Recent developments w.r.t. CONTACT

Part I – background & review

Edwin Vollebregt

VORTECH CMCC
CONTACT MECHANICS COMPUTING AND CONSULTING

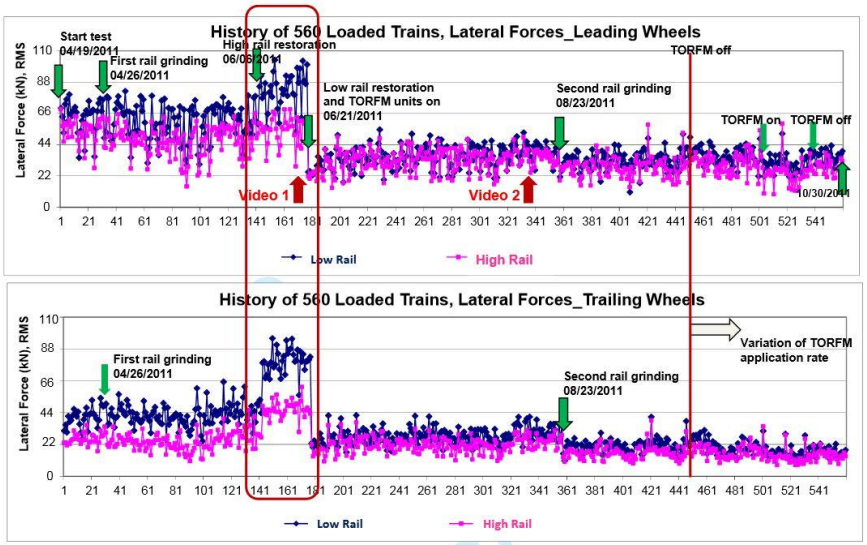
10th International Conference on Contact Mechanics
August 30, 2015 - September 3, 2015 | Colorado Springs, Colorado, USA

Recent developments w.r.t. CONTACT

Part I – Background and extensive review

Part II – Conformal contact analysis

Part III – Non-steady contact: the rocking phenomenon



(Wu & Kerchof, 2014)

(Kerchof, 2013)

Importance of wheel-rail contact forces

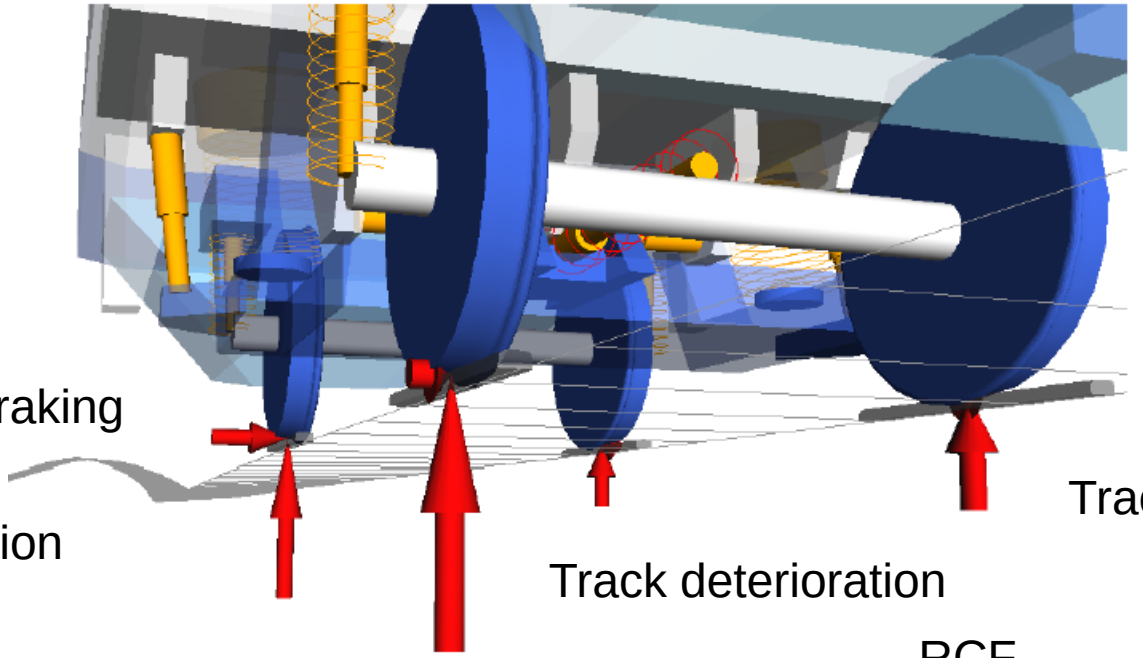
Curving behavior

Flange climb

Hunting motion

Dynamic amplification

Ride quality



Track-shifting forces

Traction and braking

Wheel flats

Track friendliness

Low adhesion

Track deterioration

Crack initiation

RCF

Switches & crossings

Crack growth

Corrugation

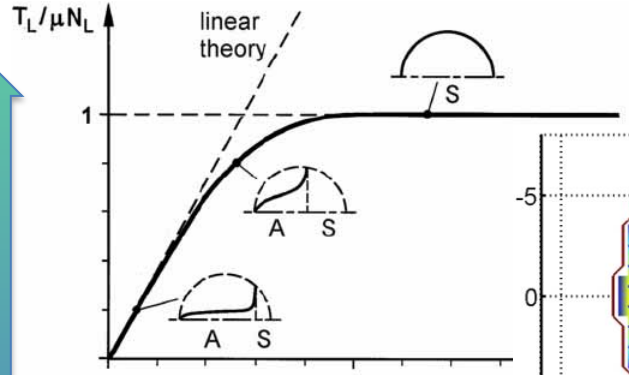
Wear

(picture: Ch. Weidemann)

Multi-body simulation + boundary elements

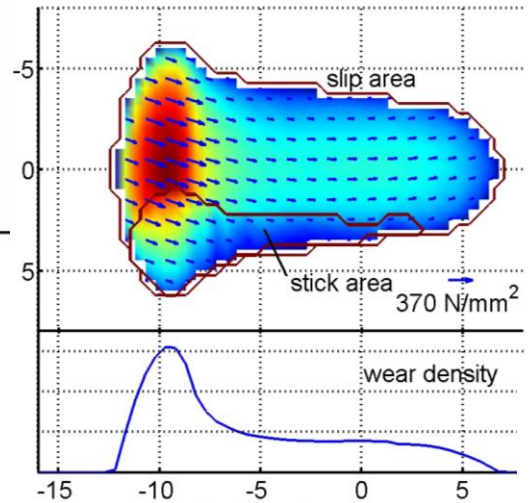
Fast

Slow

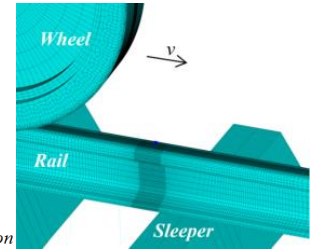


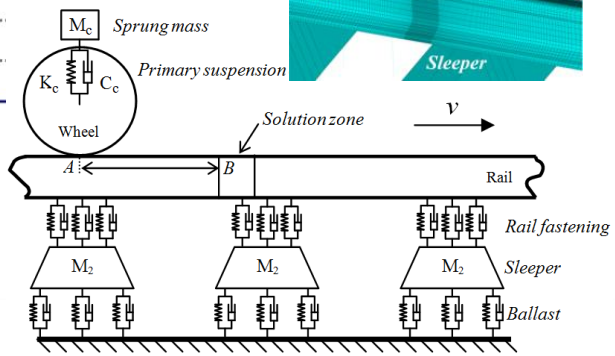
Simplified algorithms

CONTACT: BEM



LS-Dyna: FEM





(Zhao & Li, 2011)

Rough

Detailed

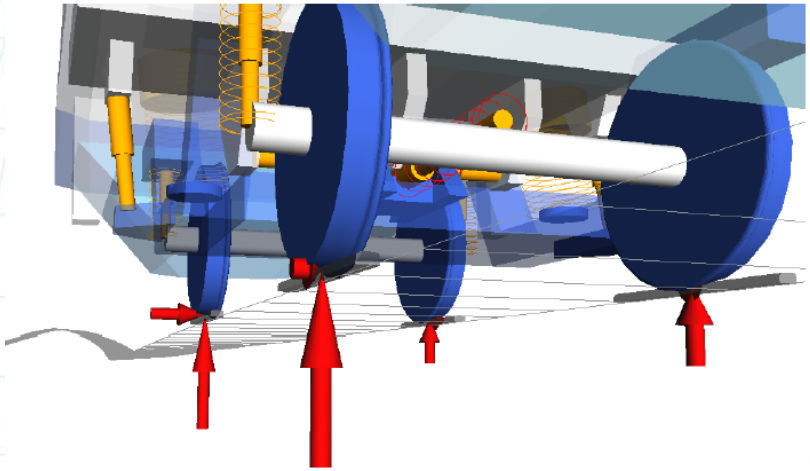
A quick overview of w/r contact analysis

Vehicle dynamics doesn't care about

- Size & shape of contact area
- Stress distribution
- Maximum pressure, etc.

Must know

- Total forces, moments
- Location of the forces



Schematizing the contact forces

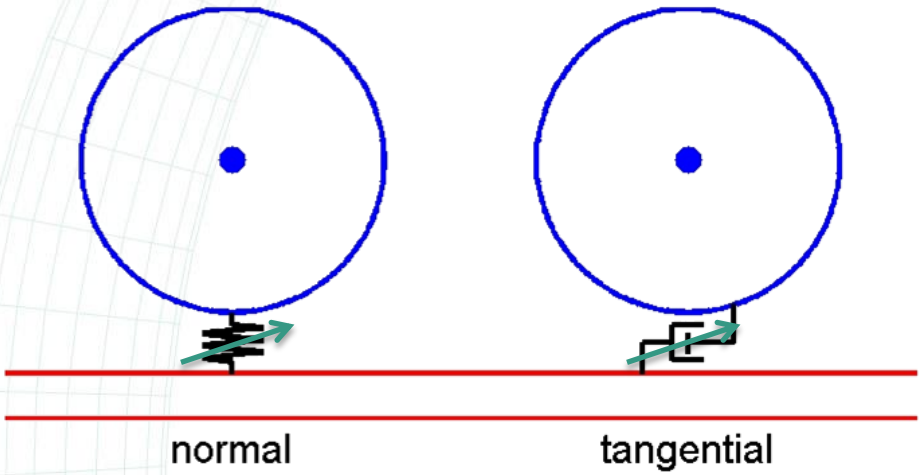
The contact spring is strongly anisotropic:

Normal contact

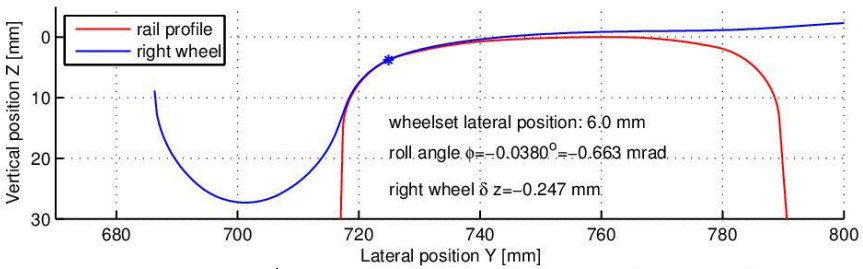
- Responds to position, approach, interpenetration
- Sensitive to geometry

Tangential contact

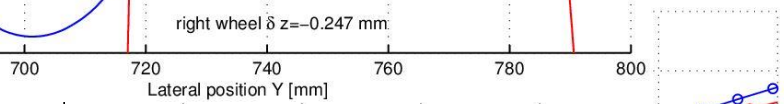
- Responds to velocity, slip, creepage
- Sensitive to friction parameters

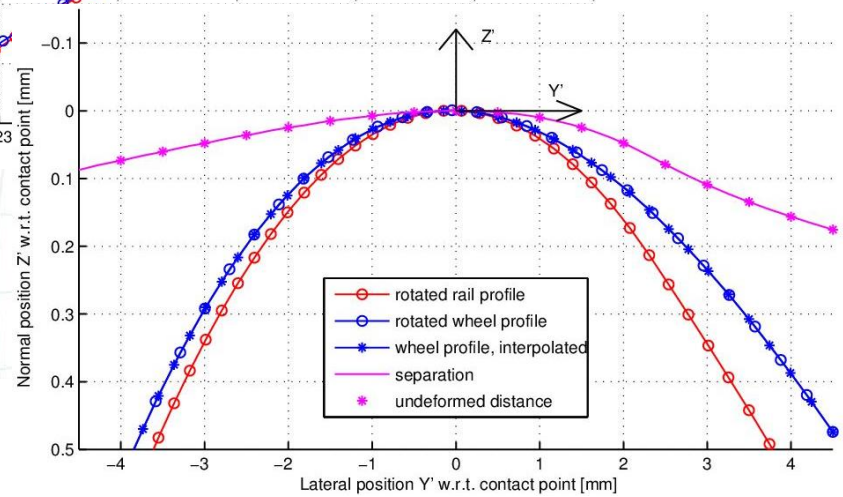


Dealing with anisotropy



1. Find the initial contact point
2. Determine the contact angle
3. Compute forces in local coordinates.



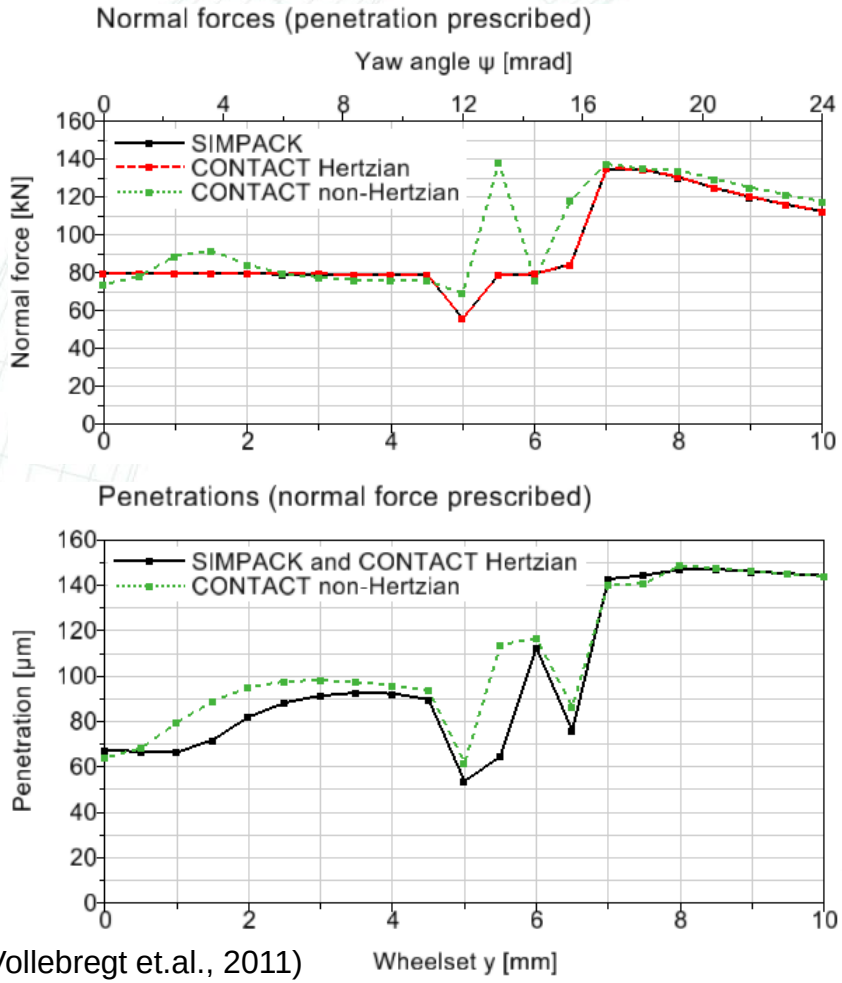


Deals with normal and tangential contact separately.

Normal contact algorithms

1. Winkler approach
2. Hertz theory
3. Multi-Hertzian – equivalent ellipse
4. Semi-Hertzian – STRIPES
5. Linear elasticity theory, half-space
6. Linear elasticity theory, conformal
7. Finite elements

Effective “spring stiffness” may differ 20 – 100 %.



(Vollebregt et.al., 2011)

Normal contact algorithms

Simplified theories

1. ~~Winkler approach~~
2. Hertz theory
3. Multi-Hertzian – equivalent ellipse
4. Semi-Hertzian – STRIPES
5. Linear elasticity theory, half-space
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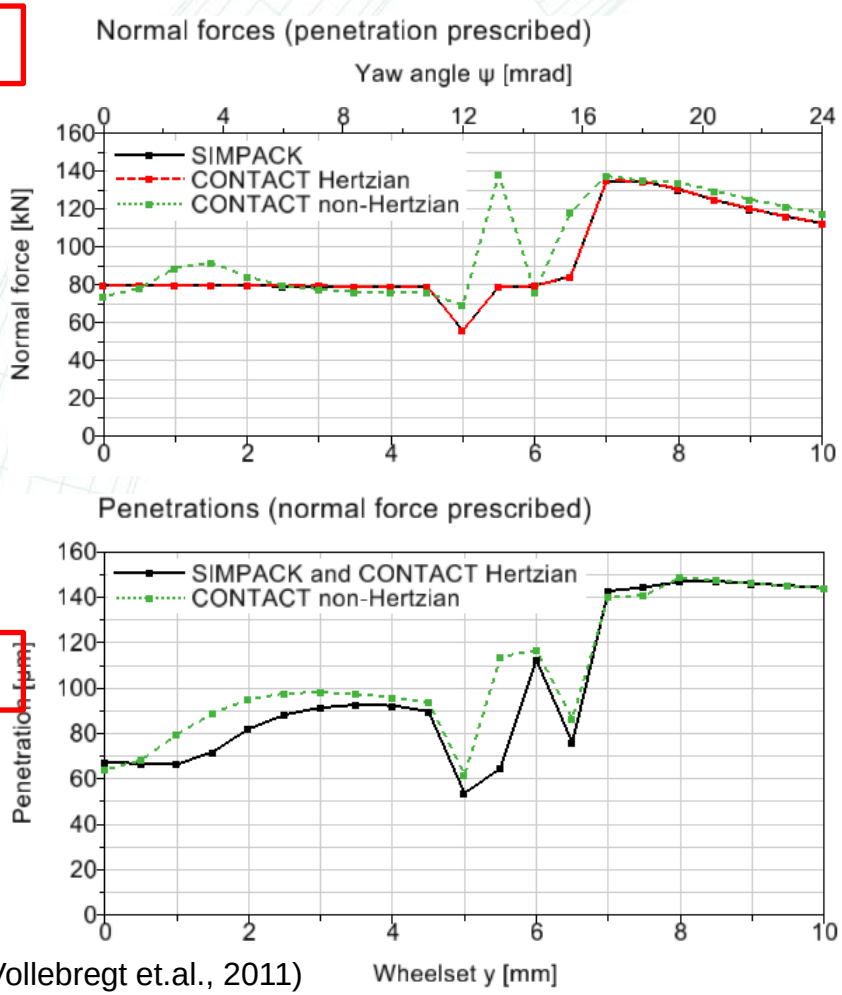
7. Finite elements

Non-Hertzian theories

Effective “spring stiffness” may differ 20 – 100 %.

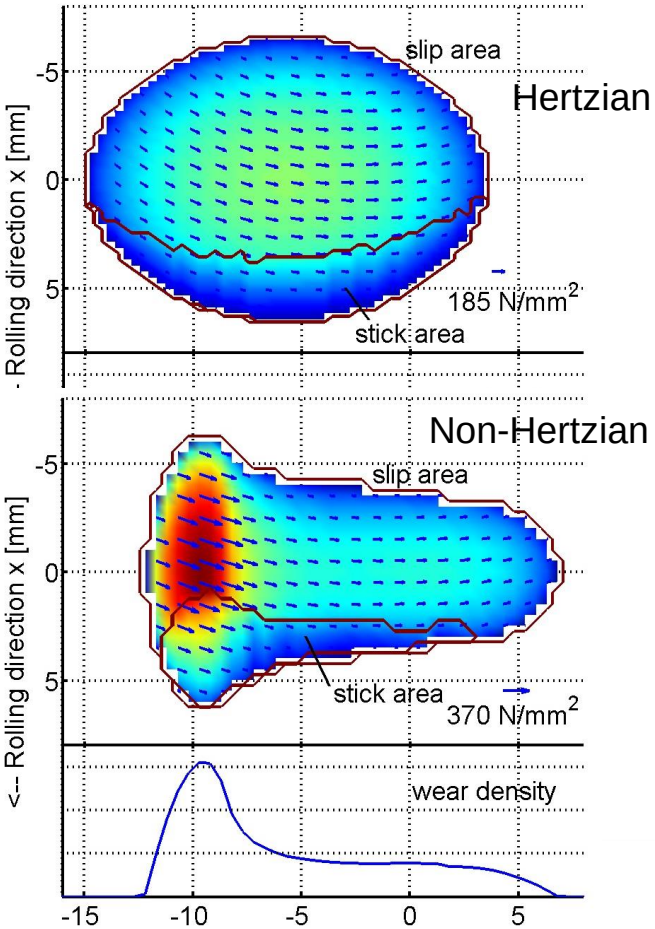


(Vollebregt et.al., 2011)

Tangential contact algorithms

1. Linear theory
2. Shen-Hedrick-Elkins
3. Polach's method
4. FASTSIM
5. Table-based approach
6. Linear elasticity theory, half-space
7. Linear elasticity theory, conformal
8. Finite elements

Affected a lot already by the normal contact algorithm!



Tangential contact algorithms

Simplified theories

1. Linear theory
2. Shen-Hedrick-Elkins
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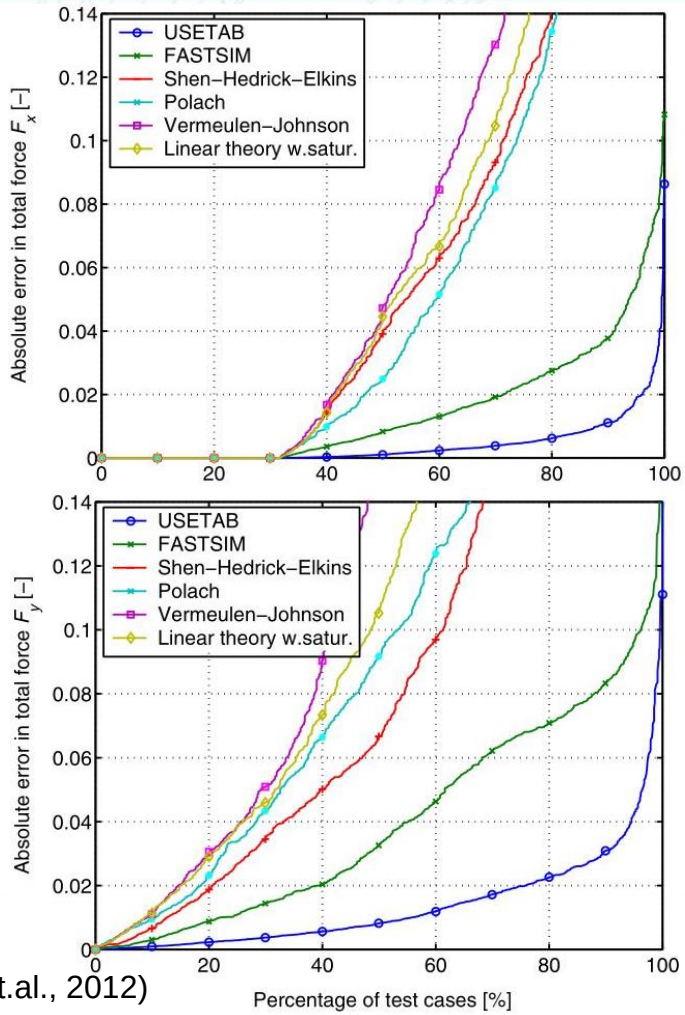
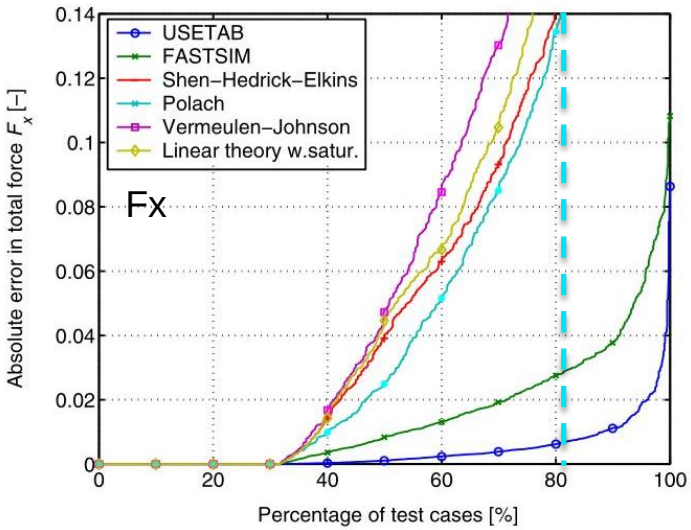
Full theories

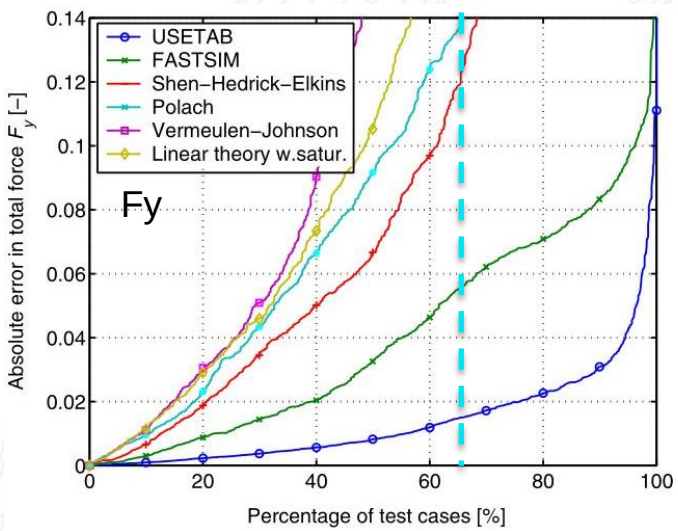
Affected by the normal contact algorithm!



(Vollebregt et.al., 2012)

Polach's contact algorithm



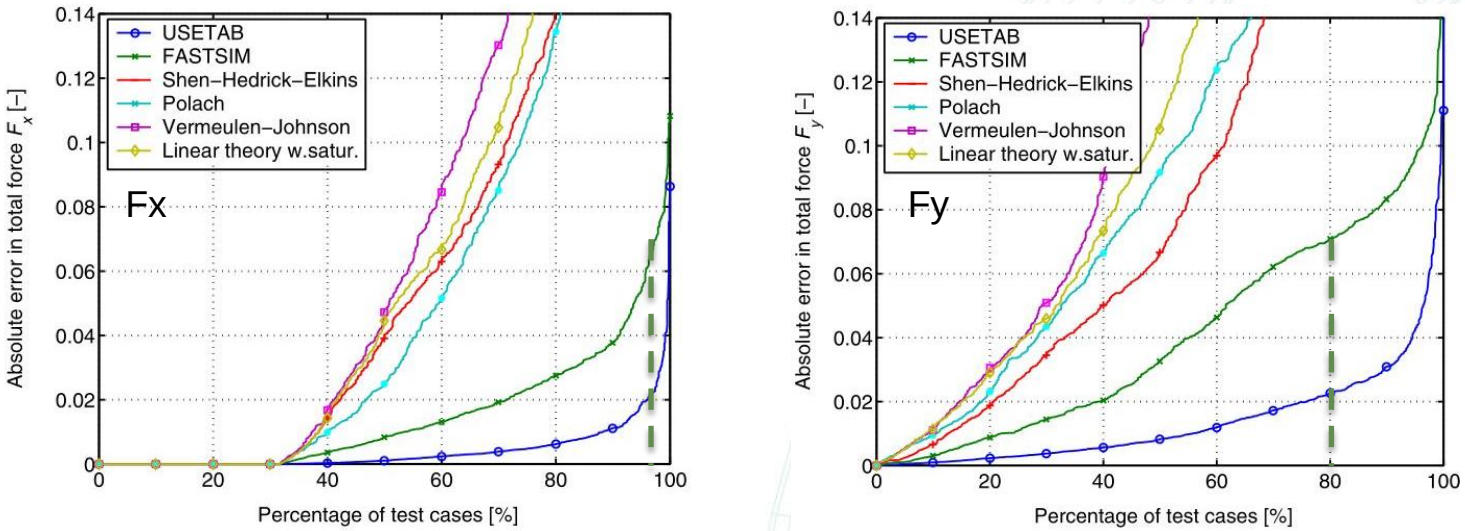


(Vollebregt et.al. 2012):

1. Polach's method deviates $>30\%$ in $>30\%$ of the times,
2. Especially when spin creepage is involved,
3. Much more spin-creepage occurs than one may think.

This gets worse in non-Hertzian situations

The FASTSIM algorithm



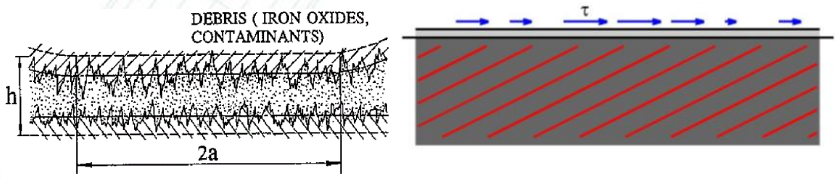
1. (Vollebregt et.al. 2012): Fastsim deviates $>15\%$ in $>20\%$ of the times,
2. (Vollebregt & Wilders, 2011): The error doubles when using 11×11 discretisation elements, this is solved in FASTSIM2,
3. (Vollebregt, 2015): Fastsim is not suited for falling friction,
4. Fastsim is also not suited for transient scenarios.

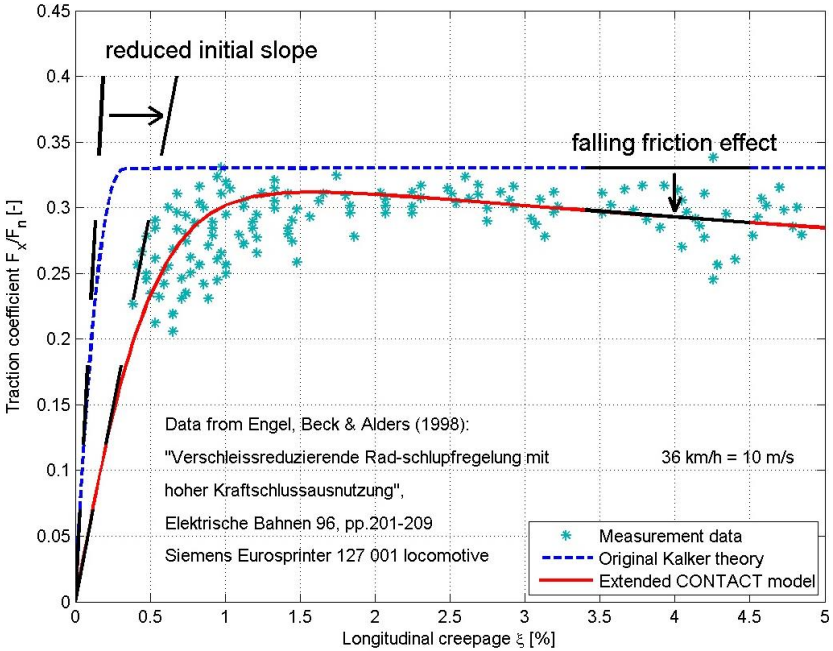
Beyond Coulomb friction

1. Linear theory
2. Shen-Hedrick-Elkins
3. Polach's method
4. Modified FASTSIM
5. Table-based, Percent_Kalker
6. Table-based, Extended CONTACT
7. Linear elasticity theory, half-space
8. Linear elasticity, conformal
9. Finite elements

Fastsim: (Spiryagin, Polach and Cole, 2013);
(Meierhofer et.al., 2014)
Table-based: (Klauser and Vollebregt, 2015)
Finite elements: (Zhao and Li, 2012).

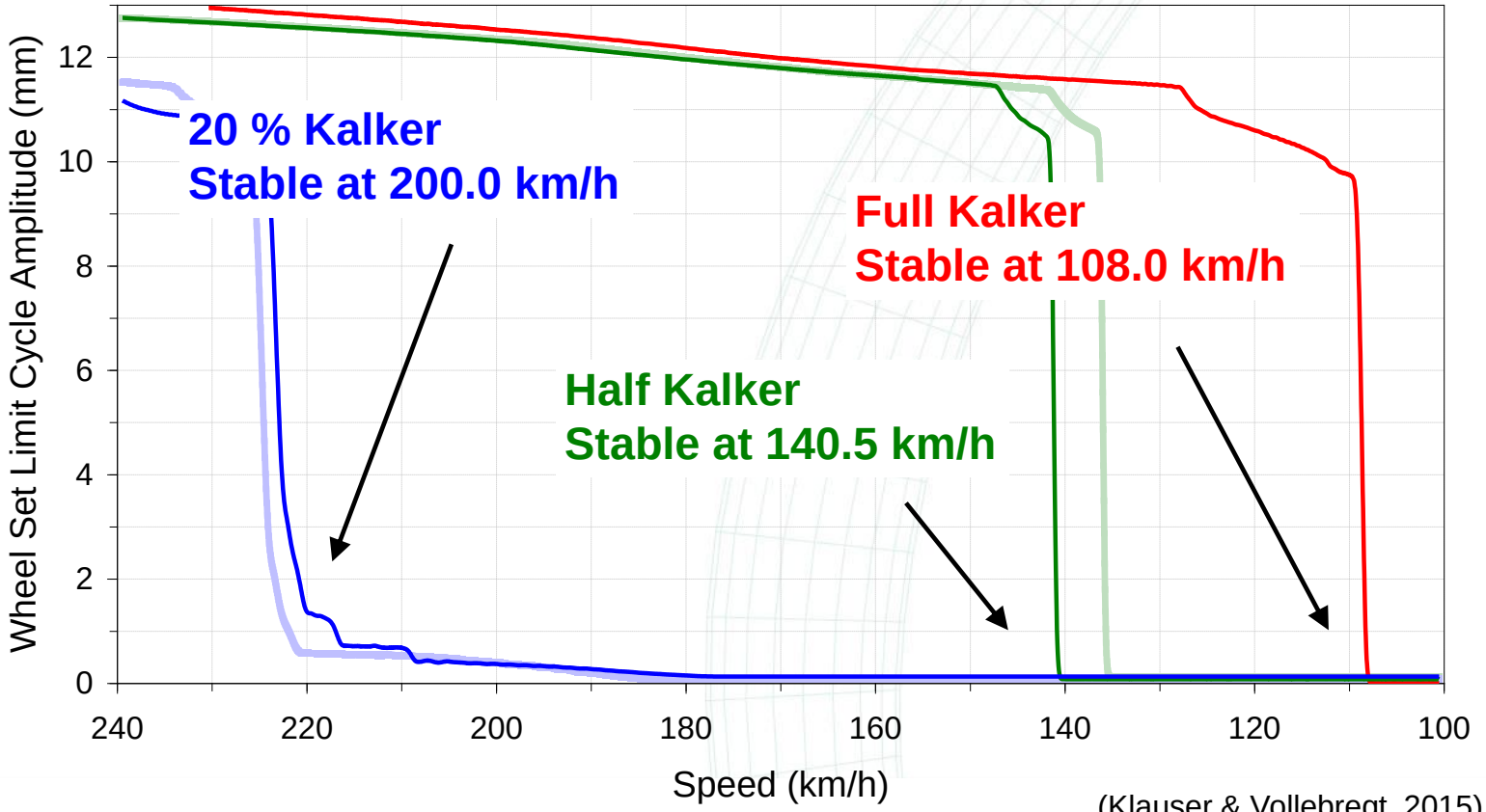
(Hou et.al., 1997)





(Vollebregt, 2014)

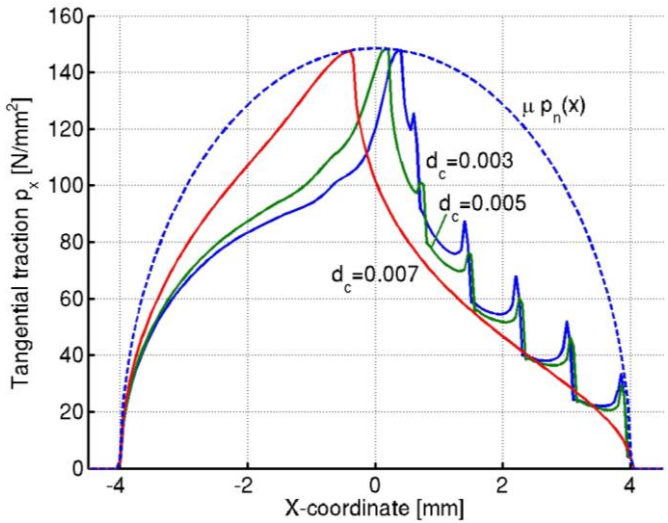
Wheel-set limit cycle

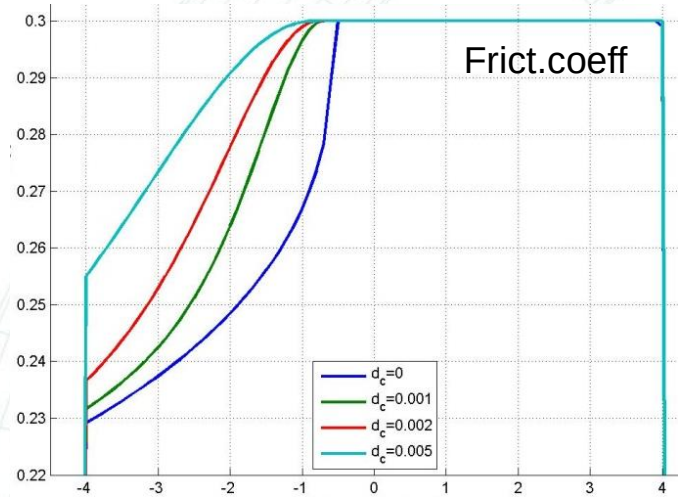


(Klauser & Vollebregt, 2015)

Falling friction is intricate

Traction





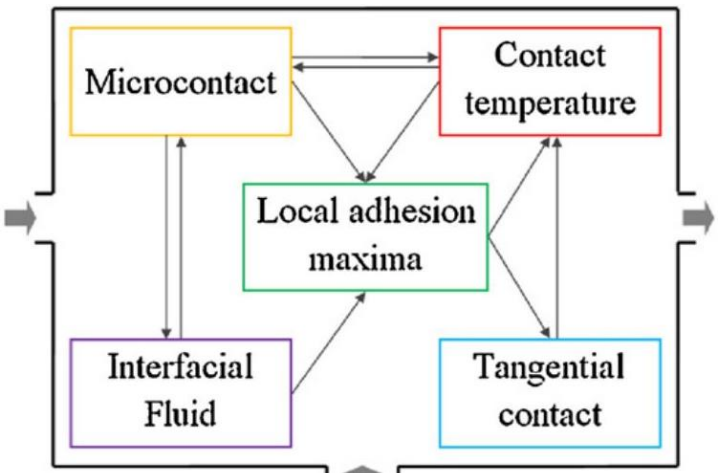
(Vollebregt & Schuttelaars, 2011):

1. "Instantaneous" friction laws $\mu = \mu(s)$ lead to traction build-up & collapse
2. Make sure that $\mu_{kin} > 0$ when $s \to \infty$.

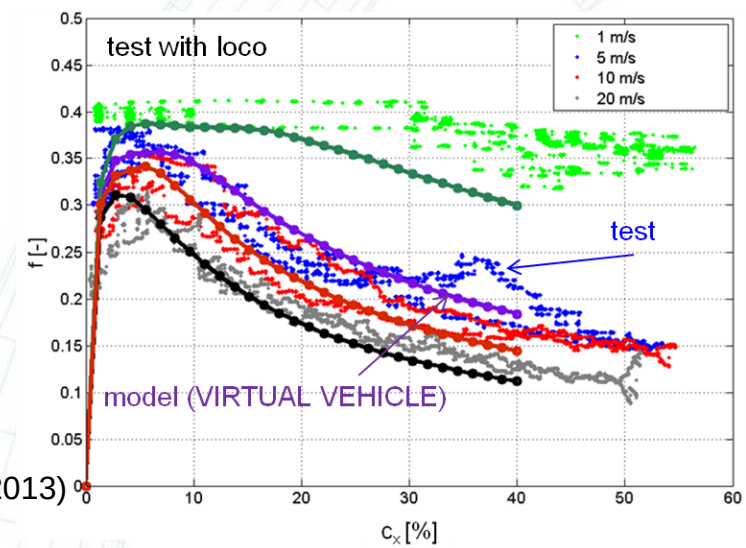
(Vollebregt, 2014):

3. Introduce "time-delay" through "friction memory".

Falling friction is intricate



(Tomberger et.al., 2011)



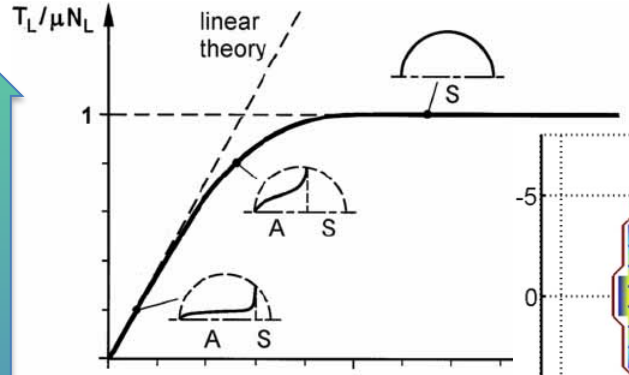
(Six, 2013)

1. Fastsim is inaccurate w.r.t. slip velocity, hence the temperature is rough estimate
2. (Vollebregt, 2015): Fastsim is not suited for falling friction

Multi-body simulation + boundary elements

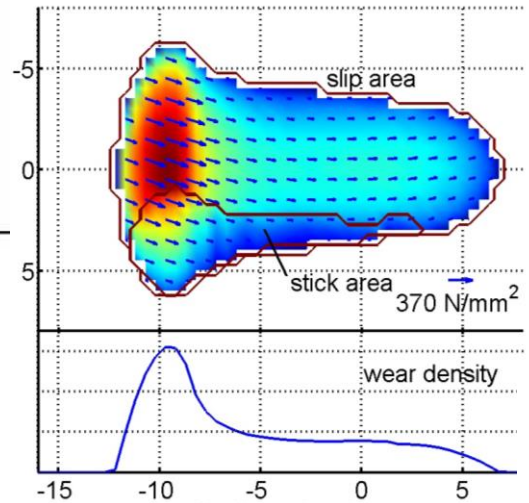
Fast

Slow

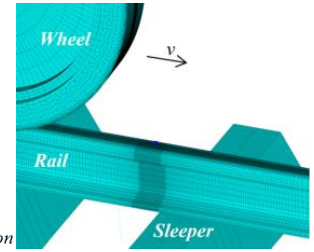


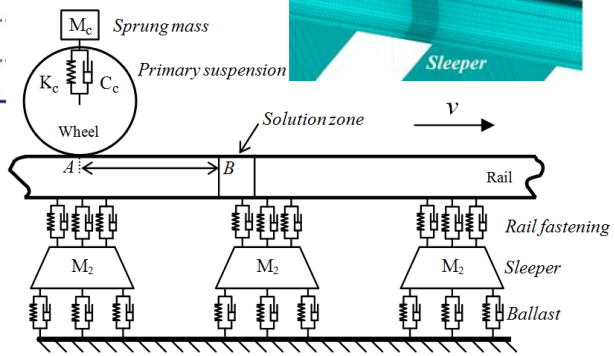
Simplified algorithms

CONTACT: BEM



LS-Dyna: FEM





(Zhao & Li, 2011)

Rough

Detailed

Calculation of wheel-rail contact forces

Wheel/rail profiles

Friction

Track geometry

Track irregularities

Track bed stiffness

Voided sleepers

Rail bending

Wheel-wheel interaction

Loose fasteners

Rail roll

Mass, velocity

Traction & braking

Unsprung mass

Suspension

Car-car interaction

Axle bending

Axle torsion

Polygonal wear

RCF cracks

Surface roughness

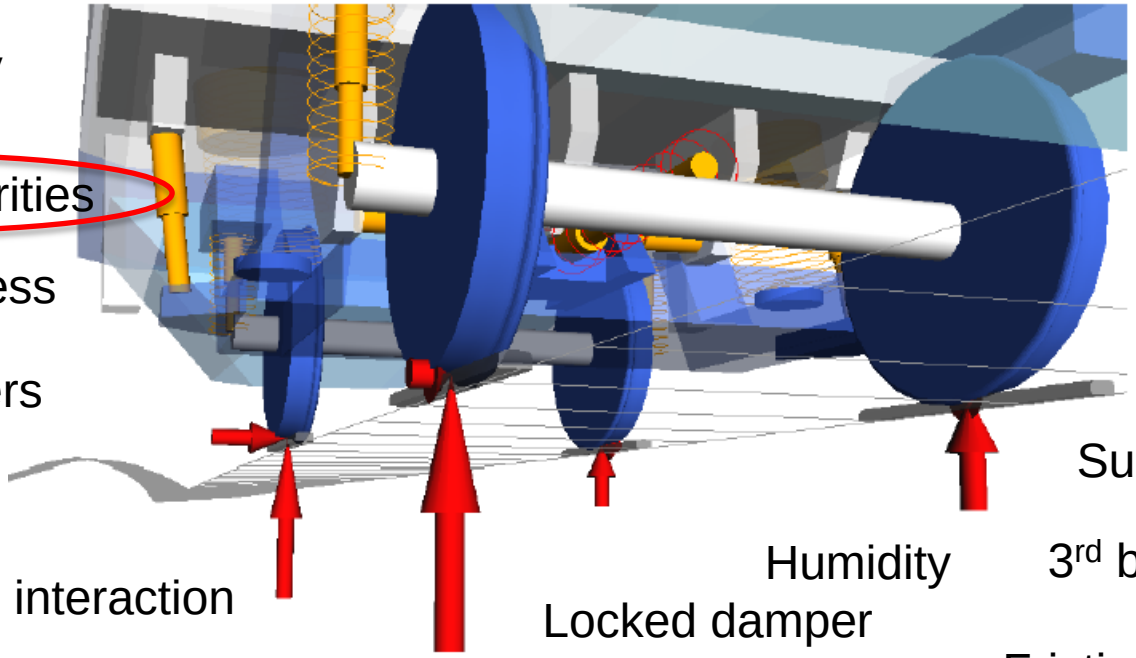
3rd body layer

Friction modifiers

Humidity

Locked damper

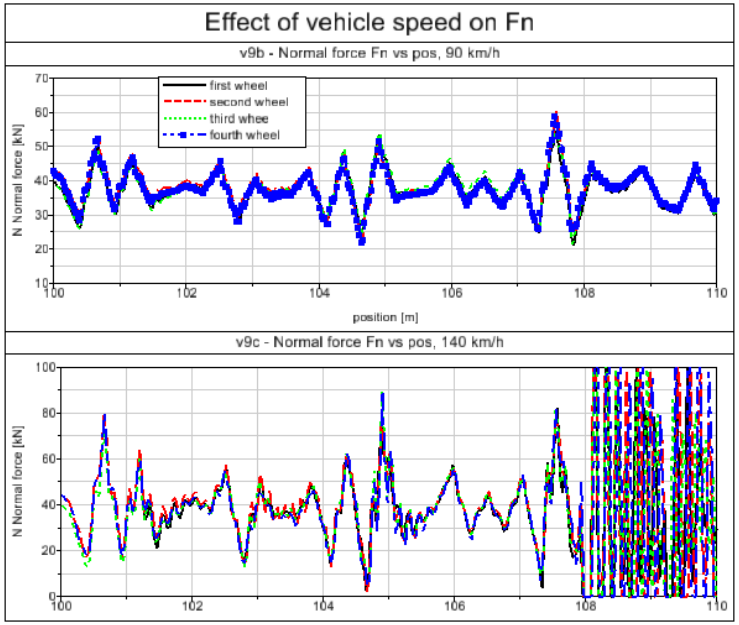
Misaligned wheels

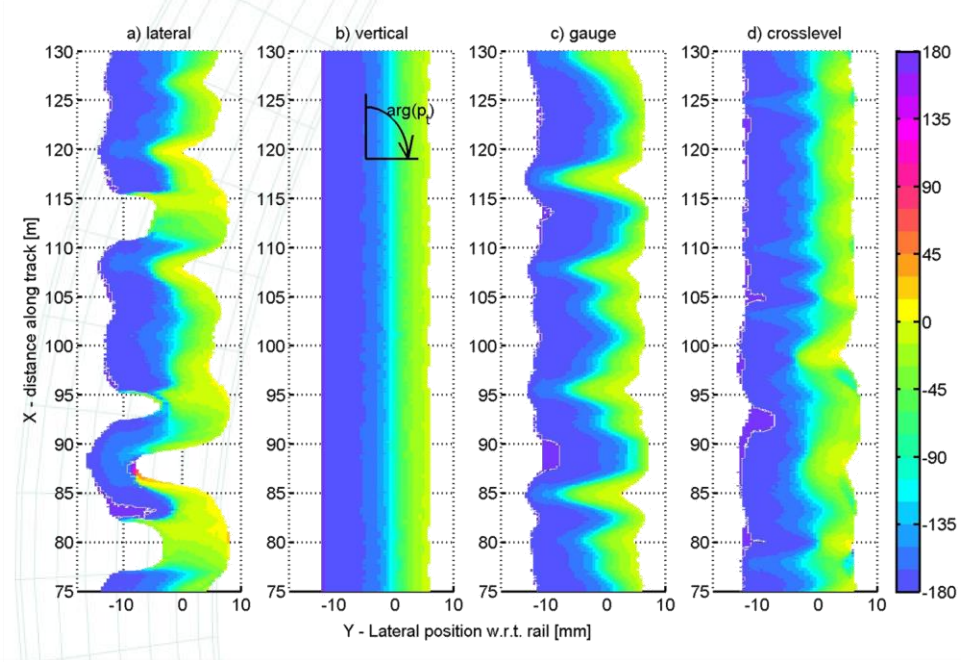


(picture: Ch. Weidemann)

Effects of track irregularities

Needs sufficiently long stretch of track, and good support for track flexibility.





(Vollebregt & Steenbergen, 2014)

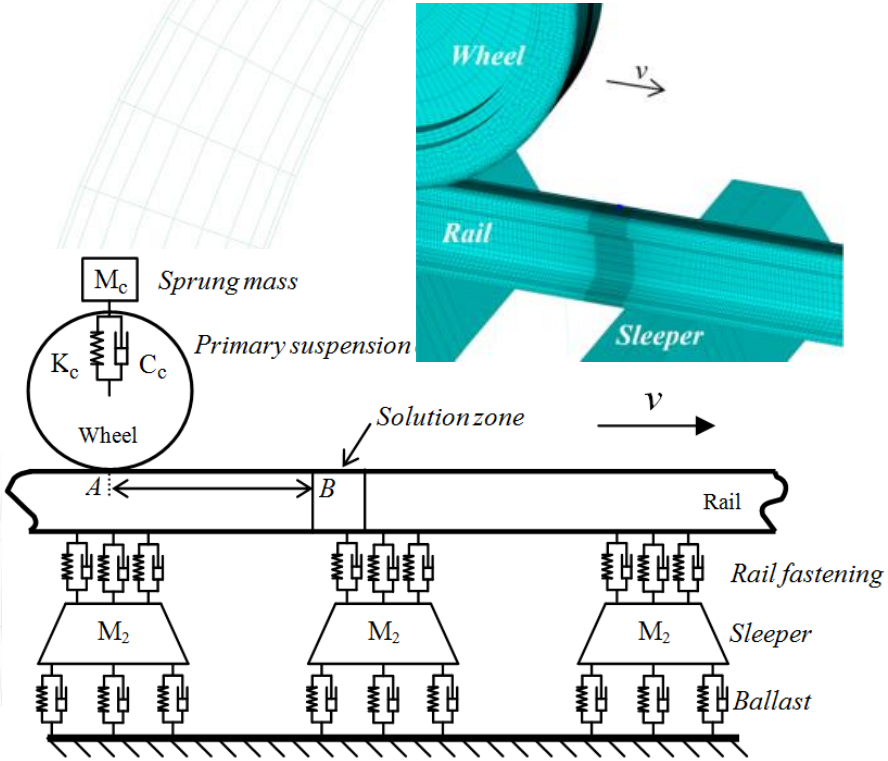
Limitations of “full-FEM” approach

Not easily included in “full FE” modelling:

1. Bogie dynamics, suspension
2. Track geometry, spiral & curve
3. Track irregularities
4. Stiffness variation, e.g. bridge
5. Fast calculation times

Embed flexible bodies or FEM inside MBS approach

Compute contact with BEM.



(Zhao & Li, 2011)

Part I – Conclusions

W/R contact is studied for a variety of purposes

- Simplified approaches are often sufficient
- BEM (CONTACT) is available for long stretches of track
- FEM is useful for specific scenarios.

Work towards integrated approach – embed FEM in MBS simulation

W/R contact is influenced by many factors

- Consider non-Hertzian & conformal contact geometry
- Consider the reduced slope and falling friction phenomena
- More research is needed to improve our understanding.

References

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- (Zhao Xin & Li, 2012) – Three dimensional finite element solution of wheel-rail rolling contact with velocity dependent friction, CM2012.

Recent developments w.r.t. CONTACT

Part II – conformal contact analysis

Edwin Vollebregt

VORTECH CMCC
CONTACT MECHANICS COMPUTING AND CONSULTING

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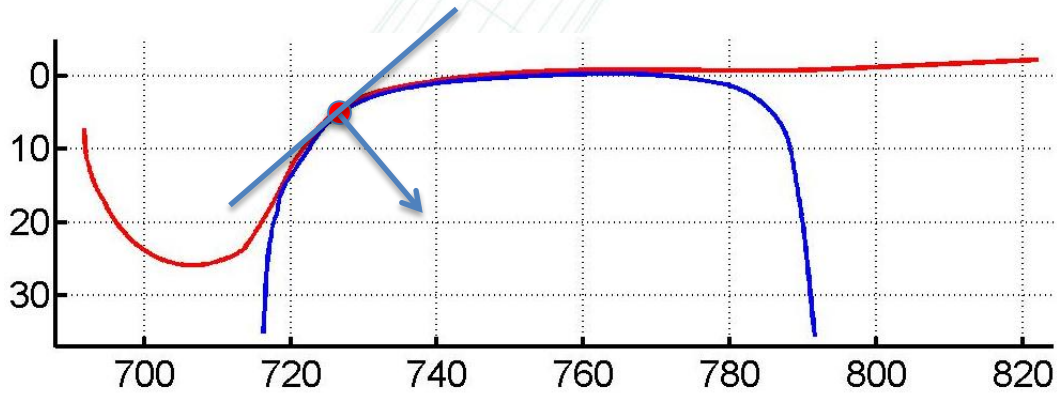
Planar contact analysis

1. Find the initial contact point
2. Determine the contact angle
3. Compute normal and tangential forces.



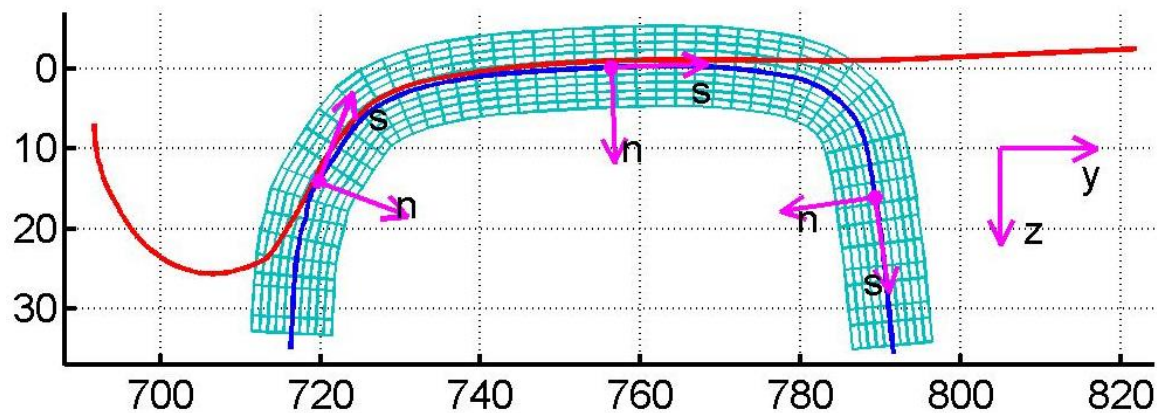
Highly sensitive to the initial contact point!

Conformal contact analysis

1. Introducing generalized curvi-linear coordinates (x, s, n)
2. Normal problem uses local normal direction (n)
3. Tangential problem uses local (x, s) directions

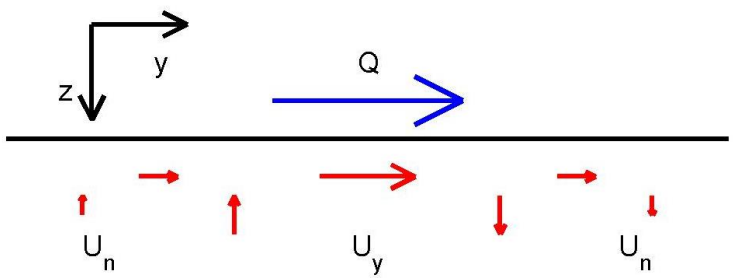
Normal problem:

$$e_n = h_n + u_n,$$
$$e_n \geq 0,$$
$$p_n \geq 0,$$
$$p_n \cdot e_n = 0$$

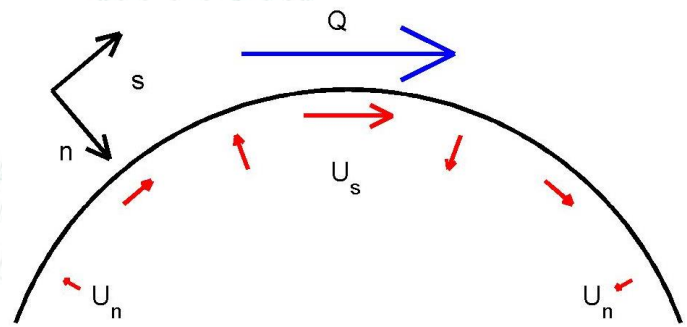


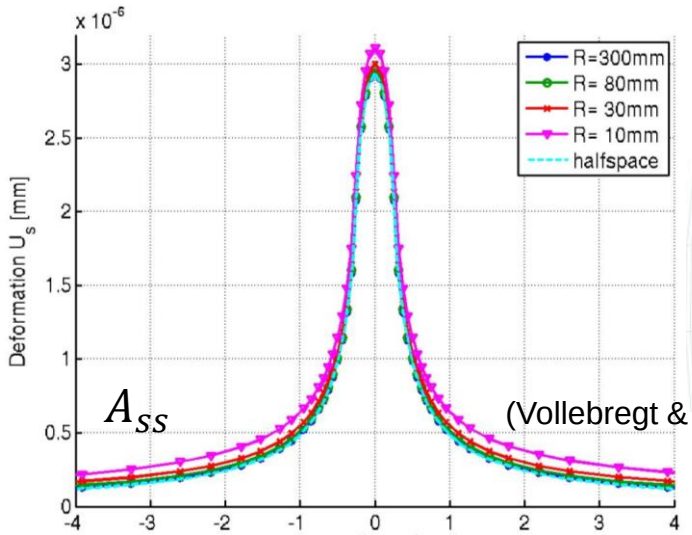
Using boundary elements

Half-space

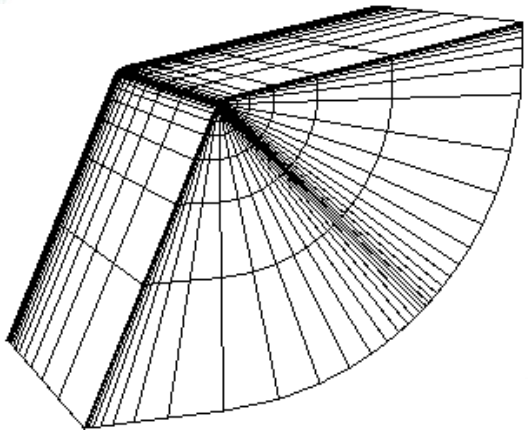


Quasi quarter-space

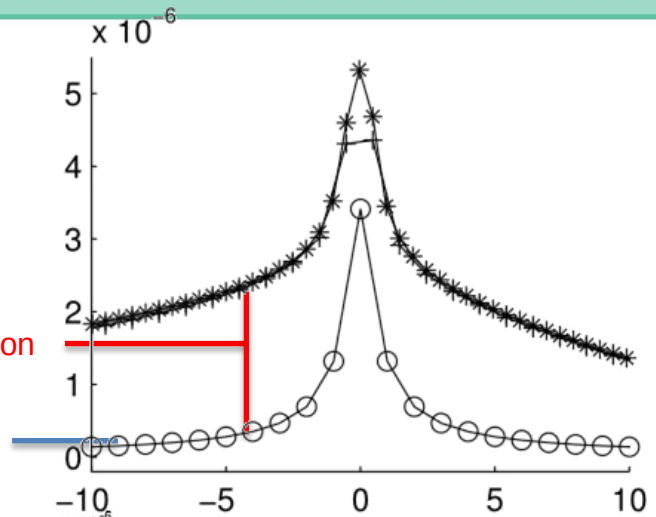




(Vollebregt & Segal, 2014)



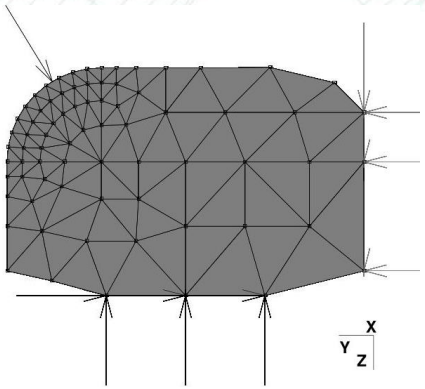
Using boundary elements

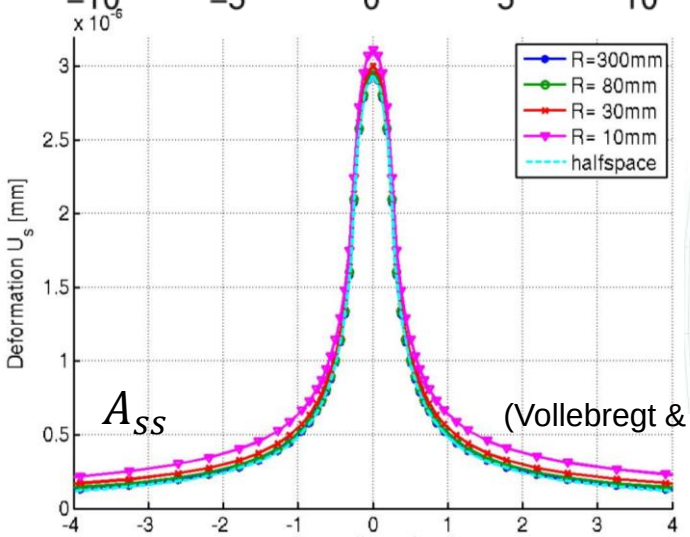


Global deflection

Half-space

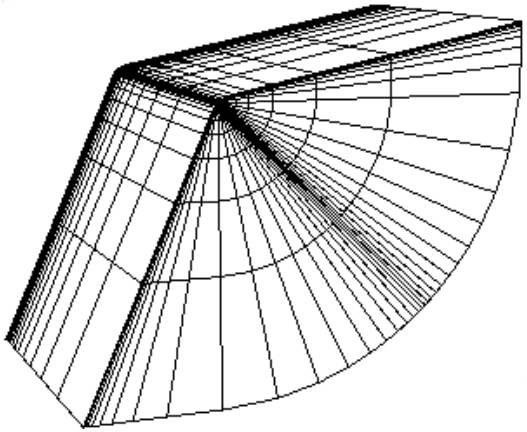
(Li, 2002)





A_{ss}

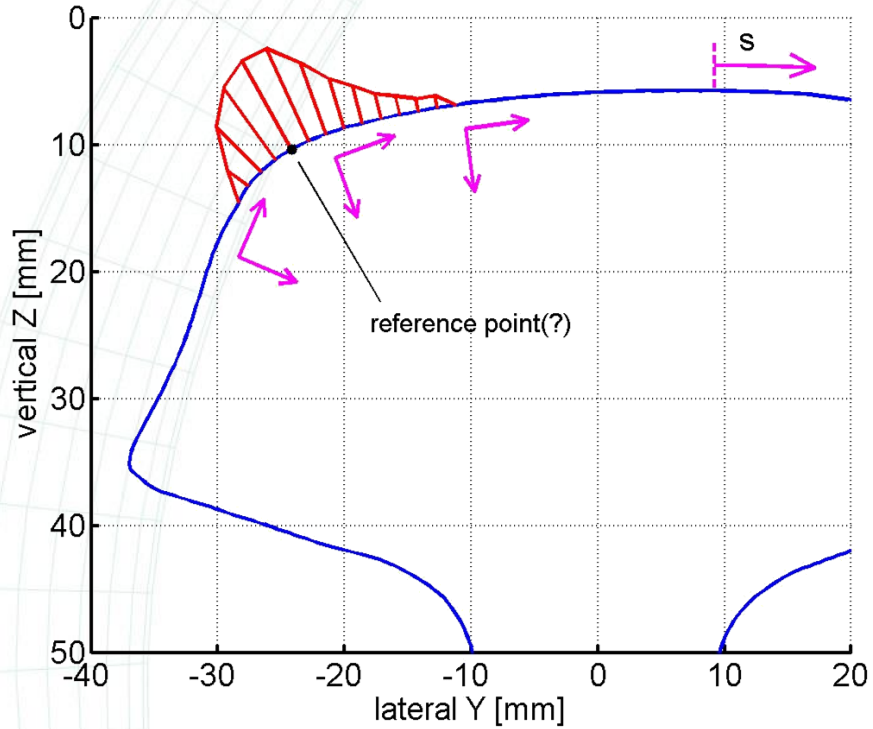
(Vollebregt & Segal, 2014)



Conformal contact analysis

Total forces: add tractions vectorially, using (x, y, z) coordinates.

Insensitive to the initial contact point!

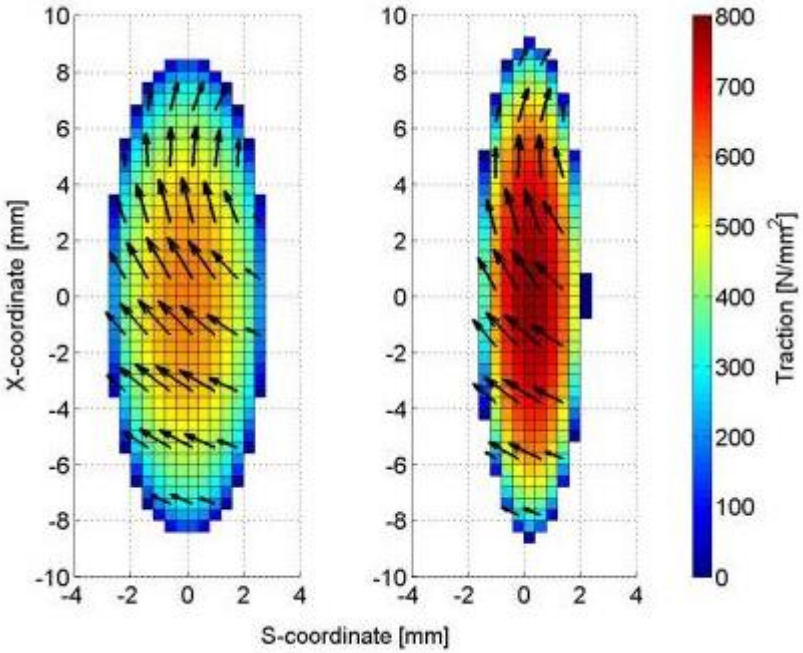


Part II – Conclusions

Worn profiles benefit from conformal contact analysis

- Using curvilinear coordinates
- FEM may be used off-line,
  for numerical influence coefficients
- Avoid global deflection being
  computed twice

Needs automation and application in practical scenarios.



(Vollebregt & Segal, 2014)

Recent developments w.r.t. CONTACT

Part III – new insights in non-steady rolling contact

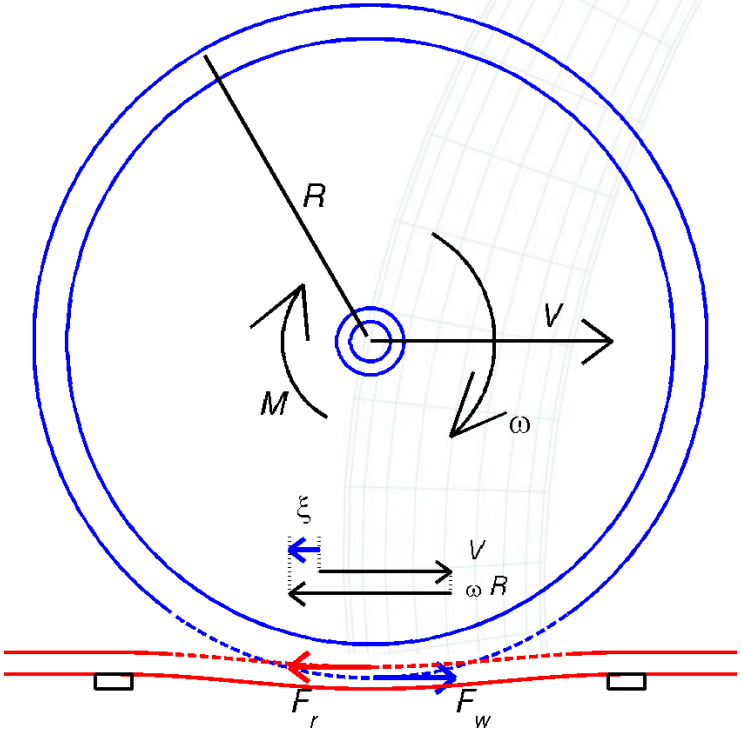
Edwin Vollebregt

VORTECH CMCC
CONTACT MECHANICS COMPUTING AND CONSULTING

10th International Conference on Contact Mechanics
August 30, 2015 - September 3, 2015 | Colorado Springs, Colorado, USA

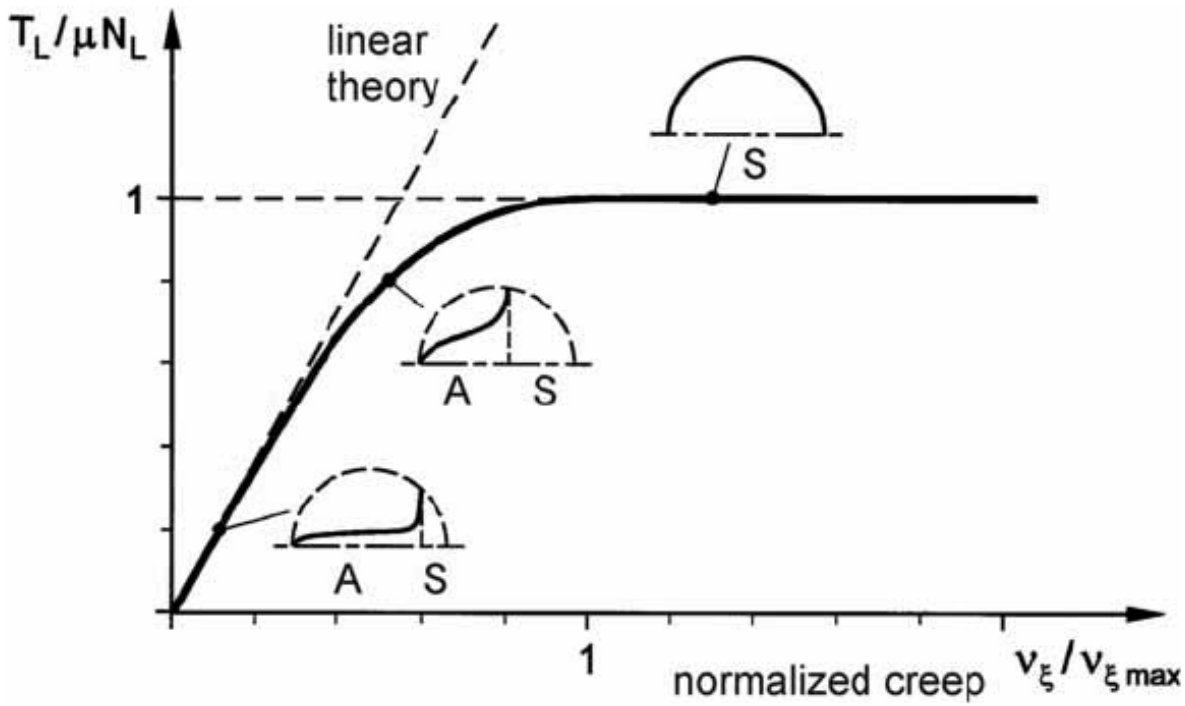
Reynolds (1876) – the creep phenomenon

A slight difference may exist between forward and circumferential velocity.



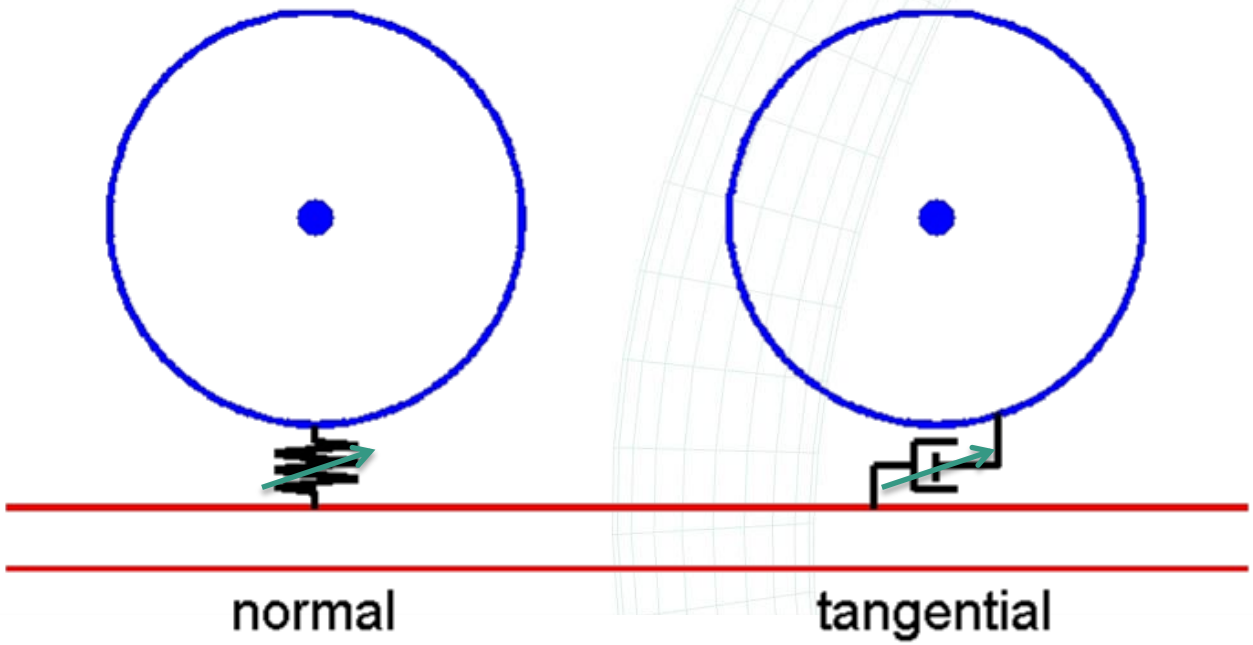
Carter (1926) – creep versus creep force

Creepage invokes a resisting creep force.



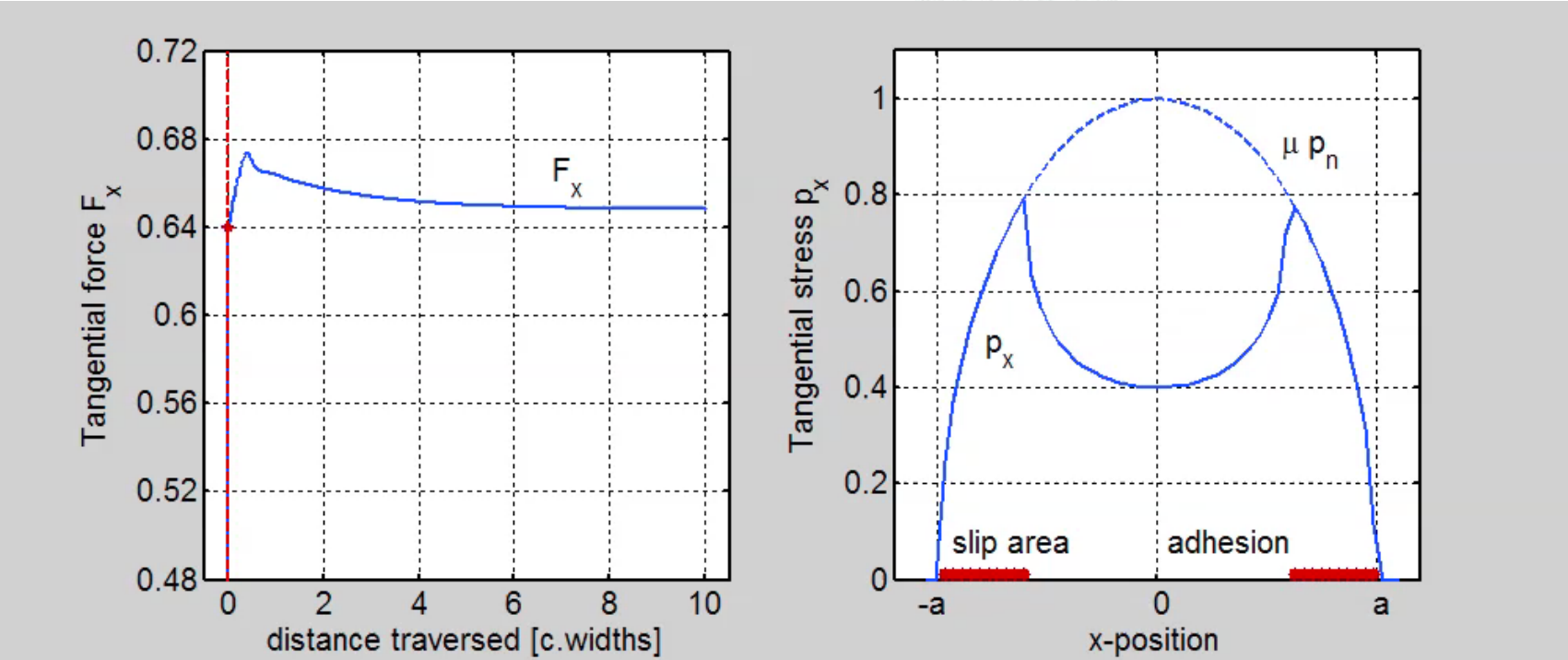
Carter (1926) – creep versus creep force

The creep force is like a dashpot – proportional to the velocity difference.



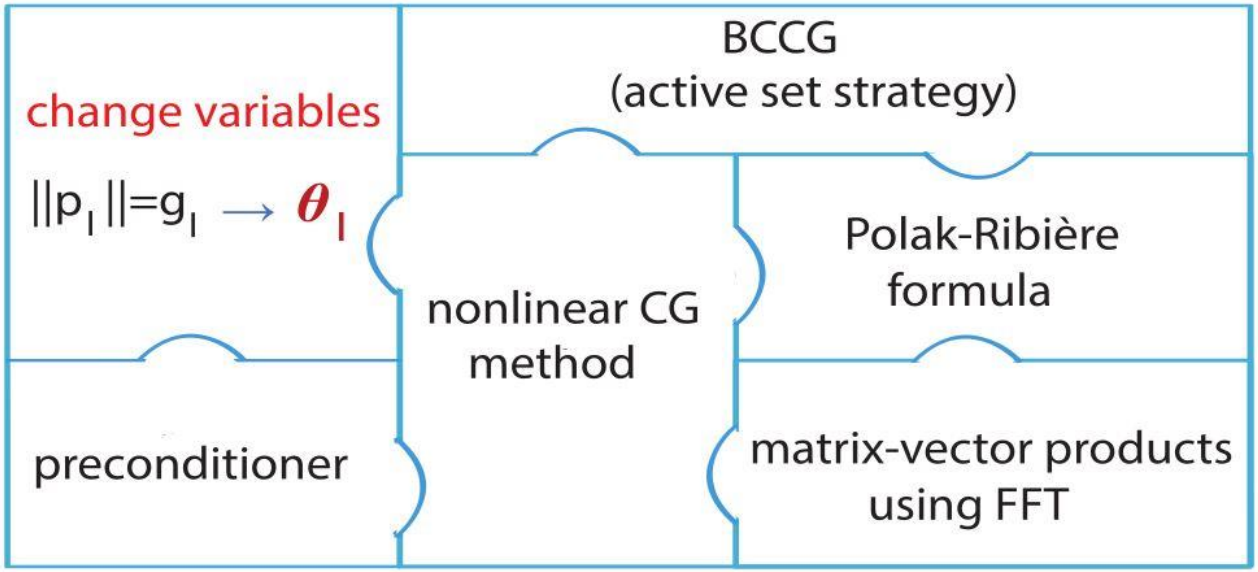
Kalker (1971) – transient effects

"Transients die out quickly, within just a few contact widths"



Speed-up of CONTACT

The solvers NormCG and TangCG speed up CONTACT 5 – 100 times.



(Vollebregt, 2014), (Zhao, Vollebregt & Oosterlee, 2015)

New model – on-line contact force calculation

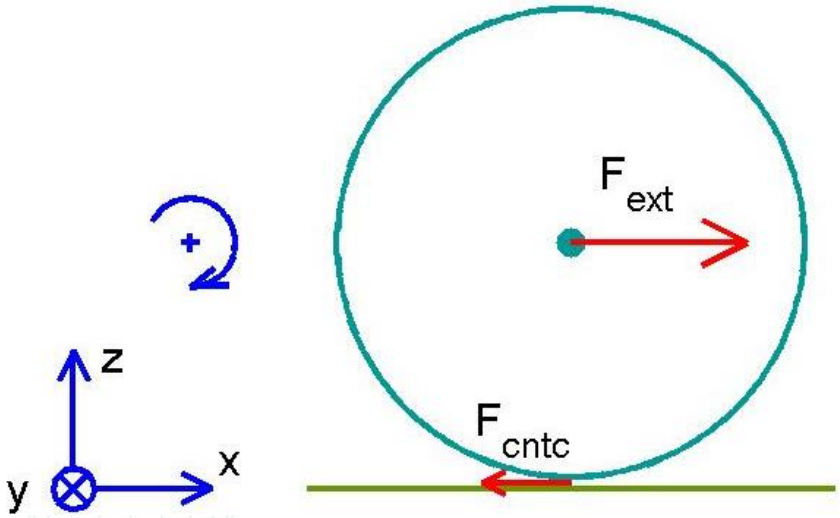
Dynamic equations

$$\frac{dx}{dt} = v$$

$$\mathrm{m}\frac{dv}{dt} = F_{ext} - \boxed{F_{cntc}}$$

$$\frac{d\theta}{dt} = \omega$$

$$\mathrm{I}\frac{d\omega}{dt} = T_{ext} + \boxed{rF_{cntc}}$$



New model – on-line contact force calculation

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Contact model

$$w_x = \xi = \frac{\boxed{v} - \boxed{\omega r}}{\boxed{v}}$$

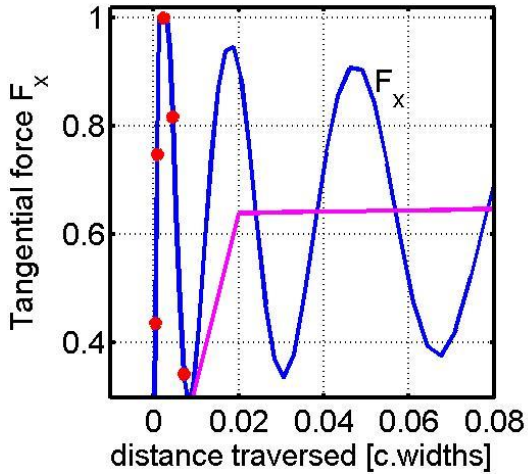
$$s_x = w_x - \frac{1}{\boxed{v}}\frac{Du_x}{Dt}$$

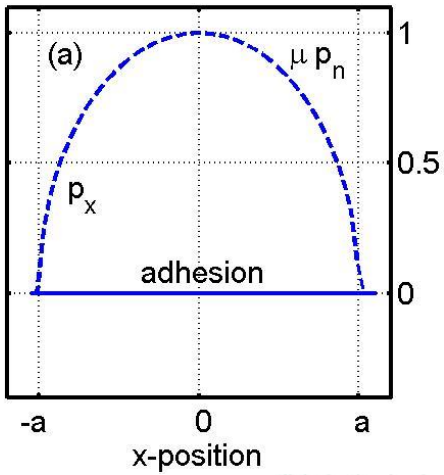
$$u_x(x) = \int_C A_{xx}(x, x')\, p_x(x')dx'$$

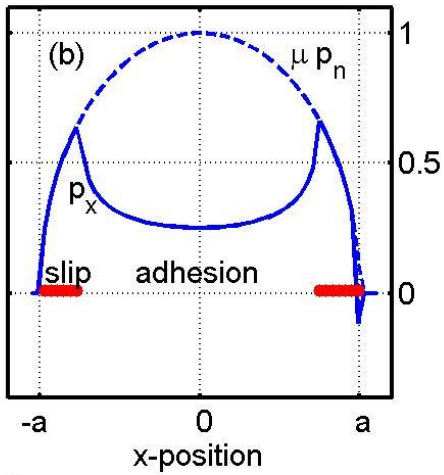
$$|p_x| < \mu p_n \rightarrow \; s_x = 0$$

$$\boxed{F_{cntc}} = \int_C p_x(x)dx$$

New insights – the rocking phenomenon





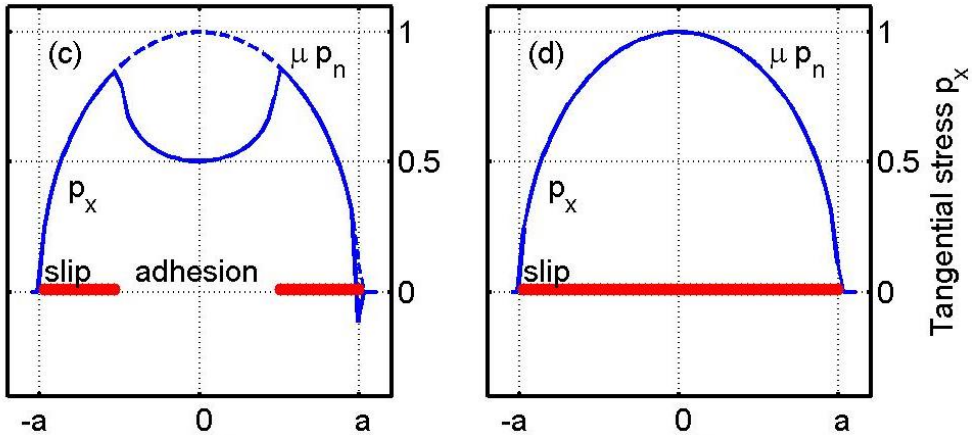


(a) Start from rest,

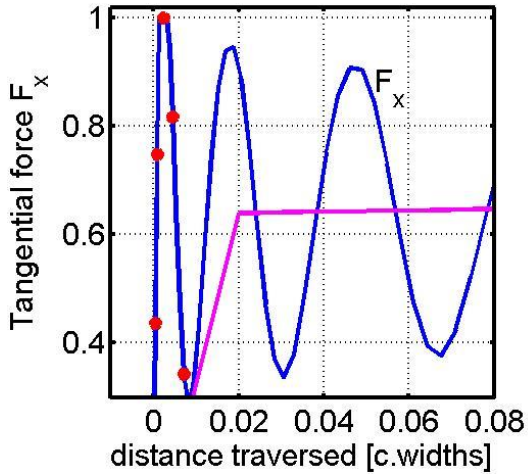
(b) Shifting + rotating,

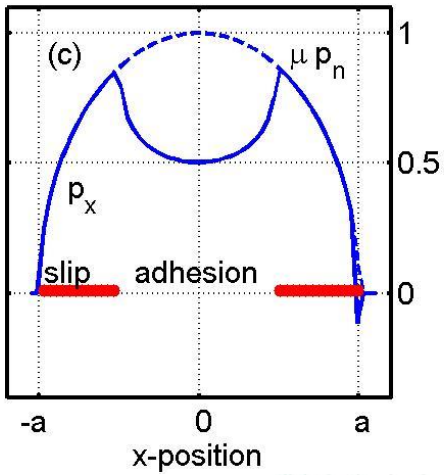
(c) Picking up speed,

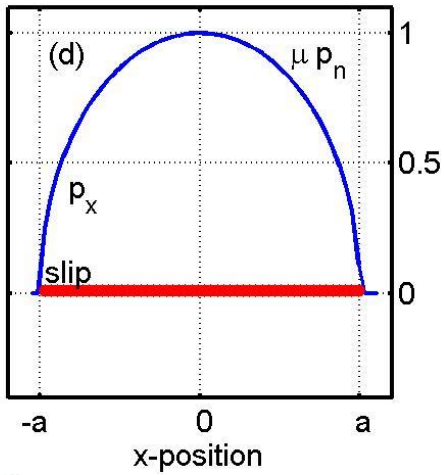
(d) Overshoot,



New insights – the rocking phenomenon





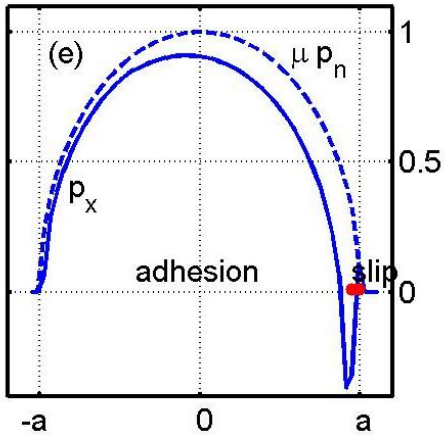


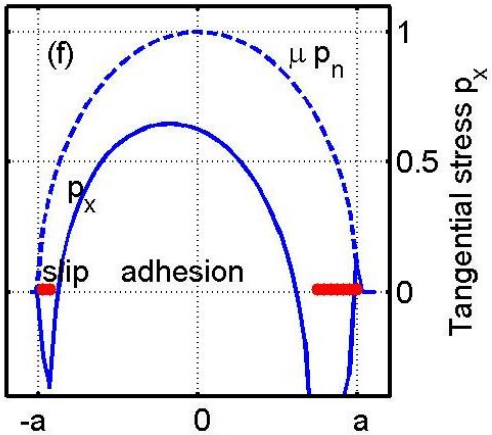
(c) Picking up speed,

(d) Increasing rotation,

(e) Creepage reversed,

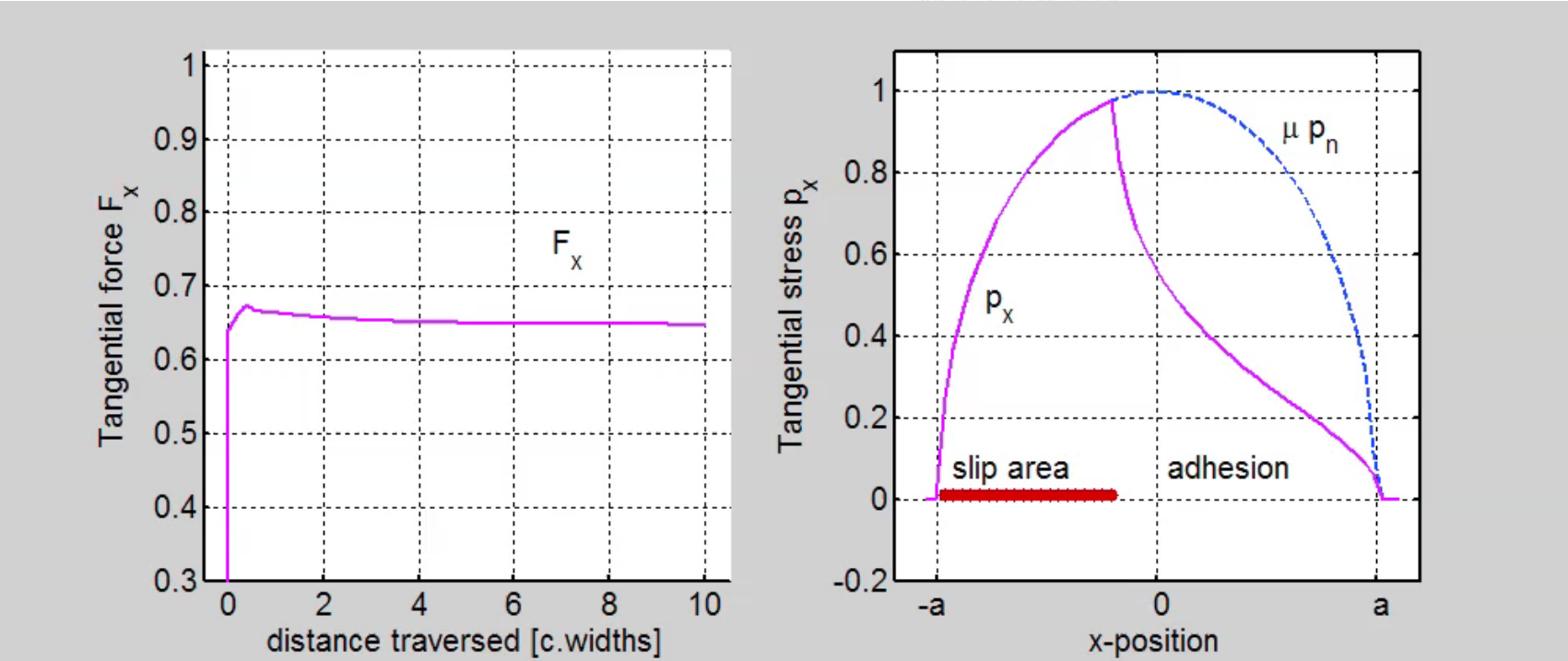
(f) Undershoot, …



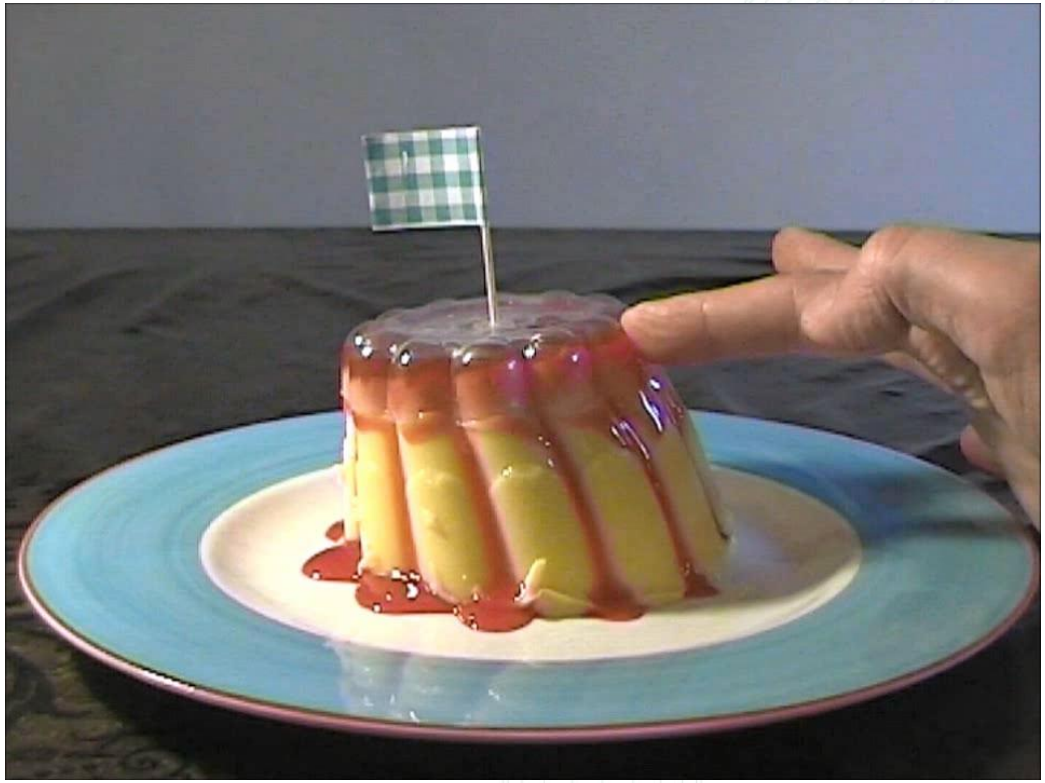


New insights – transient effects

Feed-back of contact force on creepage

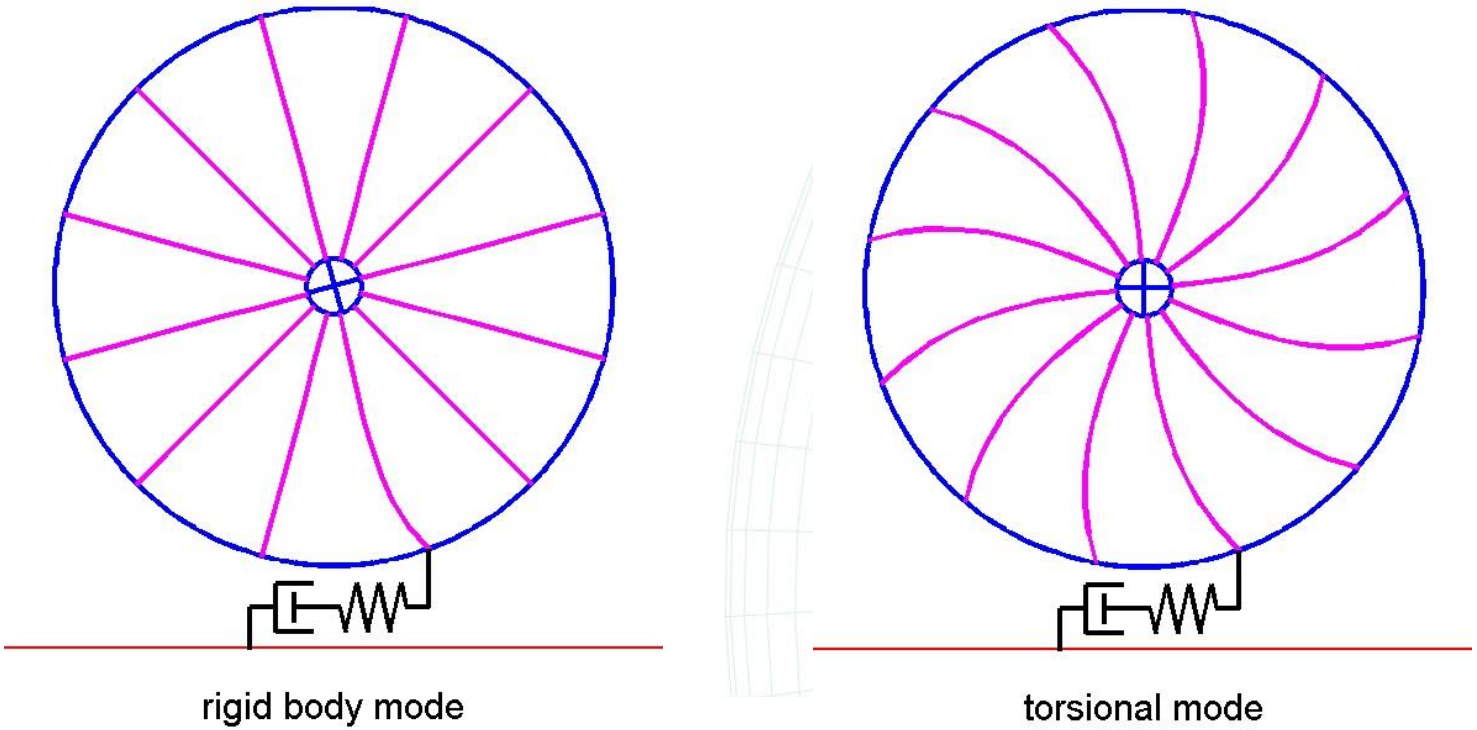


Elastic deformation



New insights – rocking oscillation

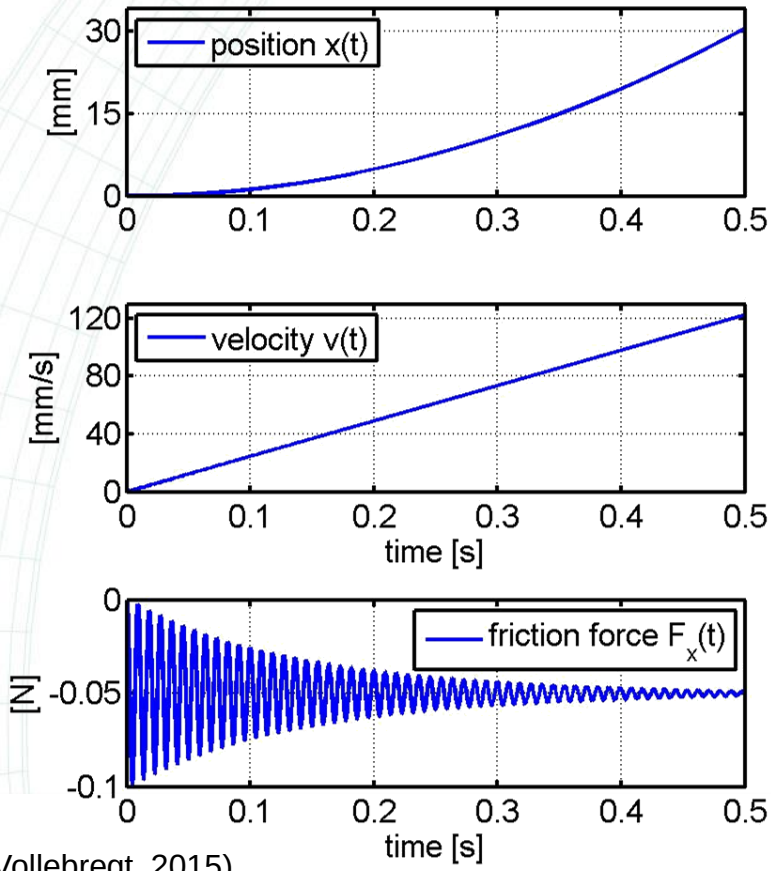
The whole wheel rocks as a rigid body.



New insights in rolling contact

Summary:

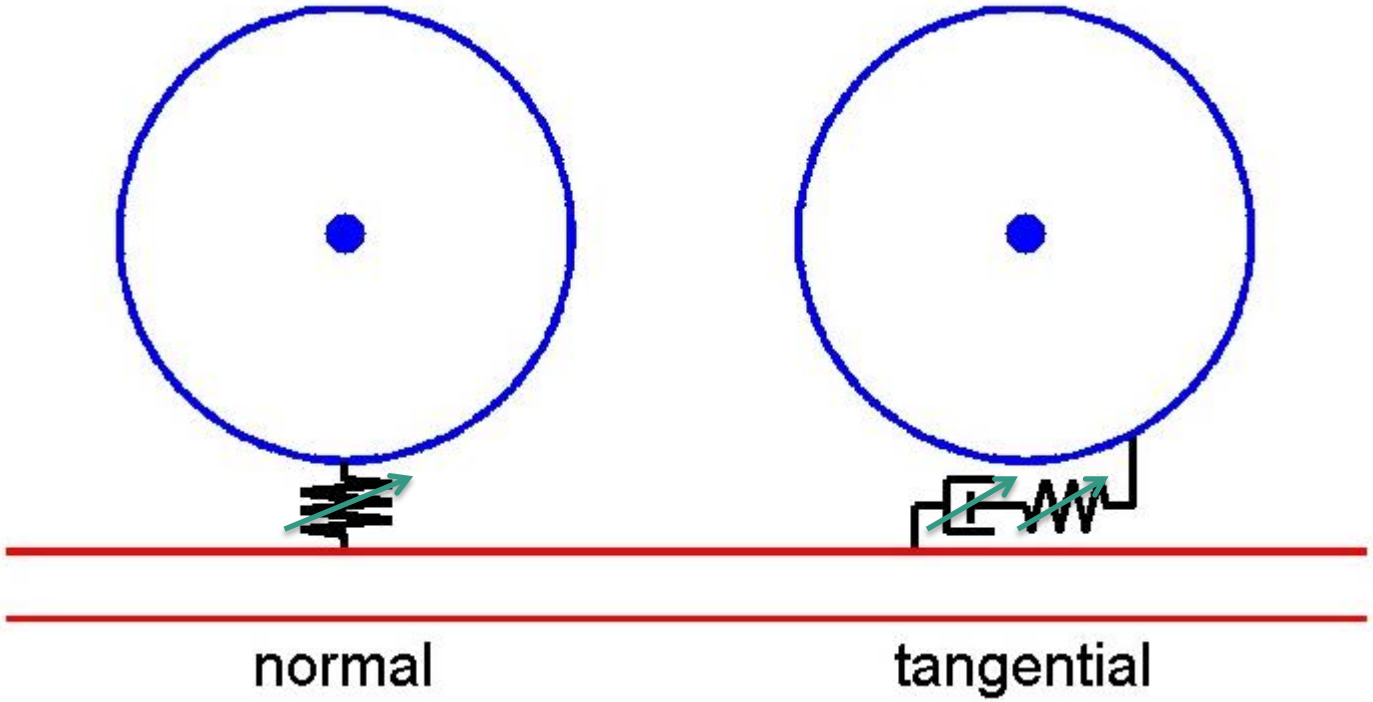
- Transient effects don't die out quickly.
- The contact force has a tendency to oscillate.
- Solid rolling objects have a tendency to "rock and roll".



(Vollebregt, 2015)

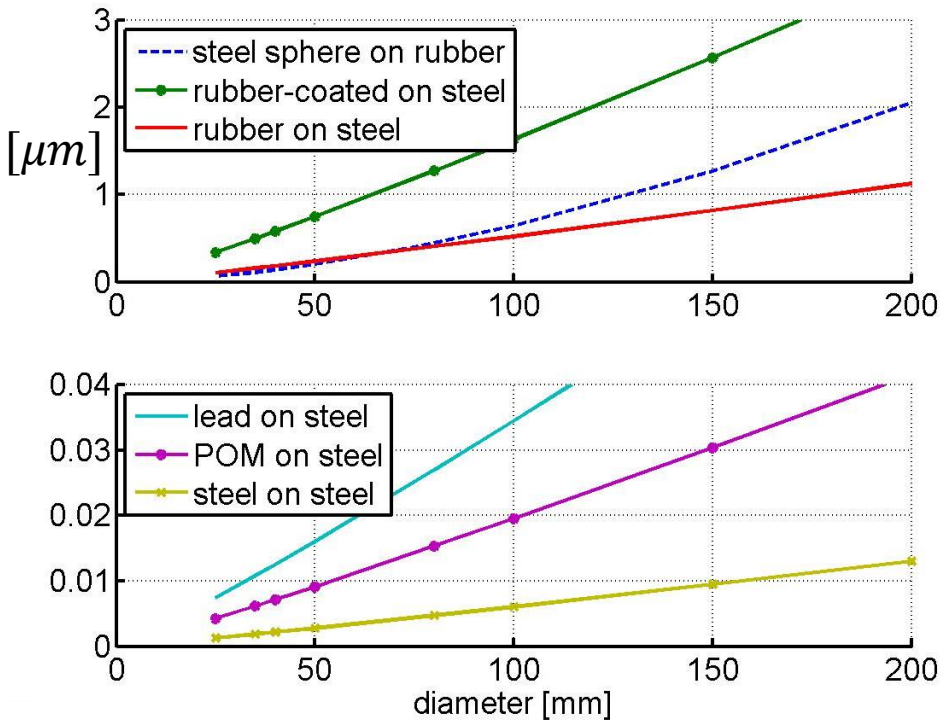
New insights – creep versus creep force

The creep force responds to position ("lag") and to velocity (difference).

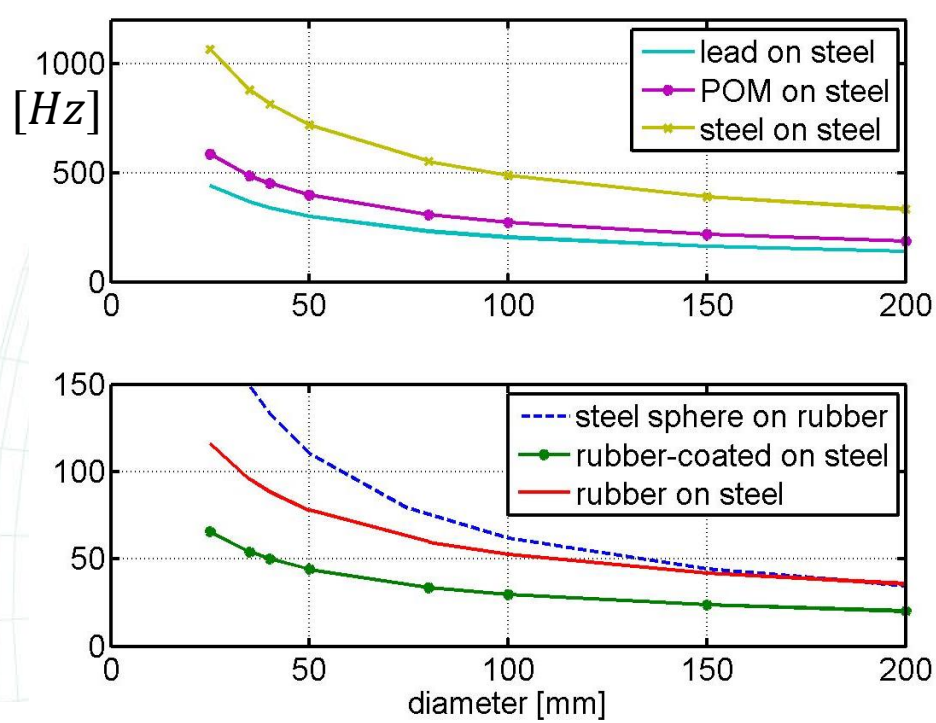


Experimental confirmation?

Small amplitude



High frequency



Part III – Conclusions

Rolling objects have a tendency to “rock while rolling”.

- Triggered by change of friction force, e.g. at welds & irregularities
- This could explain the short pitch corrugation phenomenon.

Future work:

- Experimental confirmation
- On-line integration of CONTACT in MBS
- Investigate corrugation, squeal, RCF.

(picture: S.Grassie)

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- (Kalker, 1971) – A minimum principle for the law of dry friction. Part 2: Application to nonsteady rolling elastic cylinders, J. Applied Mechanics 38, 881-887.
- (Li, 2002) – Wheel-rail rolling contact and its application to wear simulation, PhD thesis.
- (Reynolds, 1876) – On rolling friction, Phil.Trans. Royal Society of London 166, 155-174.
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- (Vollebregt, 2015) – New insights in non-steady rolling contact, IAVSD conference, Graz.
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- (Zhao, Vollebregt & Oosterlee, 2015) – A fast nonlinear conjugate gradient based method for 3D concentrated frictional contact problems, JCP 288, 86-100.