Recent developments w.r.t. CONTACT

Part I – background & review

Edwin Vollebregt
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

Hunting motion

Flange climb

Dynamic amplification

Ride quality

Track-shifting forces

Traction and braking

Wheel flats

Low adhesion

Track friendliness

Switches & crossings

Track deterioration

Crack initiation

Wear

Corrugation

RCF

Crack growth

(picture: Ch. Weidemann)
Multi-body simulation + boundary elements

CONTACT: BEM

LS-Dyna: FEM

Simplified algorithms

T/L/μN

linear theory

CONTACT: BEM

Simplified algorithms

370 N/mm²

wear density

Wheel

Sprung mass

Primary suspension

Solution zone

Wheel

Rail

Sleeper

Rail fastening

Ballast

(Zhao & Li, 2011)
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
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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

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, conformal
8. Finite elements

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 $11 \times 11$ 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).
Wheel-set limit cycle

(Klauser & Vollebregt, 2015)
Falling friction is intricate

(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”.

(Vollebregt & Schuttelaars, 2011): 
1. “Instantaneous” friction laws \( \mu = \mu(s) \) lead to traction build-up & collapse 
2. Make sure that \( \mu_{kin} > 0 \) when \( s \to \infty \).
Falling friction is intricate

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

CONTACT: BEM

LS-Dyna: FEM

(Simplified algorithms)

(Tao & Li, 2011)
Calculation of wheel-rail contact forces

Wheel/rail profiles
Friction
Track geometry
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
Humidity
Locked damper
Misaligned wheels

Friction modifiers

(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.
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Recent developments w.r.t. CONTACT

Part II – conformal contact analysis

Edwin Vollebregt

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

\[ A_{SS} \]

(Vollebregt & Segal, 2014)
Using boundary elements

Global deflection

Half-space

\( A_{SS} \)

(Li, 2002)

(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

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

\[
\begin{align*}
\frac{dx}{dt} &= v \\
m \frac{dv}{dt} &= F_{\text{ext}} - F_{\text{cntc}} \\
\frac{d\theta}{dt} &= \omega \\
I \frac{d\omega}{dt} &= T_{\text{ext}} + rF_{\text{cntc}}
\end{align*}
\]
New model – on-line contact force calculation

Dynamic equations

\[
\frac{dx}{dt} = v
\]

\[
m \frac{dv}{dt} = F_{ext} - F_{cntc}
\]

\[
d\theta/dt = \omega
\]

\[
I \frac{d\omega}{dt} = T_{ext} + rF_{cntc}
\]

Contact model

\[
w_x = \xi = v - \omega r
\]

\[
s_x = w_x - \frac{1}{v} \frac{Du_x}{Dt}
\]

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

\[|p_x| < \mu p_n \rightarrow s_x = 0
\]

\[
F_{cntc} = \int_C p_x(x) dx
\]
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

![Graph showing tangential force and stress](image-url)
Elastic deformation
New insights – rocking oscillation

The whole wheel rocks as a rigid body.

rigid body mode

torsional mode
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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