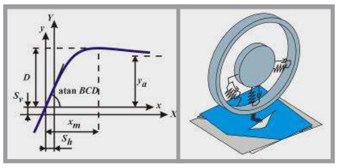
delfttyre
TNO innovation for life

MF-Tyre/MF-Swift



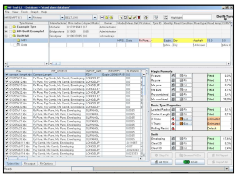
Dr. Antoine Schmeitz

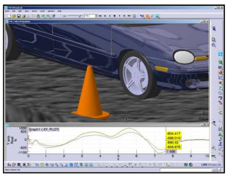
---

delfttyre
TNO innovation for life

Introduction

TNO's tyre modelling toolchain





tyre (virtual) testing
signal processing
→ TYDEX files →
parameter fitting + database
MF-Tool
→ tyre property file →
tyre model *MF-Tyre* *MF-Swift*
MBS solver

Measurement | Identification | Simulation

Introduction

What is MF-Tyre/MF-Swift?

- **MF-Tyre/MF-Swift is an all-encompassing tyre model for use in vehicle dynamics simulations**

This means:

- emphasis on an accurate representation of the generated (spindle) forces
- tyre model is relatively fast
- can handle continuously varying inputs
- model is robust for extreme inputs
- model the tyre as simple as possible, but not simpler for the intended vehicle dynamics applications

Introduction

Model usage and intended range of application

- All kind of vehicle handling simulations:
  - e.g. ISO tests like steady-state cornering, lane changes, J-turn, braking, etc.
  - Sine with Dwell, mu split, low mu, rollover, fishhook, etc.
- Vehicle behaviour on uneven roads:
  - ride comfort analyses
  - durability load calculations (fatigue spectra and load cases)
- Simulations with control systems, e.g. ABS, ESP, etc.
- Analysis of drive line vibrations
- Analysis of (aircraft) shimmy vibrations; typically about 10-25 Hz
- Used for passenger car, truck, motorcycle and aircraft tyres

 5 Dr. Antoine Schmeitz MF-Tyre/MF-Swift

Modelling aspects and contents (1)

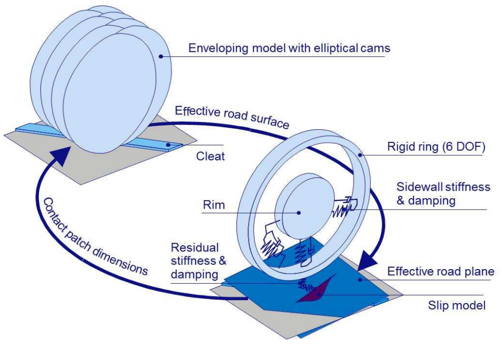
1. **Basic tyre properties and constitutive relations**
   - for tyre radii, contact patch size, stiffness, rolling resistance
   - nonlinear, effects of loads, velocity, inflation pressure
2. **Inclusion of measured tyre steady-state slip characteristics**
   - described by load and inflation pressure dependent Magic Formula
   - responses to sideslip, longitudinal slip, camber and turn slip
3. **Tyre transients / relaxation length properties**
   - carcass compliance
   - proper contact transient properties due to finite contact length
4. **Inclusion of belt dynamics**
   - primary natural frequencies (rigid ring modes) and gyroscopic effects
5. **Tyre rolling over uneven road surface**
   - tyre deformation on obstacles, arbitrary uneven roads

 6 Dr. Antoine Schmeitz MF-Tyre/MF-Swift

Modelling aspects and contents (2)

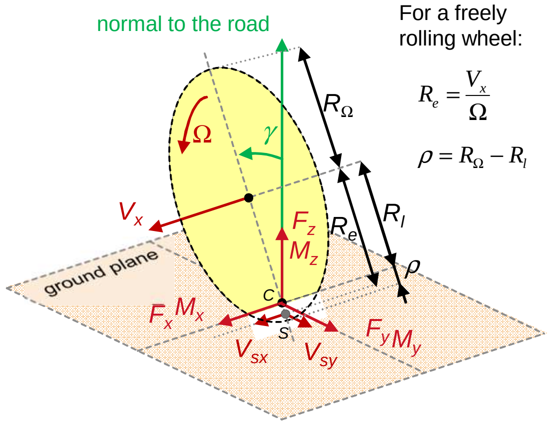
6. **Model usage and availability**
   - selection of complexity level
   - road definition
7. **Model parameterisation**
   - measurement requirements
   - MF-Tool
8. **Concluding remarks**

1. Basic tyre properties and constitutive relations



Some definitions

- free tyre radius R_Ω
- loaded radius R_l
- effective rolling radius R_e
- tyre deflection ρ
- forward velocity V_x
- wheel spin velocity Ω
- longitudinal slip velocity V_{sx}
- lateral slip velocity V_{sy}
- longitudinal force F_x
- lateral force F_y
- vertical force F_z
- overturning moment M_x
- rolling resistance moment M_y
- self aligning moment M_z
- inclination angle γ



For a freely rolling wheel:

$$R_e = \frac{V_x}{\Omega}$$

$$\rho = R_\Omega - R_l$$

delfttyre
TNO innovation for life

Constitutive relations

- Tyre radii, stiffness, contact patch dimensions, rolling resistance, etc. are non-constant for different operating conditions (load, velocity, etc.)
- In MF-Swift nonlinear empirical relations are used to describe these basic tyre properties

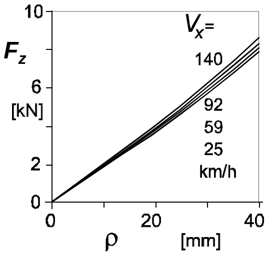
— coefficient from curve fitting

Examples:

- vertical force

$$F_z = f\left(\rho, \Omega, F_x, F_y, p_i\right)$$

$$F_z = \left(1 + \underline{q_{v2}}\frac{R_0}{V_0}|\Omega| - \left(\frac{\underline{q_{Fcx}}F_x}{F_{z0}}\right)^2 - \left(\frac{\underline{q_{Fcy}}F_y}{F_{z0}}\right)^2\right) \cdot \left(\underline{q_{Fz1}}\frac{\rho}{R_0} + \underline{q_{Fz2}}\left(\frac{\rho}{R_0}\right)^2\right)(1 + \underline{p_{Fz1}}dp_i)F_{z0}$$



delfttyre
TNO innovation for life

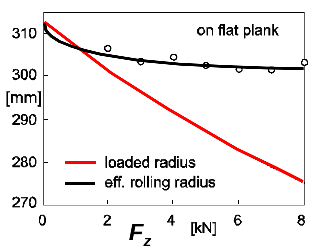
Constitutive relations

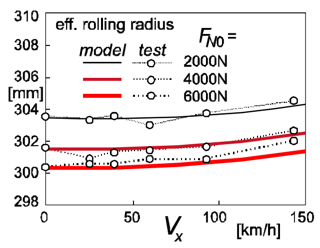
- effective rolling radius

— coefficient from curve fitting

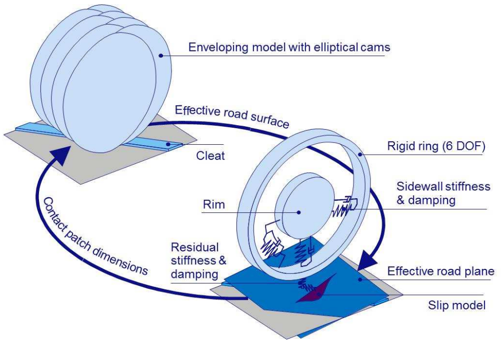
$$R_e = R_\Omega - \frac{F_{z0}}{c_z}\left(\underline{D_{reff}}\arctan\left(\underline{B_{reff}}\frac{F_z}{F_{z0}}\right) + \underline{F_{reff}}\frac{F_z}{F_{z0}}\right)$$

$$R_\Omega = R_0\left(\underline{q_{re0}} + \underline{q_{v1}}\left(\frac{\Omega R_0}{V_0}\right)^2\right)$$



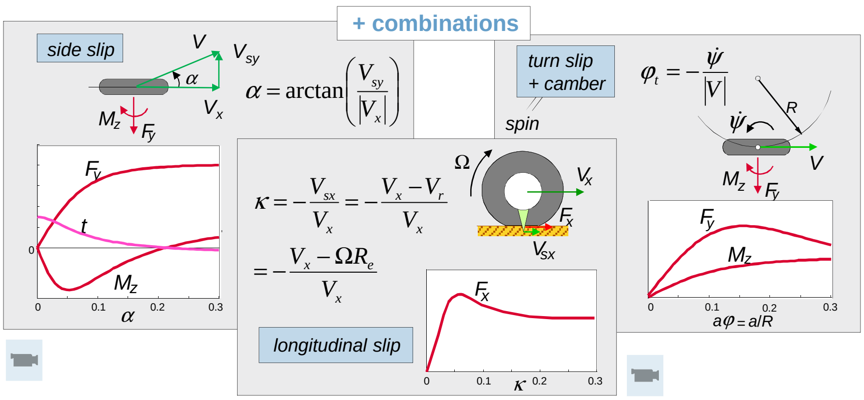


2. Inclusion of measured tyre steady-state slip characteristics (*magic formula*)



Magic Formula

- Descriptions are available for the three steady-state modes of slip
- Equations depend on vertical load F_z, inclination angle γ and inflation pressure p_i ; [Fx, Fy, Mx, My, Mz] = MF (Fz, κ, α, γ, φ, p_i, V)



 13 Dr. Antoine Schmeitz MF-Tyre/MF-Swift

delfttyre TNO innovation for life

Magic Formula

- Notion: the base tyre characteristics $F_x=f(\kappa)$, $F_y=f(\alpha)$ and $M_z=f(\alpha)$ have a sinusoidal shape, with a "stretched" horizontal axis for large values of slip
- This consideration is the basis for a tyre model known as "**Magic Formula**"
- Some notes:
  - First versions developed by Egbert Bakker (Volvo) and prof. Pacejka (TU Delft, TNO)
  - MF-Tyre software developed and distributed by TNO since 1996
  - Probably the most popular tyre model for vehicle handling simulations (worldwide!)

 14 Dr. Antoine Schmeitz MF-Tyre/MF-Swift

delfttyre TNO innovation for life

Base Magic Formula

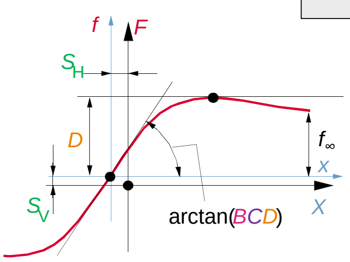
$$f = D \sin[\, C \arctan\{ Bx - E(Bx - \arctan(Bx))\}\,]$$

$$F(x) = f(x) + S_V$$
$$x = X + S_H$$

X: input, e.g. α or κ

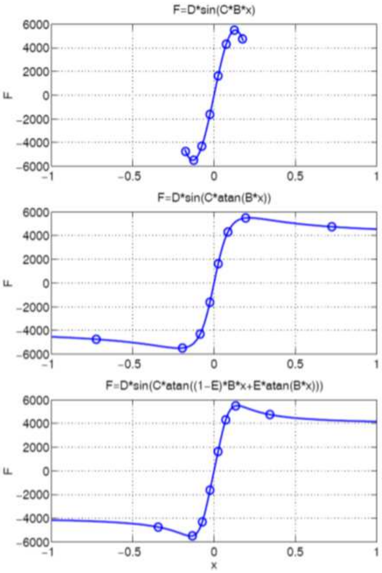
F: output, e.g. F_y or F_x

D	:	peak factor
C	:	shape factor
B	:	stiffness factor
E	:	curvature factor
$S_{H,V}$	:	hor./vert. shift



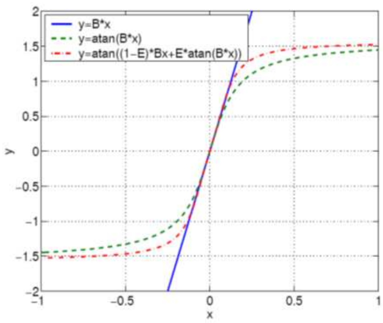
Note:
- *C* determines the limit value when x→∞
- *BCD* determines the slope near the origin
- *B*, *E* & *C* determine the location of the peak

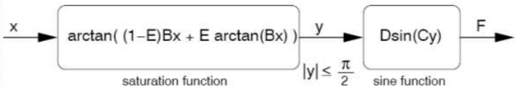
Stretching the sine…



parameters in this example:

B=8, C=1.5, D=5500, E=-2





Example: pure longitudinal slip characteristics

$$F_{x0} = D_x \sin(C_x \arctan((1-E_x)B_x\kappa_x + E_x \arctan(B_x\kappa_x)))$$

where:

$$\kappa_x = \kappa + S_{Hx} = \kappa + p_{Hx1} + p_{Hx2}df_z$$
$$D_x = F_z\mu_x\lambda_{\mu x} = F_z(p_{Dx1} + p_{Dx2}df_z)\lambda_{\mu x}$$
$$C_x = p_{Cx1}$$
$$E_x = p_{Ex1} + p_{Ex2}df_z + p_{Ex3}df_z^2$$
$$K_x = B_xC_xD_x = F_z(p_{Kx1} + p_{Kx2}df_z)\lambda_{Kx}$$

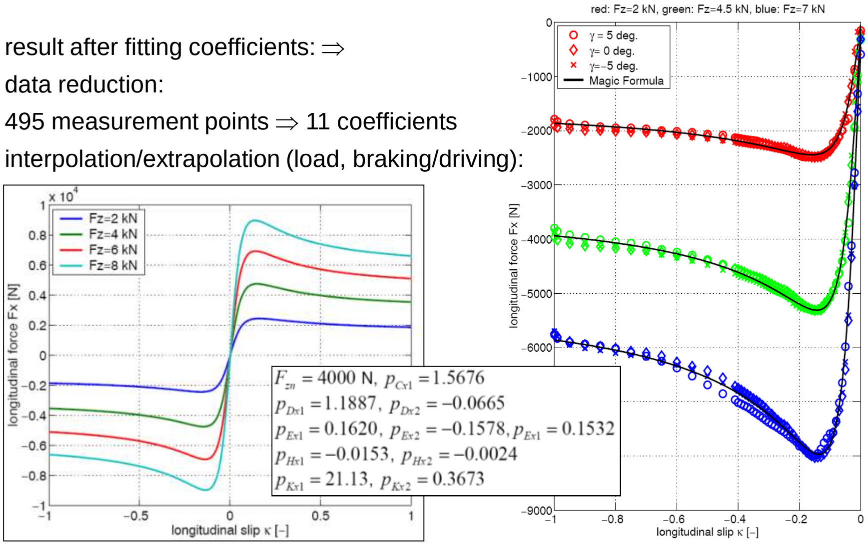
note:

- $K_x = C_{f\kappa}$: longitudinal slip stiffness
- B_x is calculated from C_x, D_x and K_x
- equations simplified for educational reasons…

- coefficients p are determined in curve fitting process
- scaling coefficients λ:
  - equal 1 during fitting process
  - may be used to adjust tyre characteristics
- vertical load increment:
  $$df_z = \frac{F_z - F_{z0}}{F_{z0}}$$
  - F_{z0} is nominal load

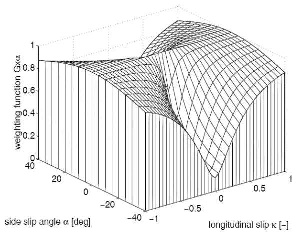
Example: pure longitudinal slip characteristics

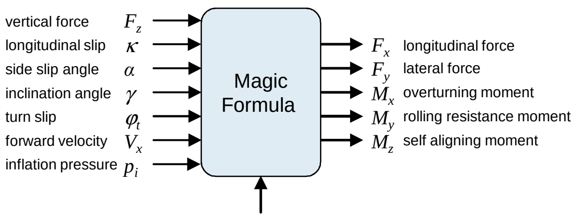
- result after fitting coefficients: ⇒
- data reduction:
  495 measurement points ⇒ 11 coefficients
- interpolation/extrapolation (load, braking/driving):



Magic Formula

- Similar equations exist for F_x, F_y, M_x, M_y and M_z
- Combined slip: reduction of F_x and F_y by applying a weighting function G to the 'pure' characteristics
  Example: $F_x = G_{x\alpha} \cdot F_{x0}$
- In total 144 parameters that are curve fitted using an automated process;
  typical fit errors of a few percent



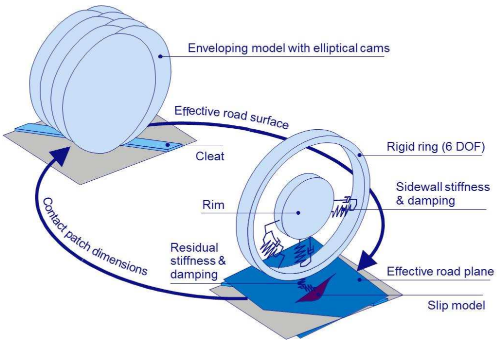


parameters: general (4), F_x (29), F_y (50), M_x (15), M_y (8), M_z (38)

19

Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

3. Tyre transients / relaxation length properties



20

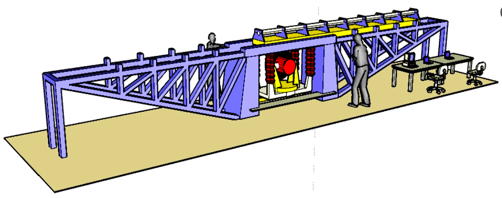
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

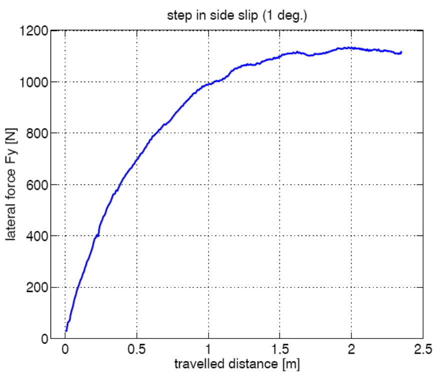
Tyre transients

Measure step response to side slip angle

Procedure:

1. Apply steering angle of 1 deg.
2. Load the tyre
3. Start rolling the track at low velocity (e.g. 0.05 m/s)



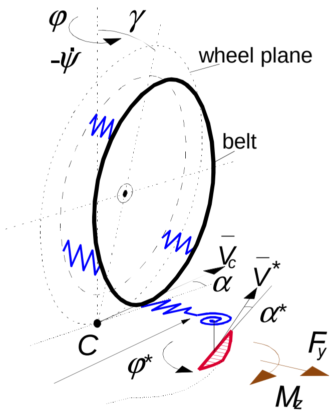


Tyre transients

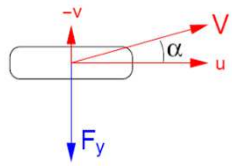
- Tyre cannot instantaneously react to changes in slip
- Travelled distance required to build up forces
- Relaxation effects exist for all modes of slip

This is due to:
1. carcass compliance
2. finite contact length

In MF-Swift both are considered:
1. carcass stiffness → springs
2. contact patch slip model
   (Magic Formula (MF) slip model and
   contact patch transients)



Simplified example carcass stiffness



- Assume linear tyre model for small slip angles:

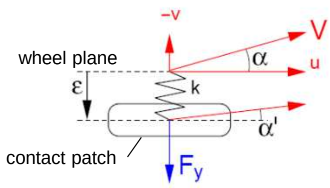
$$F_y = C\alpha \qquad \alpha = -\frac{v}{u}$$

- Create dynamic tyre model by accounting for tyre sidewall stiffness:

$$F_y = C\alpha' = k\varepsilon \longrightarrow C\dot{\alpha}' = k\dot{\varepsilon}$$

- Dynamic side slip angle: $\alpha' = -\dfrac{v + \dot{\varepsilon}}{u}$

$$\frac{C}{k}\frac{1}{u}\dot{\alpha}' + \alpha' = -\frac{v}{u} = \alpha$$



- Introducing the relaxation length σ (=C/k) and V≈u:

$$\frac{\sigma}{V}\dot{\alpha}' + \alpha' = \alpha \qquad F_y = C\alpha'$$

Simplified example carcass stiffness

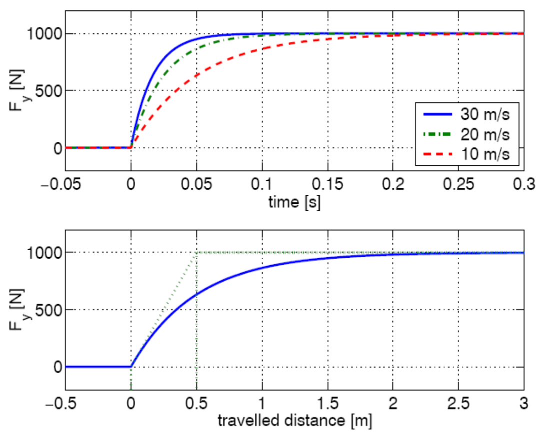
- First order dynamics between lateral force and side slip angle input, transfer function:

$$H_{F_y,\alpha}(s) = \frac{C}{\frac{\sigma}{V}s + 1} \qquad \text{time constant: } \frac{\sigma}{V}$$

- Relaxation length σ does not depend on forward velocity *V*:
  - response time reduces when increasing *V*;
  - travelled distance required to build up the lateral force remains the same.

Simplified example carcass stiffness

step response (α = 1 deg, *C* = 1000 N/deg, σ = 0.5 m)



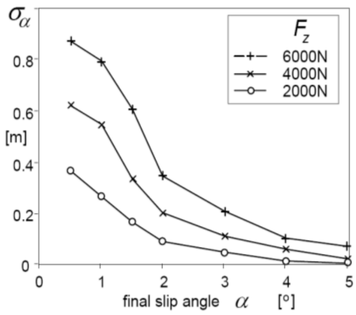
Tyre relaxation effects

- Experiments show that relaxation length depends on:
  - vertical load F_z
  - slip level
  - inflation pressure
- Thus also relaxation effects when F_z is changed at e.g. constant side slip

Modelling

Slip and vertical load dependency can be included by using nonlinear slip characteristics (MF) and load and inflation pressure dependent carcass stiffness

processed measurements: relaxation lengths σ_α from small changes in side slip angle ($\Delta\alpha = 0.5°$)



Contact patch slip model

- For shorter wavelengths λ (0.1 < λ < 5 m) of e.g. side slip, the finite length of the contact patch needs to be considered
- Important for aligning torque response to sideslip and for turn slip

MF-Swift contact patch slip model:

- Contact patch has stiffness (stiffness of tread elements)
- From physical brush model derived differential equations for contact patch transients (relaxation lengths depend on slip and tread stiffness)
- Nonlinear slip characteristics from Magic Formula model
  (basically the brush model slip characteristics are replaced by the more accurate Magic Formula characteristics)

27
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

delfttyre
TNO innovation for life

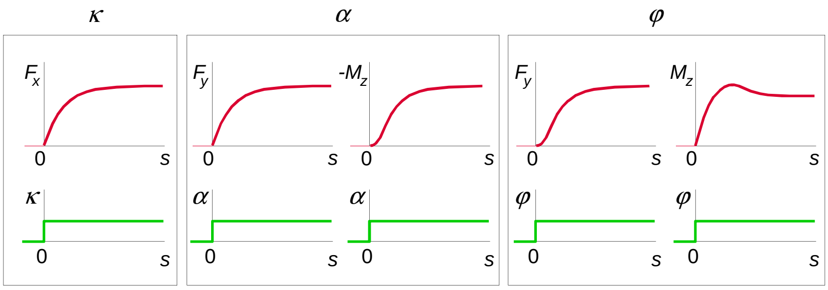
Contact patch slip model

In total 7 nonlinear 1st-order differential equations (derived from brush model):

- one 1st-order differential equation for κ_c'
- two 1st-order differential equations for α_c' and α_t'
- four 1st-order differential equations for φ_c'

κ_c', α_c', α_t', φ_c' inputs into Magic Formula

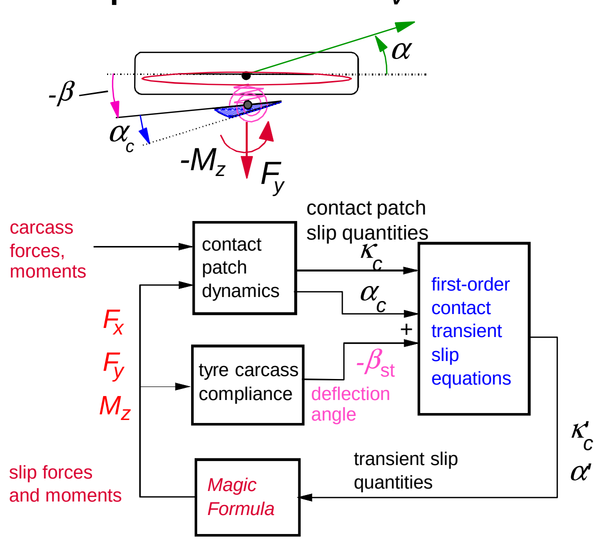
contact patch step responses



28
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

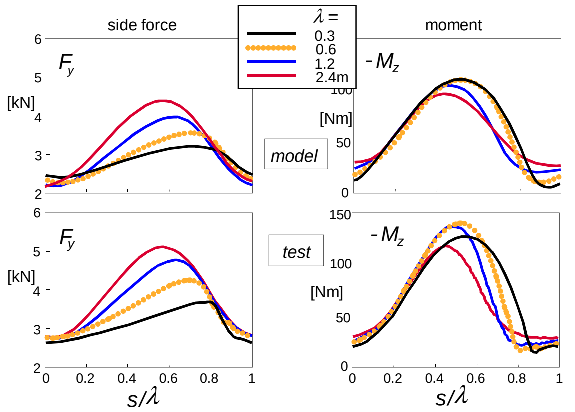
delfttyre
TNO innovation for life

Contact patch slip model



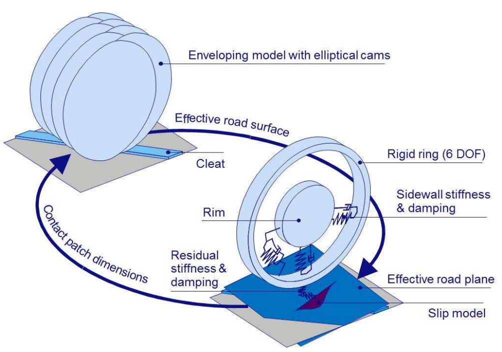
Wheel load oscillations at constant side slip

$F_z = F_{zo} + F_{zv}\sin(2\pi s/\lambda)$ $F_{zo} = 4000\,\text{N}$ $F_{zv} = 2000\,\text{N}$ $\alpha = 5^\circ$ $V = 0.6$ m/s



Copyright TNO, 2013

4. Inclusion of belt dynamics

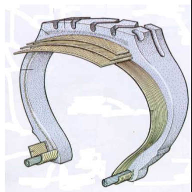


31

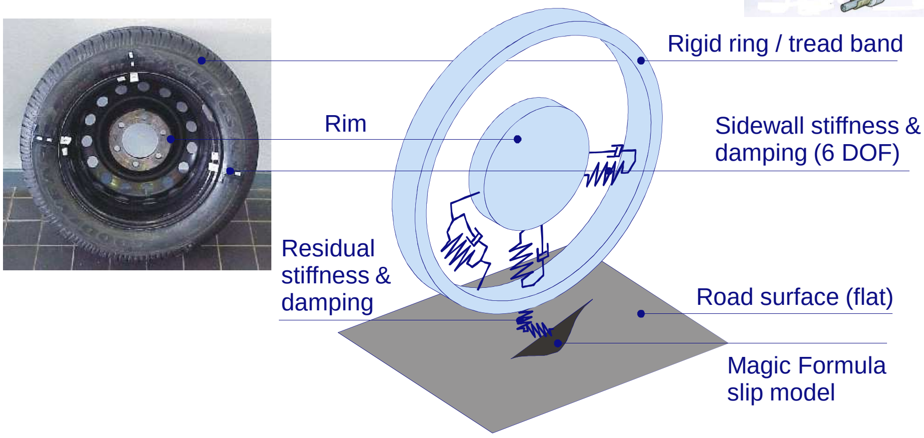
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

delfttyre
TNO innovation for life

MF-Swift: inclusion of belt dynamics



- First mode shapes are rigid belt vibrational modes
- Below about 100 Hz we can suffice considering these modes



32

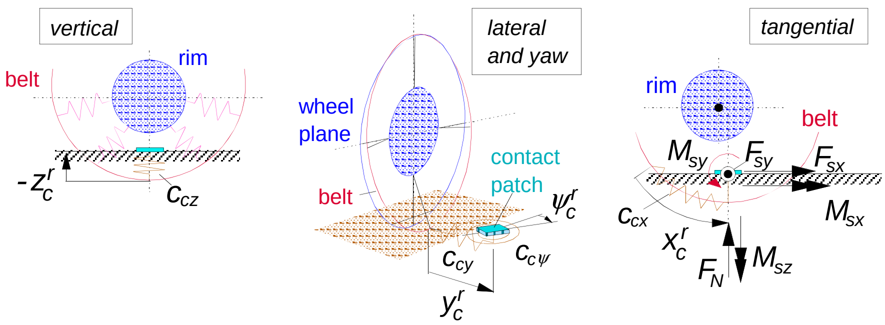
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

delfttyre
TNO innovation for life

Residual stiffness

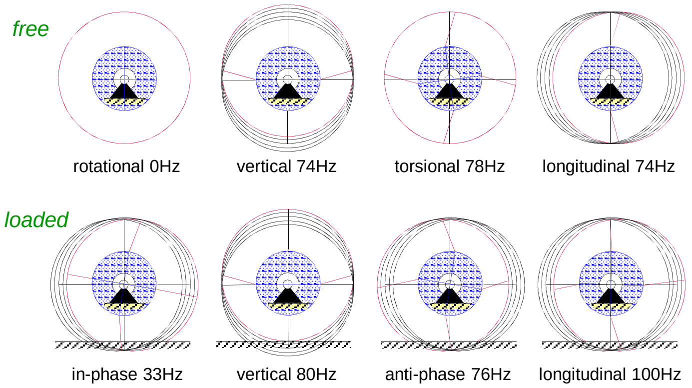
Residual stiffness elements (c_{cz}, c_{cy}, $c_{c\psi}$, c_{cx}) between belt and contact patch

- assure correct overall tyre stiffness resulting in correct loaded radius vs. vertical force and correct relaxation lengths
- describe the effects of the modes that lie above the maximum frequency of interest (high-frequency modes, i.e. non rigid belt modes)



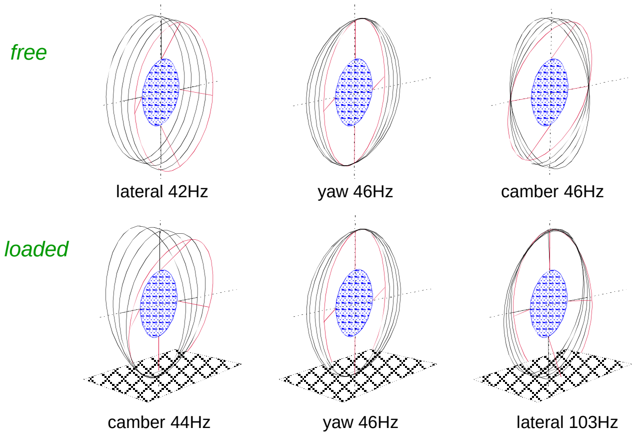
In-plane modes and natural frequencies

featured by model at stand-still
after having fitted parameters from tests on loaded and rolling tyre

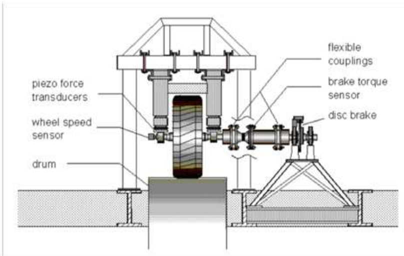


Out-of-plane modes and natural frequencies

featured by model at stand-still
after having fitted parameters from tests on loaded and rolling tyre

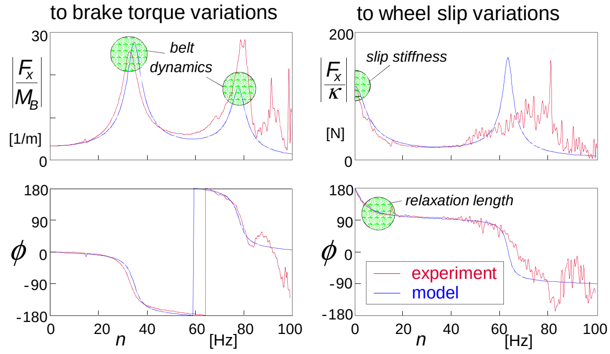


Validation: dynamic braking

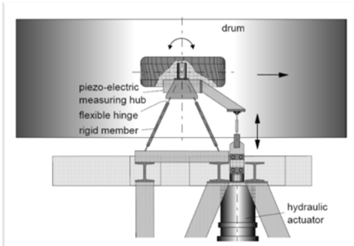


- longitudinal force response

V = 25 km/h
F_z = 4000 N

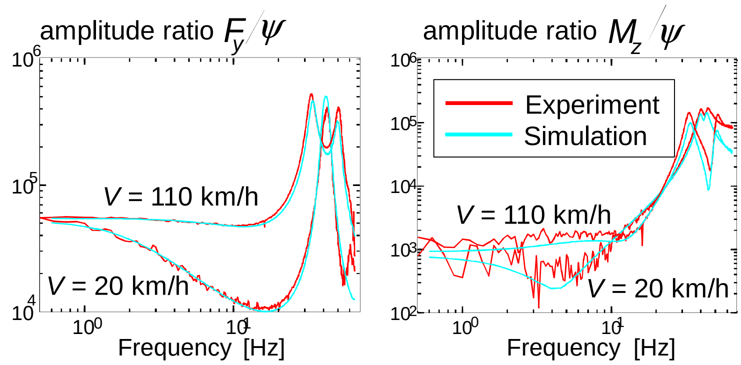


Validation: yaw oscillation



side force and moment response to yaw oscillations at different speeds

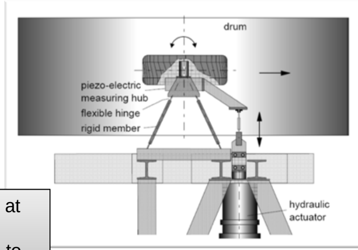
Note: splitting of single peak at low velocity into two peaks (camber and yaw mode) due to gyroscopic action



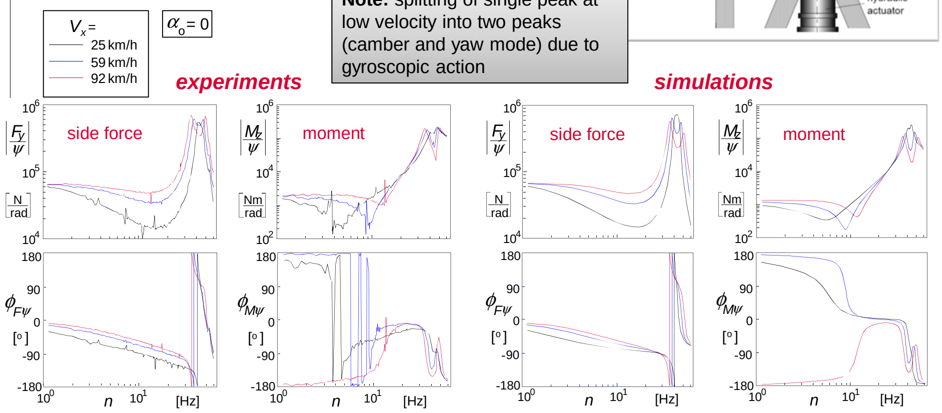
delfttyre
TNO innovation for life

Validation: yaw oscillation

- side force and moment response to yaw oscillations at different speeds



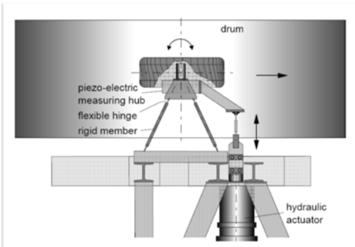
Note: splitting of single peak at low velocity into two peaks (camber and yaw mode) due to gyroscopic action

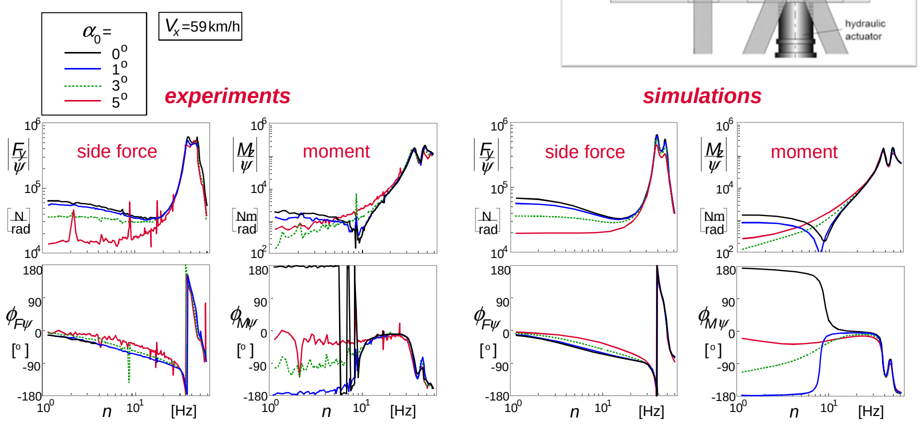


delfttyre
TNO innovation for life

Validation: yaw oscillation

- side force and moment response to yaw oscillations at different slip angles

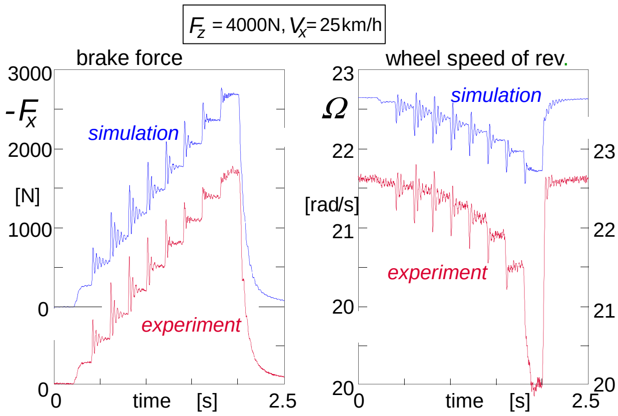




Validation: step changes in brake pressure

responses to successive step changes in brake pressure versus time

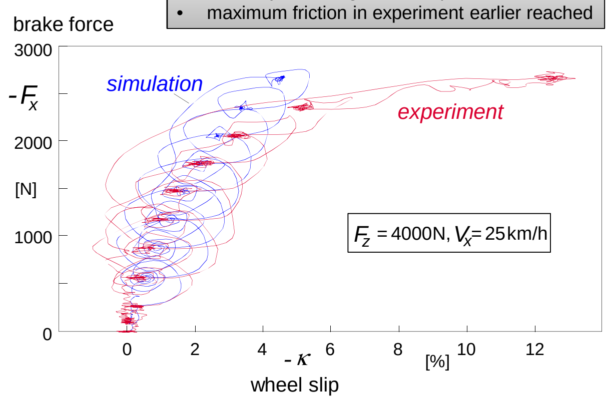
Note:
- steps in brake pressure up to wheel lock; then brake released
- vibrations (about 28 Hz) attributed to the in-phase rotational mode of the system with the brake and axle inertia included



Validation: step changes in brake pressure

responses to successive step changes in brake pressure versus longitudinal wheel slip

Note:
- similarity with longitudinal slip characteristics
- maximum friction in experiment earlier reached



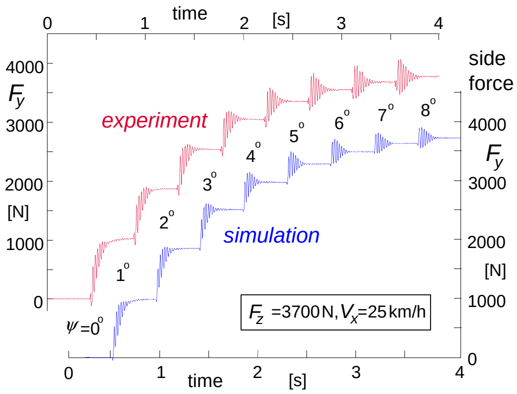
41

Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

Validation: step changes in steering angle

side force response to successive step changes in steer angle versus time

Note:
- vibrations attributed to yaw/camber mode with frequency of about 40 Hz
- decrease overall relaxation length at larger sideslip angles



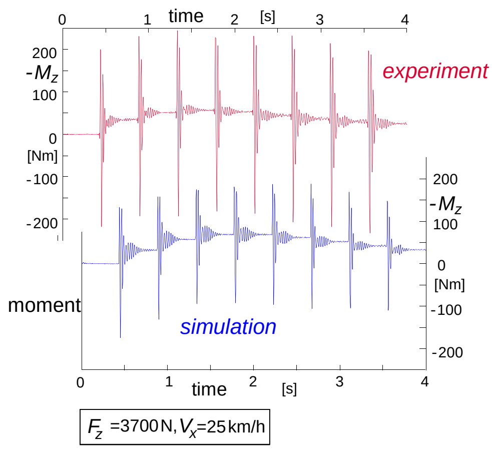
Copyright TNO, 2013

42

Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

Validation: step changes in steering angle

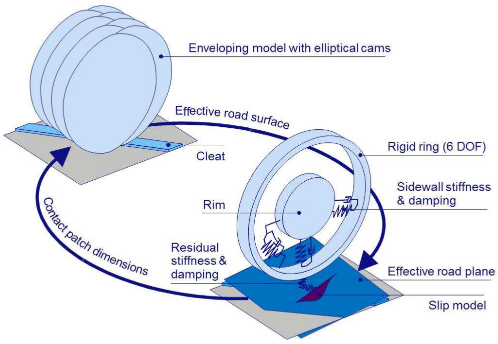
aligning moment response to successive step changes in steer angle versus time



43

Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

5. Tyre rolling over uneven road surface



Copyright TNO, 2013

44

Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

Summarising

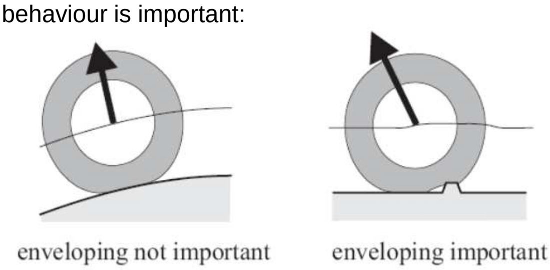
So far:

excitation of the tyre via axle motions or braking/steering on a flat road surface

Next:

tyre dynamics can also be excited via the road;

for short wavelength unevenness (e.g. short obstacles/cleats) the tyre enveloping behaviour is important:



Enveloping example: rolling over short obstacle

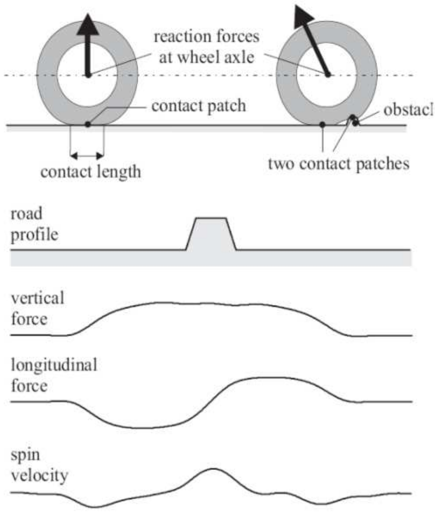
Constant axle height experiment

Three distinct responses:

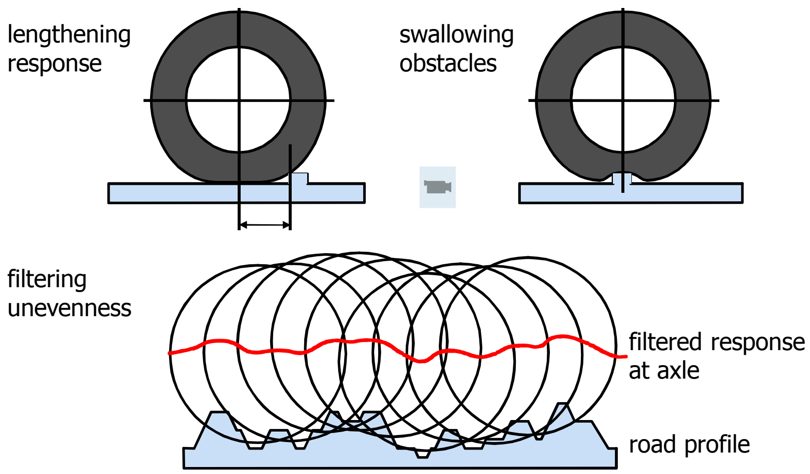
- variations in vertical force
- variations in longitudinal force
- variations in wheel spin velocity

Note:

- tyre touches obstacle before and after wheel centre is above the obstacle!
- shape of the response is totally different from obstacle shape



Phenomena enveloping behaviour



The effective road surface

Assumptions

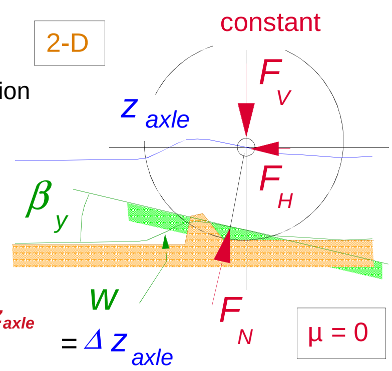
- The tyre contact zone, where the large deformations due to envelopment of the unevenness occur, dynamically deforms mainly in the same way as it does quasi-statically
- Local dynamic effects can be neglected
- Rigid ring model takes care of the tyre dynamics

Approach

- A special road filter has been developed to take care of the enveloping properties
- This filtered road surface is called the **effective road surface**
- Instead of the actual road surface, this effective road surface is the input of the rigid ring model

The effective road surface

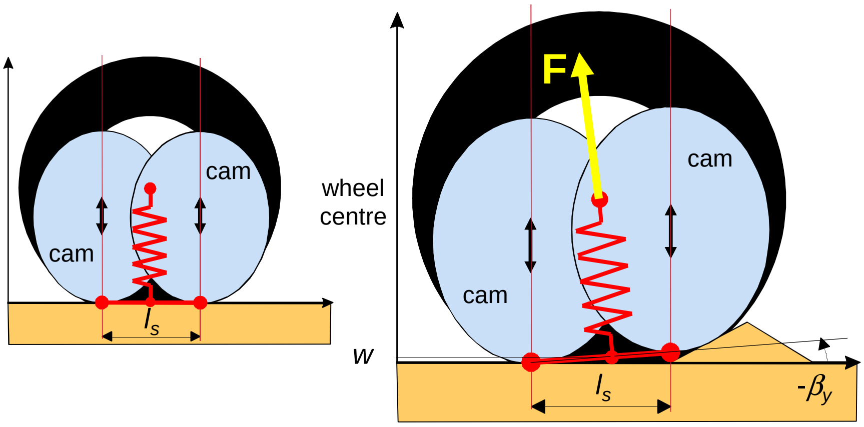
The concept of the ***effective road surface*** is that for each axle position an ***effective road plane*** can be defined the position and orientation of which is governed by the resulting tyre force.



Definition

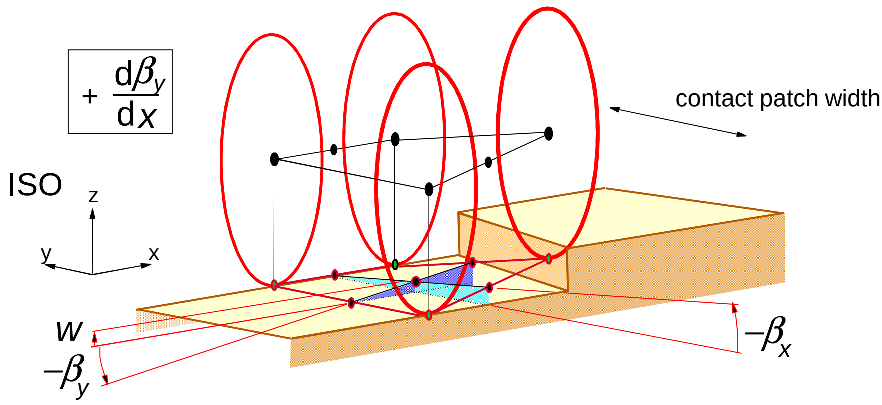
- Vertical position ***w*** of eff. road plane varies according to vertical axle movement z_{axle} at constant vertical load F_V.
- Slopes β_y (and β_x for 3D) of the eff. road plane according to orientation of the resulting tyre force F_N when moving over frictionless surface (**μ = 0**).

Tandem-cam enveloping model



3D Tandem-cam enveloping model

- Four effective road input quantities
- Road curvature $d\beta_y/dx$ used for extra variation of the eff. rolling radius

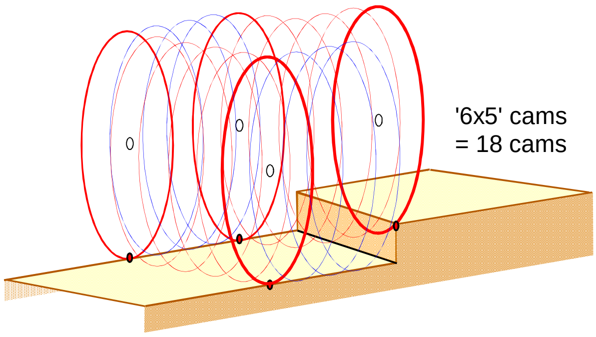


51
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

3D Tandem-cam enveloping model

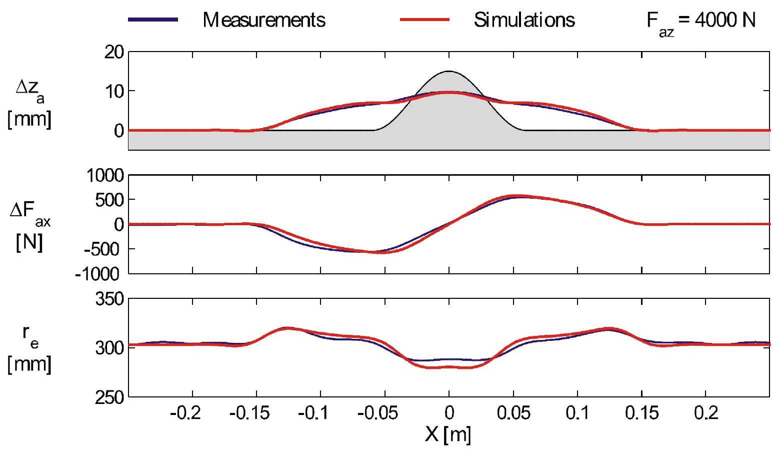
For higher accuracy on short obstacles one might introduce:

- for w and β_y:
  - more parallel tandems (multi-track)
- for β_x:
  - intermediate cams at the side edges

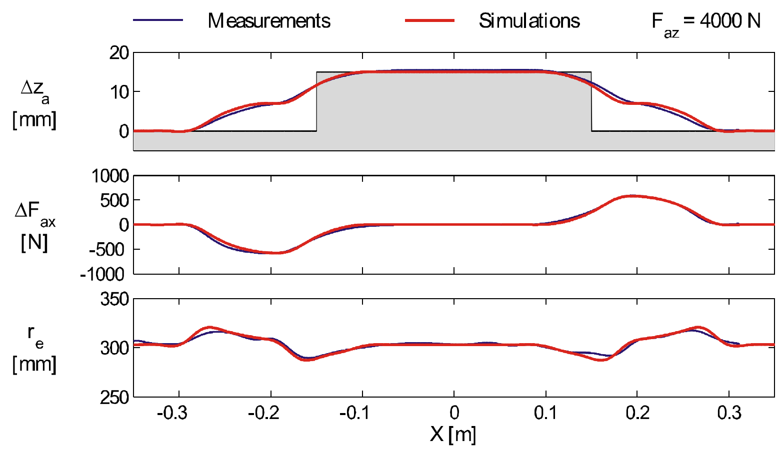


52
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift

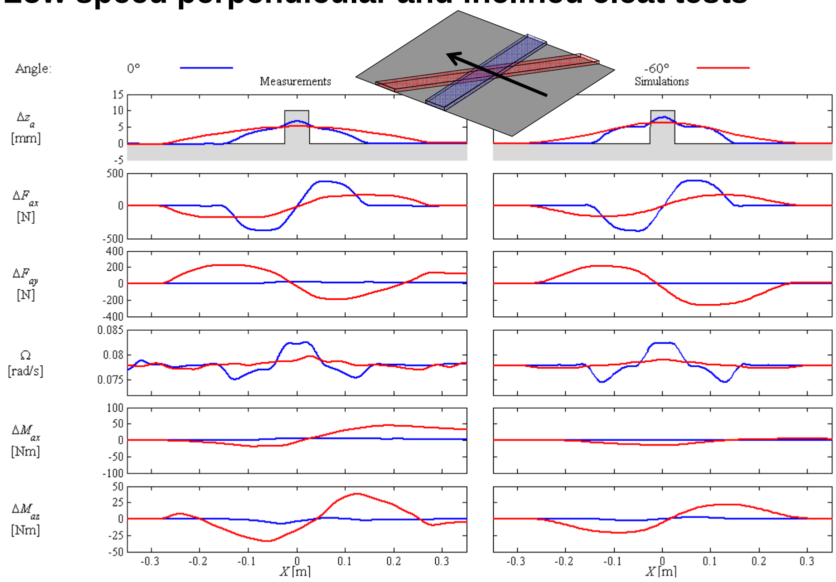
Example of validation result



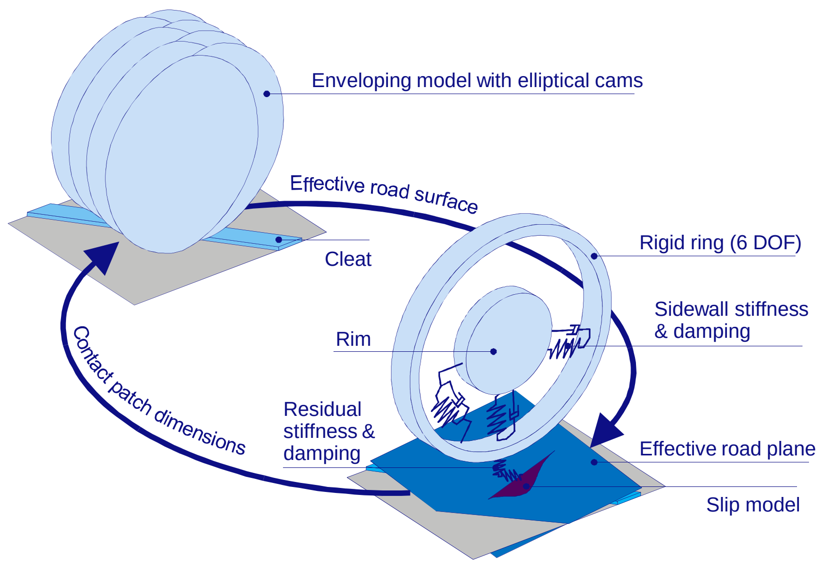
Example of validation result



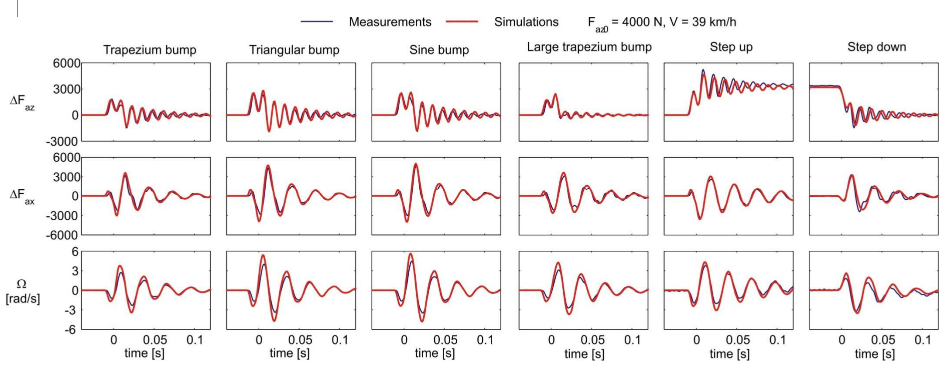
Low speed perpendicular and inclined cleat tests

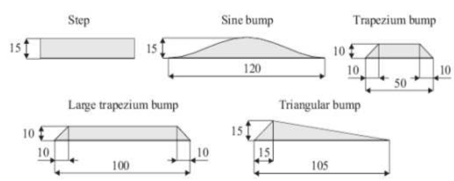


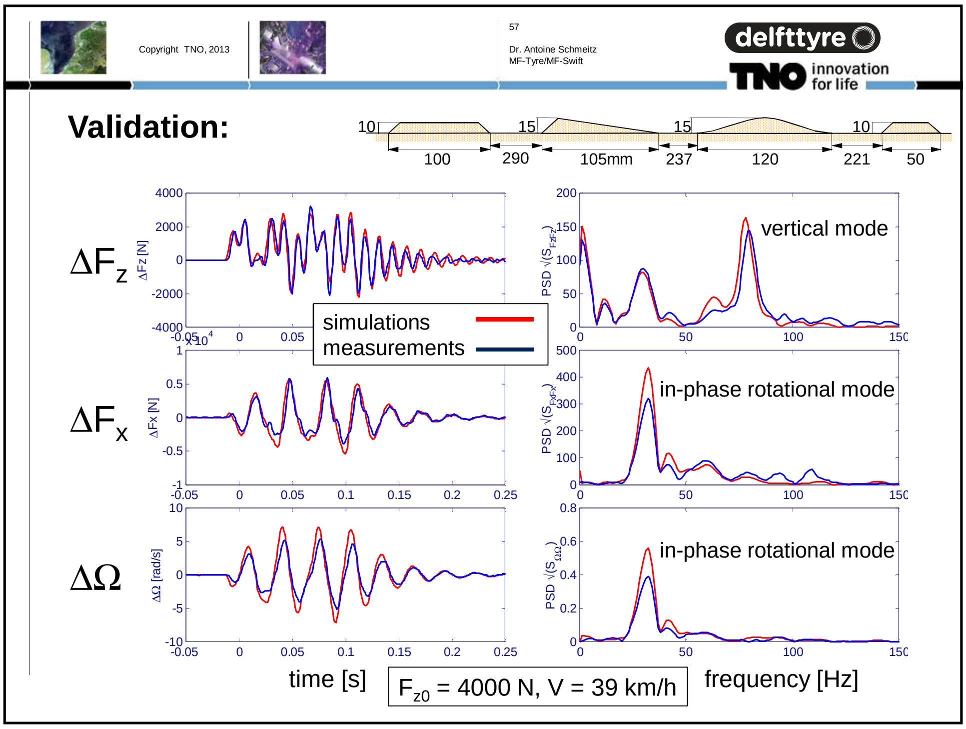
MF-Swift: 3D road unevenness

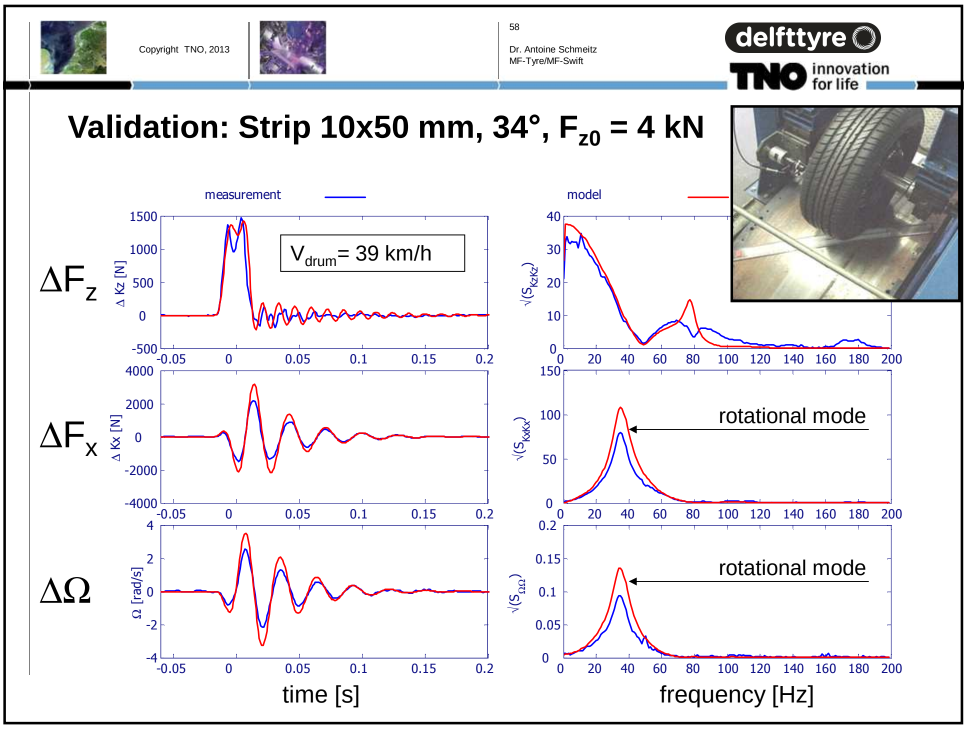


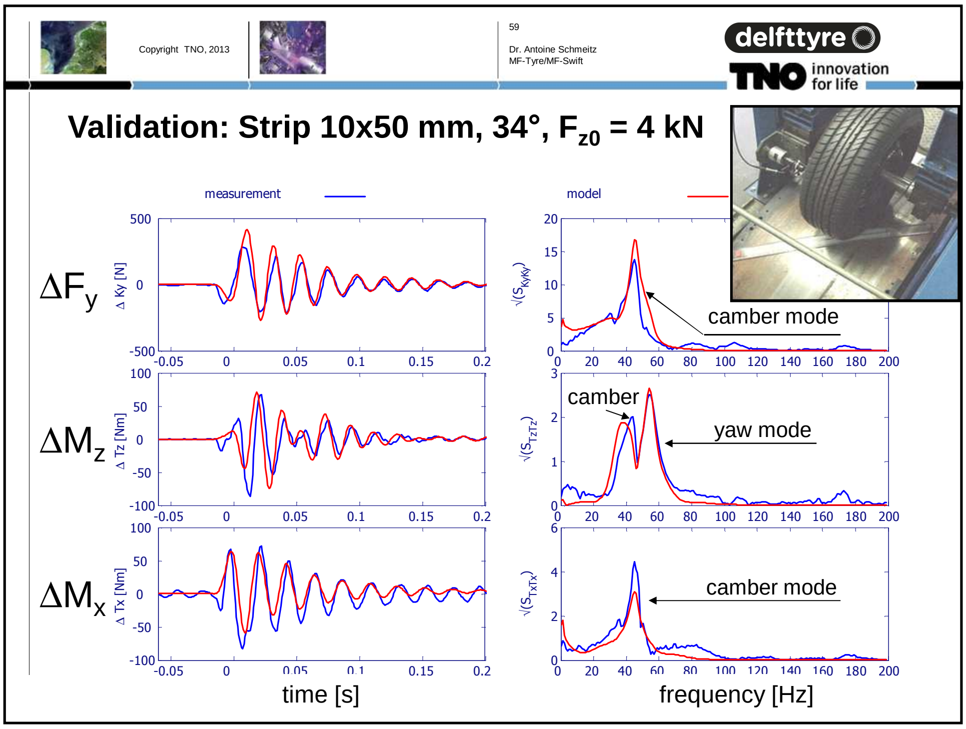
Validation: various obstacle shapes

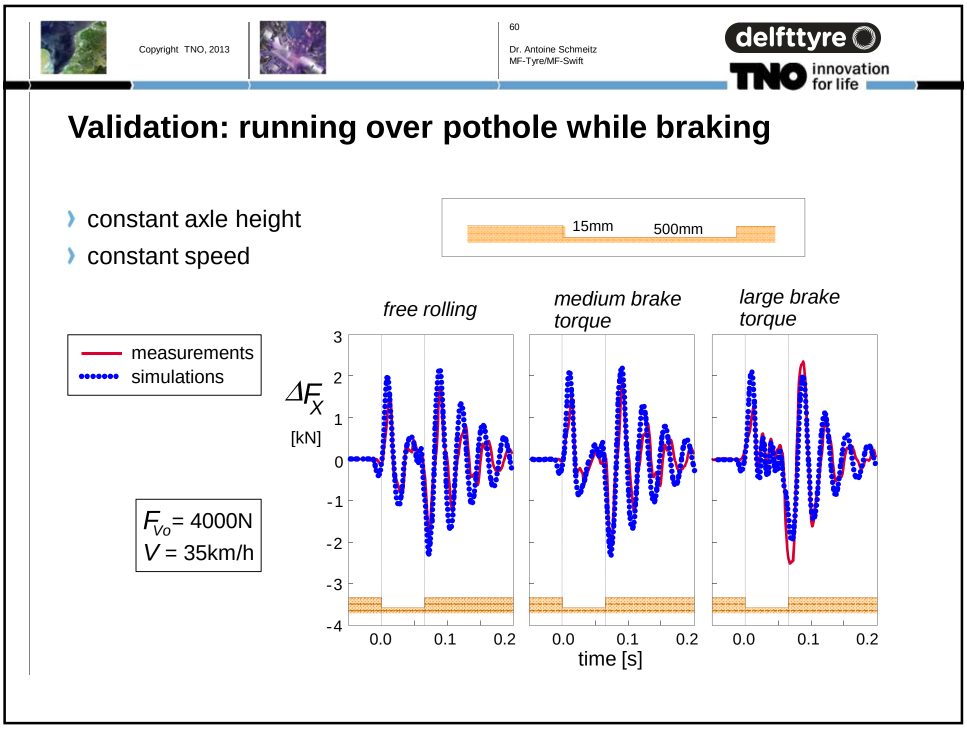





Copyright TNO, 2013
57
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift
delfttyre
TNO innovation for life
Validation:
10
15
15
10
100
290
105mm
237
120
221
50
ΔFz
ΔFx
ΔΩ
vertical mode
in-phase rotational mode
in-phase rotational mode
simulations
measurements
time [s]
Fz0 = 4000 N, V = 39 km/h
frequency [Hz]


Copyright TNO, 2013
58
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift
delfttyre
TNO innovation for life
Validation: Strip 10x50 mm, 34°, Fz0 = 4 kN
measurement
model
ΔFz
ΔFx
ΔΩ
Vdrum= 39 km/h
rotational mode
rotational mode
time [s]
frequency [Hz]

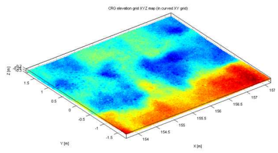

59
Copyright TNO, 2013
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift
delfttyre
TNO innovation for life
Validation: Strip 10x50 mm, 34°, F_{z0} = 4 kN
measurement
model
ΔFy
ΔMz
ΔMx
Δ Ky [N]
Δ Tz [Nm]
Δ Tx [Nm]
camber mode
camber
yaw mode
camber mode
time [s]
frequency [Hz]


60
Copyright TNO, 2013
Dr. Antoine Schmeitz
MF-Tyre/MF-Swift
delfttyre
TNO innovation for life
Validation: running over pothole while braking
constant axle height
constant speed
15mm
500mm
measurements
simulations
free rolling
medium brake torque
large brake torque
ΔFx [kN]
F_{Vo}= 4000N
V = 35km/h
time [s]

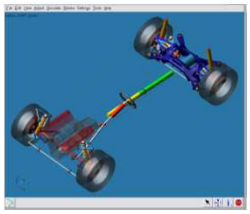
Road load simulation example

- Durability load calculation at Nissan, Japan
- SAE paper 2011-01-0190

durability road
digitised 4x4 mm grid
9.7 GB



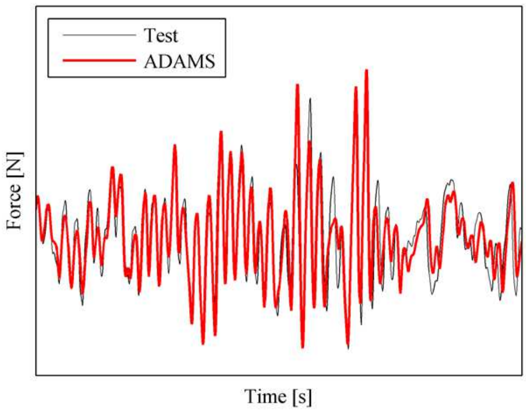
OpenCRG file
4x4 mm grid size
binary, 273 MB

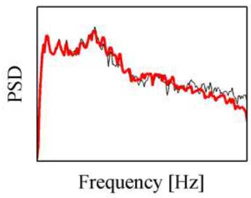


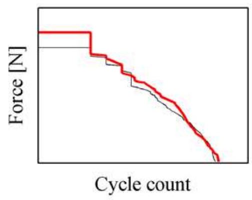
Adams model
flexible body
rigid suspension
MF-Swift 6.1.2

Road load simulation example

- Validation: front left shock absorber force

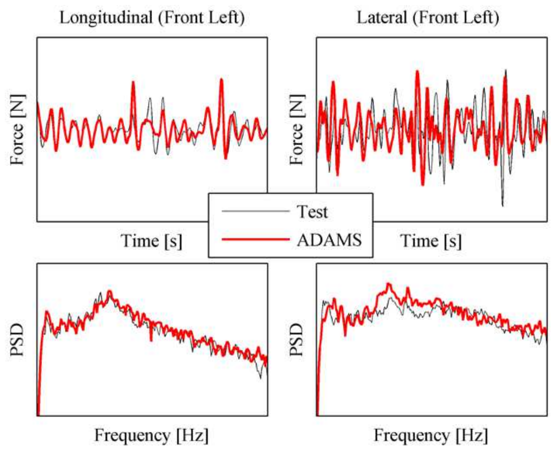




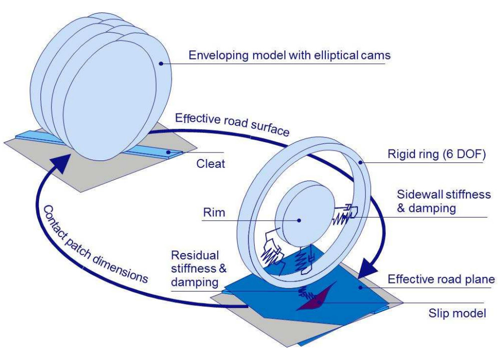


Road load simulation example

- Validation: lower link ball joint forces

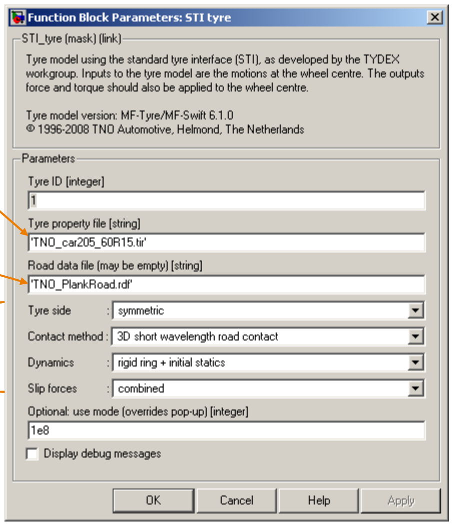


6. Model usage and availability



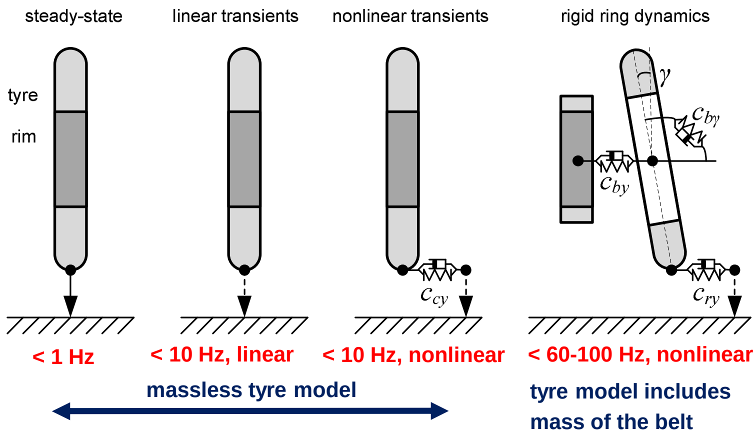
Using the tyre model

- Tyre model parameters
  - Tyre property file (*.tir)
  - Result of MF-Tool
- Road surface definition
  - Road data file (*.rdf, *.crg)
- Select model complexity
  - Operating or use mode



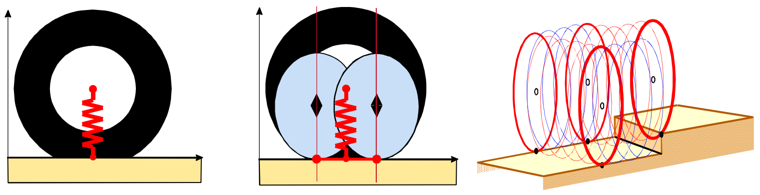
Complexity level of the model can be changed

- The most complex model is not always needed (dynamics mode)
- Within validity range simulation results are identical



Complexity level of the model can be changed

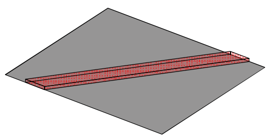
The most complex contact model is not always needed

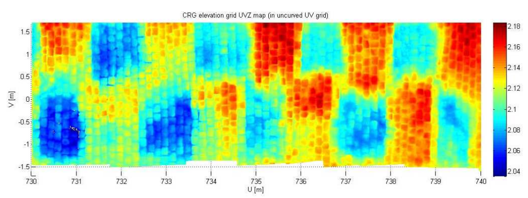


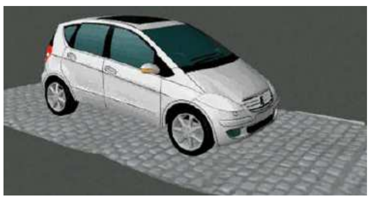
- Depending on the wavelength of the obstacles/unevenness a contact method can be selected
- For enveloping the number of contact points and cams can be chosen
- 2D/3D enveloping is generally combined with rigid ring dynamics because of the high frequency excitation

Road definition

- Road definitions inside the tyre model
  - predefined road profiles with limited set of parameters (e.g. flat, plank, sine, polyline, drum + cleat)
  - 3D measured road profiles (OpenCRG®)







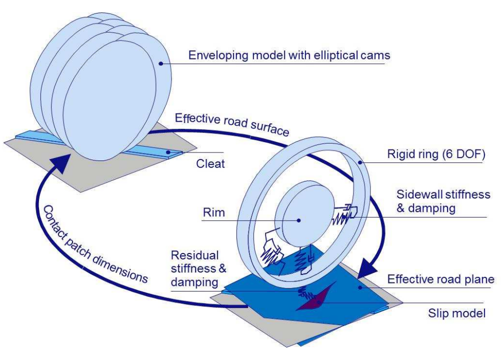
- In many packages it is also possible to use the native road definition, coming along with the simulation package.

OpenCRG® is on: **http://www.opencrg.org**

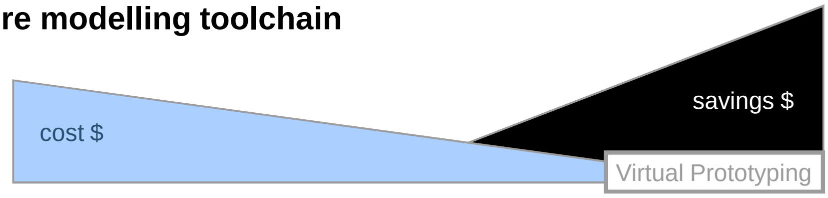
Model availability

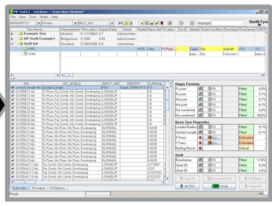
- MF-Tyre/MF-Swift is available for all major simulation packages used in vehicle dynamics

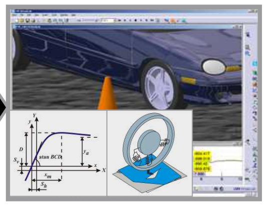
7. Model parameterisation



Tire modelling toolchain







measurement

parameter identification

simulation

accumulating error determines accuracy

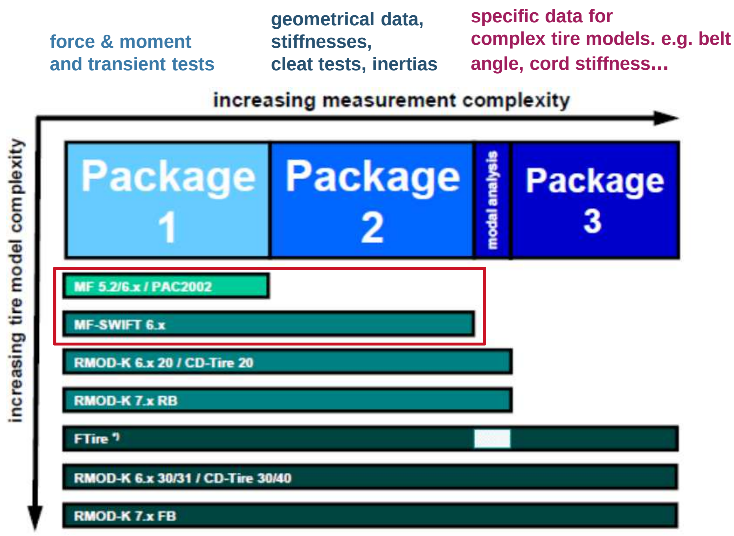
Measurement requirements

- MF-Tyre can be parameterised using the following tests:
  - Geometry, mass and inertia measurements
  - Force and moment measurements (Magic Formula dataset)
  - Loaded radius and rolling radius measurements
  - Footprint measurements
  - Stiffness measurements

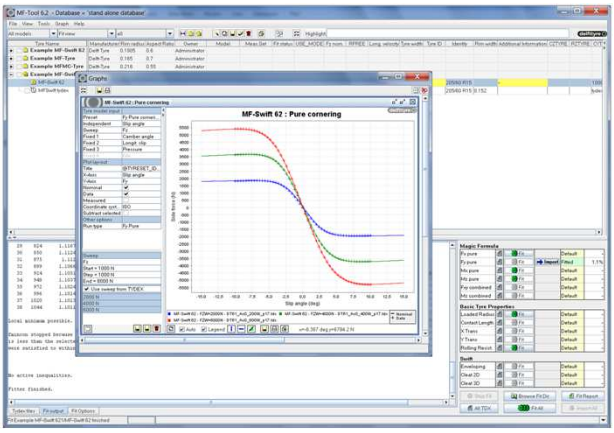
- Additionally for MF-Swift
  (enveloping and rigid ring components)
  - Cleat experiments

Measurement requirements

Source:
German OEM
AK 3.5.1

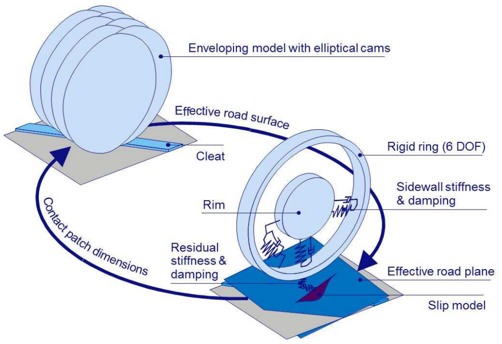


MF-Tool



- Fitting of current and historical tyre models (including MF 5.2)
- Database and plotting functionality
- Software is able to make estimates
- Available at all major tyre manufacturers
- Due to the model's semi-empirical nature different aspects of the tyre behaviour can be handled separately in (relatively) small optimisation steps and represented with maximum accuracy

8. Concluding remarks



Concluding remarks

The TNO Delft-Tyre toolchain (MF-Tyre/MF-Swift and MF-Tool) offers a versatile, high quality and cost efficient solution for tyre modelling:

- **MF-Tyre** leading Magic Formula implementation and unique features
- **MF-Swift** extension of MF-Tyre (rigid ring, enveloping, turn slip)
- **MF-Tool** provides independent parameter identification possibilities

- MF-Tyre/MF-Swift is one model for many applications
- implementations for all main simulation packages
- little measurements required
- computationally efficient
- MF-Tyre (Magic Formula) part is free of charge for many packages
- TNO provides parameter identification, training and consultancy
- well validated and open/accessible theory (many scientific publications)

Roles & responsibilities and contact information

- Model development is done by **TNO** (large independent research and technology organisation in The Netherlands)
- Worldwide sales and distribution of Delft-Tyre products (MF-Tyre/MF-Swift and MF-Tool) is done by **TASS** (**T**NO **A**utomotive **S**afety **S**olutions), which is a TNO subsidiary

tass international
Innovation for Mobility

Website:
http://www.tassinternational.com/delft-tyre

TNO, Delft-Tyre, P.O. Box 756, Helmond, The Netherlands
Willem Versteden (product manager) willem.versteden@tno.nl
Dr. Antoine Schmeitz (technical leader) antoine.schmeitz@tno.nl

Further reading

MF-Swift theory extensively described in book:

Hans Pacejka, **Tire and Vehicle Dynamics**, third edition, Butterworth-Heinemann, 2012