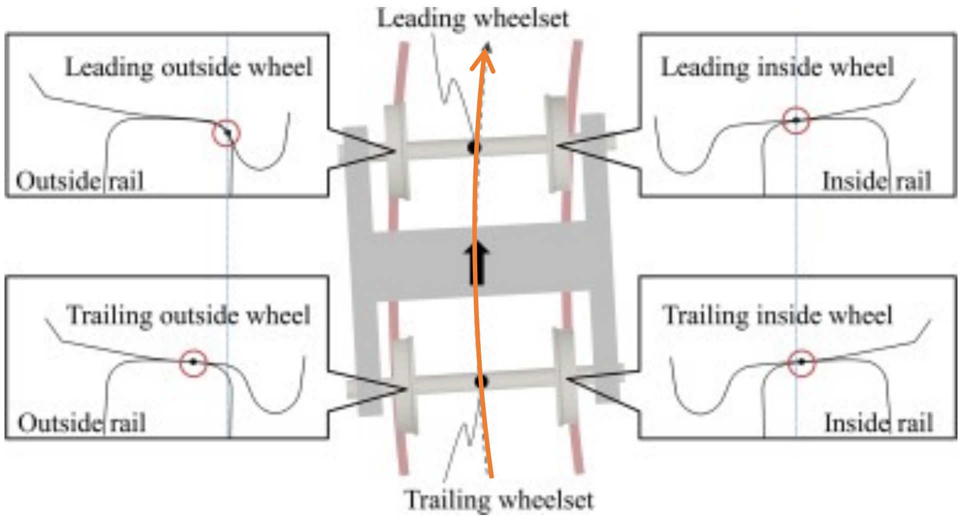
$T = T_\xi$

$Q = T_\eta$

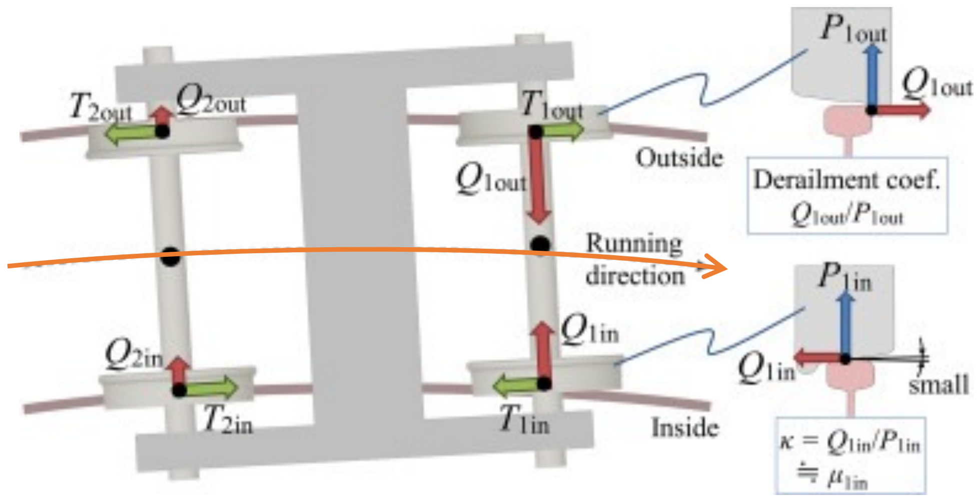
$$\begin{Bmatrix} T_\xi \\ T_\eta \\ M_\zeta \end{Bmatrix}_{\mathrm{lin}} = Gab \begin{bmatrix} C_{11} & 0 & 0 \\ 0 & C_{22} & \sqrt{ab}\, C_{23} \\ 0 & -\sqrt{ab}\, C_{23} & ab\, C_{33} \end{bmatrix} \begin{Bmatrix} \nu_\xi \\ \nu_\eta \\ \nu_\zeta \end{Bmatrix}.$$

Key role of creep forces in vehicle-track interaction

- Safety against derailment, wheel-rail forces, track loading in curves



Contact points



Creep forces

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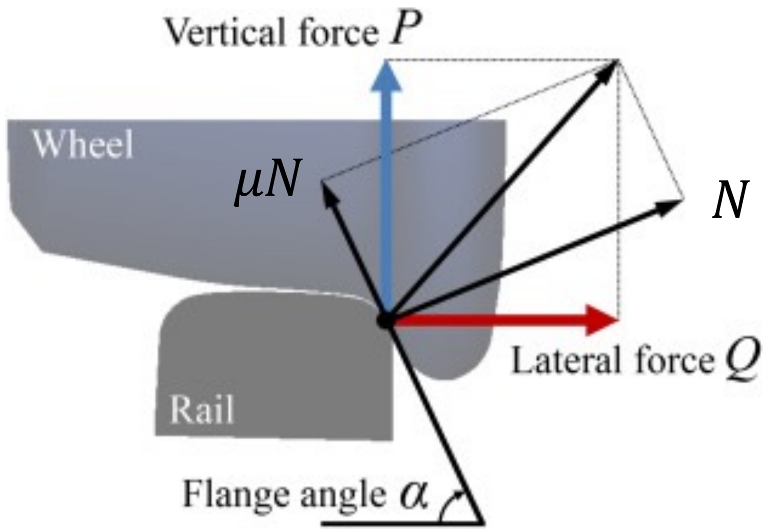
Key role of creep forces in vehicle-track interaction

- Safety against derailment, wheel-rail forces, track loading in curves



μ coefficient of friction

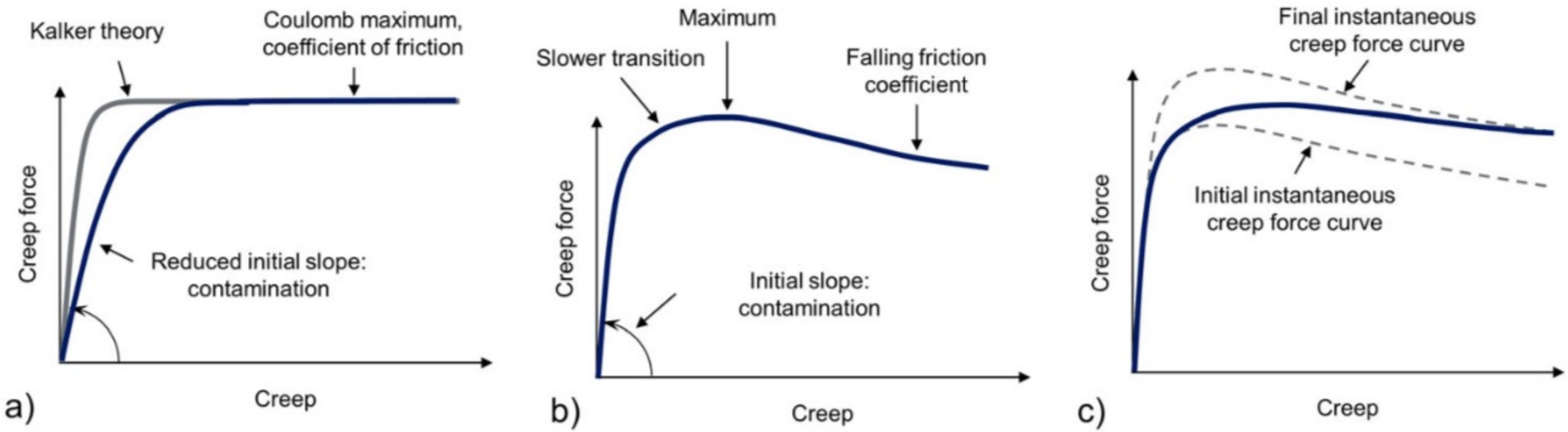
Nadal's criteria

$$\frac{Q}{P} = \frac{\tan\alpha - \mu}{1 + \mu\tan\alpha} \leq 1.2$$

$$Q = N\,sin\,\alpha - \mu N\,cos\,\alpha$$
$$P = N\,cos\,\alpha + \mu N\,sin\,\alpha$$

Nadal, M.J. (1908)

Adhesion-creep behavior



Coulomb friction

Steady surface conditions

Transient surface conditions

Vollebregt, E. (2021) VSD 59 (7)

Coefficient of friction

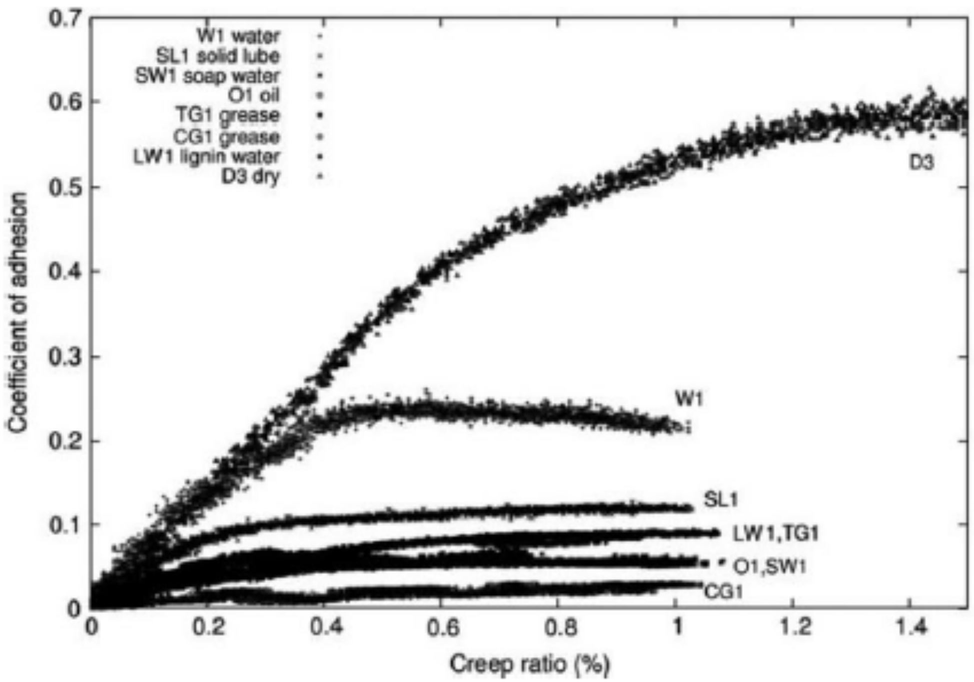
Environmental conditions

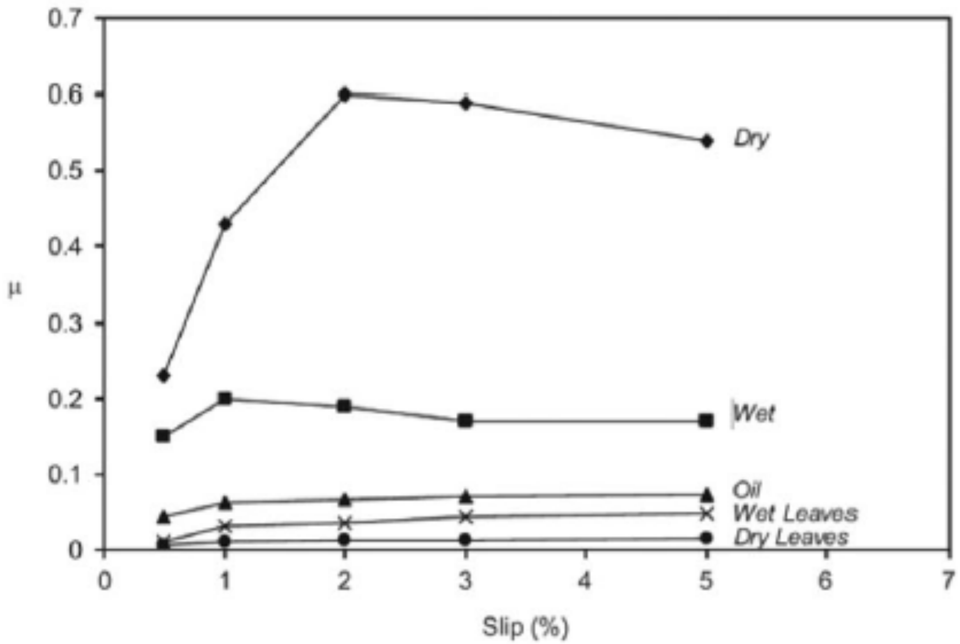
• Humidity	0.55 (10 %HR) - 0.3 (100 %HR)	Beagley, TM. et al. (1975) Wear 33
• Clean/Oil contamination	0.7 → 0.15	Beagley, TM. et al. (1975) Wear 31
• Temperature	0.5 (20°C) – 0.4 (30°C) – 0.25 (50°C)	Baek, K. et al. (2008) Wear 265

Standards

• EN 14363	0.36 (dynamic simulations)	0.49 (flange climbing)	
• USA	0.5 (flange climbing)		
• Japan	0.7 (accident measurement)		Matsumoto, A. et al. (2012) VSD 50

Creep forces and contamination

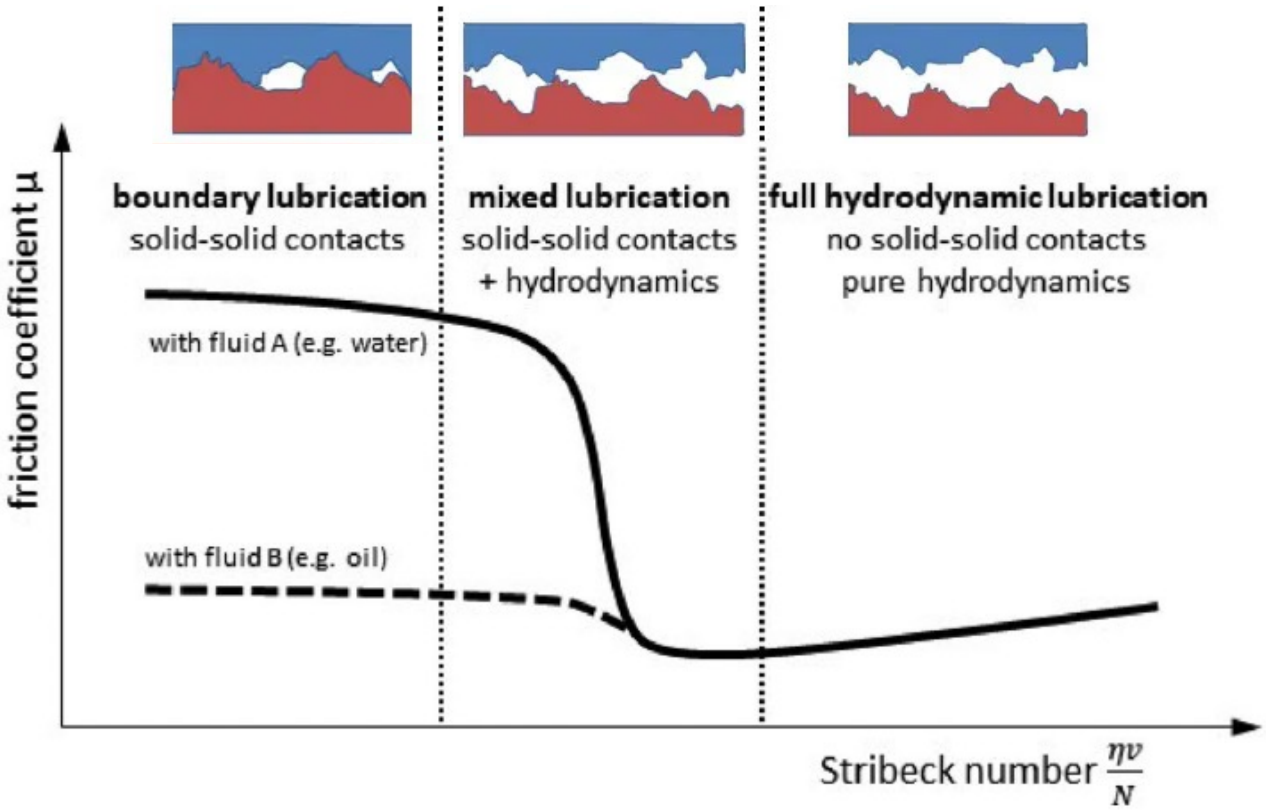




Vollebregt, E. (2021) VSD 59 (7) 1026

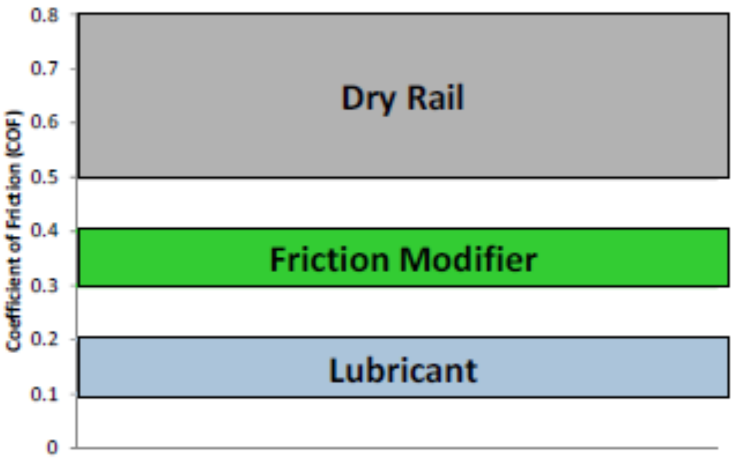
- Temperature
- Interfacial solid layers
- Fluids (water, oil, mixtures)

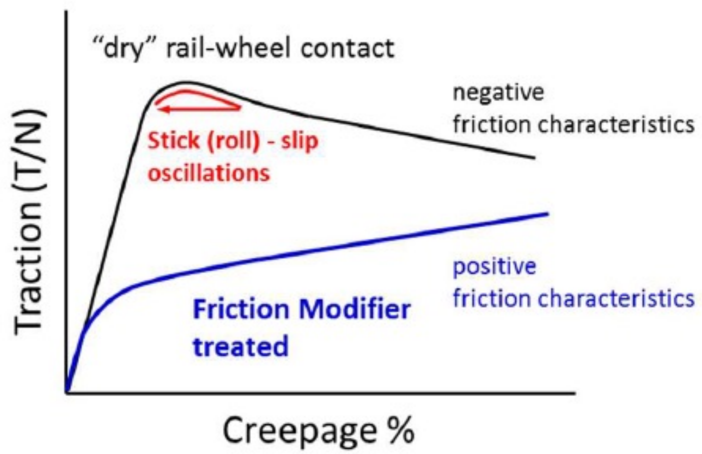
Coefficient of friction in fluid lubrication



Friction modifiers (FM)

- An additive that modifies the frictional properties of a lubricant.
- Goal: to provide one intermediate friction level and/or hold friction constant over a range conditions.

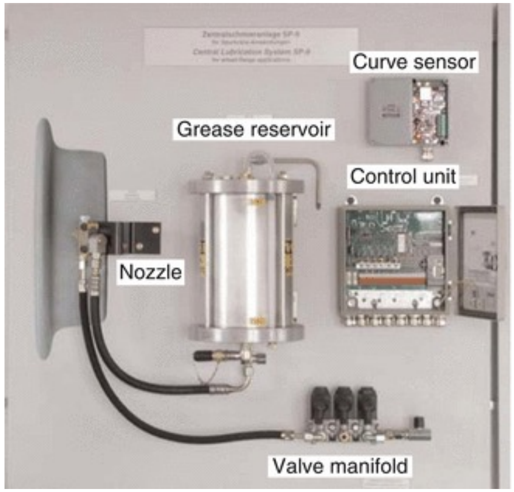




Friction management practices: FM classification

Wheel flange and rail gauge face and gauge corner

- Aim: to **reduce friction →** to reduce wear, damage, etc.
- Practice: wheel flange lubrication systems (on vehicle side) or wayside lubrication systems (on track side)



Friction management practices: FM classification

Wheel tread and top of the rail

Reduce friction

- Top of Rail Friction Modifiers (ToR-FM) μ : 0.5-0.7 → 0.3-0.4
- Aim: to reduce wear, damage, noise, energy consumption, etc.
- Attention: not to reduce the coefficient of friction to very small values → Braking and traction SAFETY

Increase friction

- Adhesion or traction enhancers (sands and traction gels)
- Aim: to mitigate low adhesion and restore friction → Braking and traction SAFETY

Friction modifiers drawback: liquid crack interaction

Test conditions: twin disc instrument at 1.5 GPa, 1% creep and 400 rpm

Studied cases:

(1) dry after 4,000 cycles;

(2) dry after 25,000 cycles;

(3) water after 25,000 cycles;

(4) TOR-FM after 25,000 cycles;

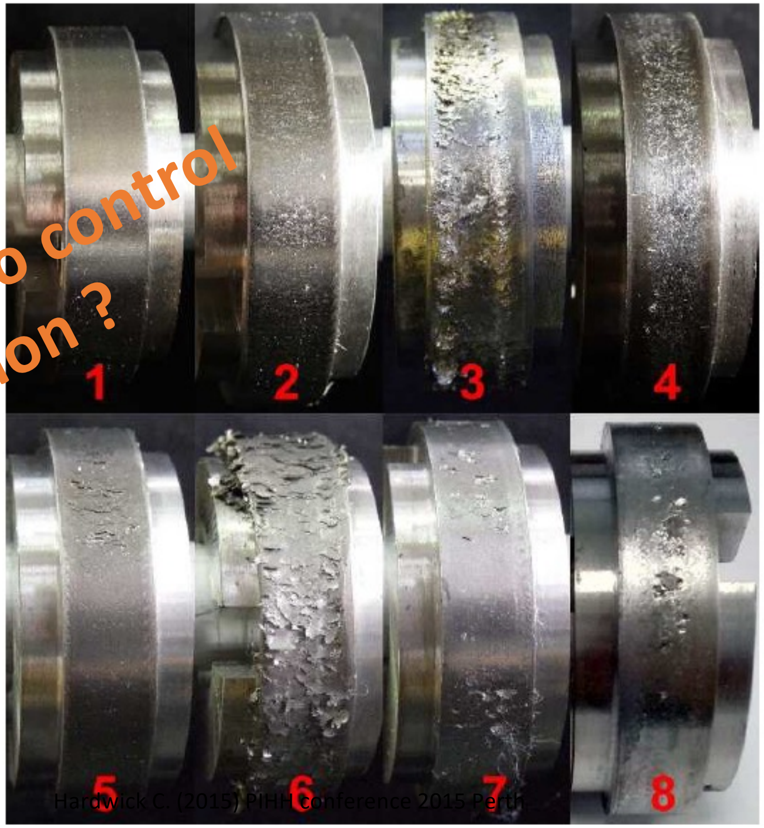
(5) GF lubricant after 25,000 cycles;

(6) TOR lubricant (oil) after 25,000 cycles;

(7) TOR lubricant (grease) after 25,000 cycles;

(8) TOR hybrid after 25,000.

Is still a good idea to control contact friction ?



Hardwick C. (2015) PIHH conference 2015 Perth

Friction control in wheel-rail contacts

THANK YOU FOR YOUR ATTENTION

Alejandro Roda

Head Accredited Laboratory HOM

25.11.2024