Adams 2023.2 - Online Help (HTML)

© 2025 Hexagon AB and/or its subsidiaries.

© 2025 Hexagon AB and/or its subsidiaries.

Using the PAC2002 Tire Model

The PAC2002 Magic-Formula tire model has been developed by MSC Software according to Tyre and Vehicle Dynamics by Pacejka [1]. PAC2002 is latest version of a Magic-Formula model available in Adams Tire.

Learn about:

© 2025 Hexagon AB and/or its subsidiaries.

■Example of PAC2002 Tire Property Files

When to Use PAC2002

Magic-Formula (MF) tire models are considered the state-of-the-art for modeling tire-road interaction forces in vehicle dynamics applications. Since 1987, Pacejka and others have published several versions of this type of tire model. The PAC2002 contains the latest developments that have been published in Tyre and Vehicle Dynamics by Pacejka [1].

In general, a MF tire model describes the tire behavior for rather smooth roads (road obstacle wavelengths longer than the tire radius) up to frequencies of 8 Hz. This makes the tire model applicable for all generic vehicle handling and stability simulations, including:

■Steady-state cornering

■Single- or double-lane change

■Braking or power-off in a turn

■Split-mu braking tests

■J-turn or other turning maneuvers

■ABS braking, when stopping distance is important (not for tuning ABS control strategies)

■Other common vehicle dynamics maneuvers

For modeling roll-over of a vehicle, you must pay special attention to the overturning moment characteristics of the tire (M_x) and the loaded radius modeling. The last item may not be sufficiently accurate in this model.

The PAC2002 model has proven to be applicable for car, truck, and aircraft tires with camber (inclination) angles to the road not exceeding 15 degrees.

Originally, Pacejka models have been developed for handling maneuvers at smooth road, as described above. However the PAC2002 has extended functionality that increases the validity towards short road obstacle wavelengths (with use of the 3D Enveloping Contact) and higher frequencies (up to 70 - 80 Hz) by using the tire belt dynamics modeling.

PAC2002 and Previous Magic Formula Models

Compared to previous versions, PAC2002 is backward compatible with all previous versions of PAC2002, MF-Tyre 5.x tire models, and related tire property files.

© 2025 Hexagon AB and/or its subsidiaries.

Modeling of Tire-Road Interaction Forces

For vehicle dynamics applications, an accurate knowledge of tire-road interaction forces is inevitable because the movements of a vehicle primarily depend on the road forces on the tires. These interaction forces depend on both road and tire properties, and the motion of the tire with respect to the road.

In the radial direction, the MF tire models consider the tire to behave as a parallel linear spring and linear damper with one point of contact with the road surface. The contact point is determined by considering the tire and wheel as a rigid disc. In the contact point between the tire and the road, the contact forces in longitudinal and lateral direction strongly depend on the slip between the tire patch elements and the road.

The figure, **Input and Output Variables of the Magic Formula Tire Model**, presents the input and output vectors of the PAC2002 tire model. The tire model subroutine is linked to the Adams Solver through the Standard Tire Interface (STI) [3]. The input through the STI consists of:

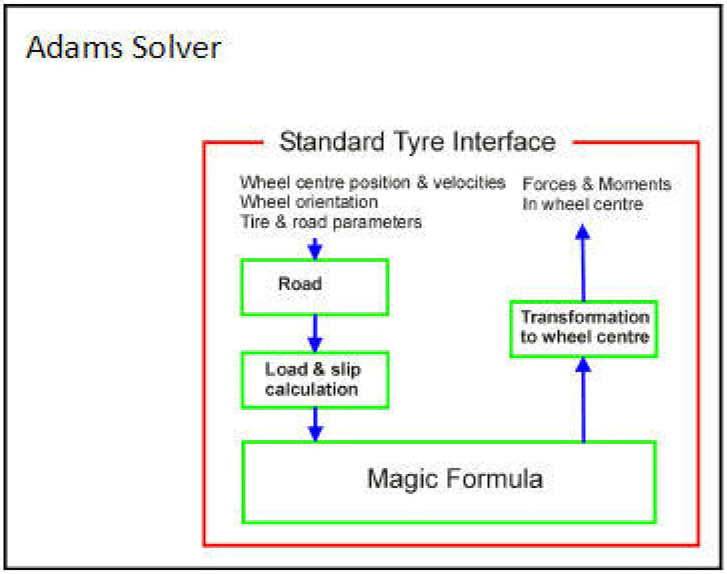
- Position and velocities of the wheel center
- Orientation of the wheel
- Tire model (MF) parameters
- Road parameters

The tire model routine calculates the vertical load and slip quantities based on the position and speed of the wheel with respect to the road. The input for the Magic Formula consists of the wheel load (F_z), the longitudinal and lateral slip (κ, α), and inclination angle (γ) with the road. The output is the forces (F_x, F_y) and moments (M_x, M_y, M_z) in the contact point between the tire and the road. For calculating these forces, the MF equations use a set of MF parameters, which are derived from tire testing data.

The forces and moments out of the Magic Formula are transferred to the wheel center and returned to Adams Solver through STI.

Input and Output Variables of the Magic Formula Tire Model

© 2025 Hexagon AB and/or its subsidiaries.



Axis Systems and Slip Definitions

- Axis Systems
- Units
- Definition of Tire Slip Quantities

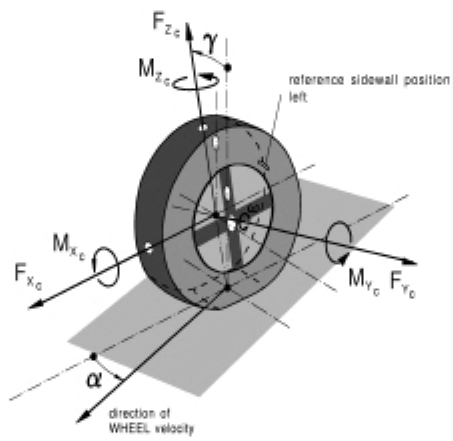
Axis Systems

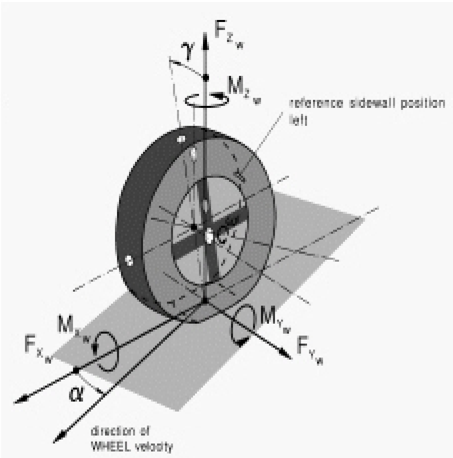
The PAC2002 model is linked to Adams Solver using the TYDEX STI conventions, as described in the TYDEX-Format [2] and the STI [3].

The STI interface between the PAC2002 model and Adams Solver mainly passes information to the tire model in the C-axis coordinate system. In the tire model itself, a conversion is made to the W-axis system because all the modeling of the tire behavior as described in this help assumes to deal with the slip quantities, orientation, forces, and moments in the contact point with the TYDEX W-axis system. Both axis systems have the ISO orientation but have different origin as can be seen in the figure below.

TYDEX C- and W-Axis Systems Used in PAC2002, Source [2]

© 2025 Hexagon AB and/or its subsidiaries.





The C-axis system is fixed to the wheel carrier with the longitudinal x_C-axis parallel to the road and in the wheel plane (x_C-z_C-plane). The origin of the C-axis system is the wheel center.

The origin of the W-axis system is the road contact-point defined by the intersection of the wheel plane, the plane through the wheel carrier, and the road tangent plane.

The forces and moments calculated by PAC2002 using the MF equations in this guide are in the W-axis system. A transformation is made in the source code to return the forces and moments through the STI to Adams Solver.

The inclination angle is defined as the angle between the wheel plane and the normal to the road tangent plane (x_W-y_W-plane).

Units

The units of information transferred through the STI between Adams Solver and PAC2002 are according to the SI unit system. Also, the equations for PAC2002 described in this guide have been developed for use with SI units, although you can easily switch to another unit system in your tire property file. Because of the non-dimensional parameters, only a few parameters have to be changed.

However, the parameters in the tire property file **must always be valid for the TYDEX W-axis system** (ISO oriented). The basic SI units are listed in the table below (also see Definitions).

SI Units Used in PAC2002

Variable type:	Name:	Abbreviation:	Unit:
Angle	Slip angle	α	Radian

© 2025 Hexagon AB and/or its subsidiaries.

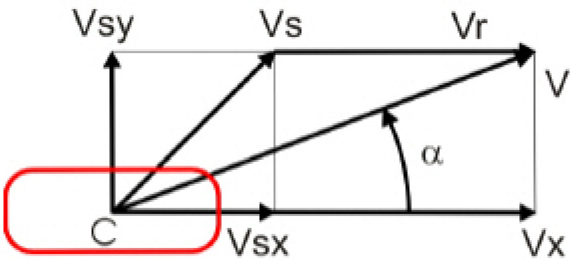
	Inclination angle	γ	
Force	Longitudinal force Lateral force Vertical load	F_x F_y F_z	Newton
Moment	Overturning moment Rolling resistance moment Self-aligning moment	M_x M_y M_z	Newton.meter
Speed	Longitudinal speed Lateral speed Longitudinal slip speed Lateral slip speed	V_x V_y V_{sx} V_{sy}	Meters per second
Rotational speed	Tire rolling speed	ω	Radian per second

Definition of Tire Slip Quantities

The longitudinal slip velocity V_{sx} in the contact point (W-axis system, see Slip Quantities at Combined Cornering and Braking/Traction) is defined using the longitudinal speed V_x, the wheel rotational velocity Ω, and the effective rolling radius R_e:

(1) $V_{sx} = V_x - \Omega R_e$

Slip Quantities at Combined Cornering and Braking/Traction



The lateral slip velocity is equal to the lateral speed in the contact point with respect to the road plane:

(2) $V_{sy} = V_y$

The practical slip quantities κ (longitudinal slip) and α (slip angle) are calculated with these slip velocities in the contact point with:

(3) $\kappa = -\frac{V_{sx}}{V_x}$

(4) $\tan\alpha = \frac{V_{sy}}{|V_x|}$

The rolling speed V_r is determined using the effective rolling radius R_e:

(5) $V_r = R_e\Omega$

Turn-slip is one of the two components that form the spin of the tire. Turn-slip ϕ is calculated using the tire yaw velocity $\dot{\psi}$:

(6) $\phi = \frac{\dot{\psi}}{V_x}$

The total tire spin φ is calculated using:

(7) $\varphi = -\frac{1}{V_x}\{\dot{\psi} - (1 - \varepsilon_\gamma)\Omega\sin\gamma\}$

The total tire spin has contributions of turn-slip and camber. ε_γ denotes the camber reduction factor for the camber to become comparable with turn-slip.

© 2025 Hexagon AB and/or its subsidiaries.

Contact Methods and Normal Load Calculation

■Contact Method

■Loaded and Effective Tire Rolling Radius

■Wheel Bottoming

Contact Methods

The PAC2002 tire model supports all Adams Tire contact methods.

■One Point Follower Contact, used by default for 2D Road, 3D Spline Road, OpenCRG Road and RGR Road.

■3D Equivalent Volume Contact, used by default for 3D Shell Road.

■3D Enveloping Contact, can be used with all road types when the keyword CONTACT_MODEL = '3D_ENVELOPING' is specified in the [MODEL] section of the tire property file.

In vertical direction, the PAC2002 tire is modeled as a parallel spring and damper. The spring deflection and damper velocity are derived with the (effective) road height and plane information supplied by the contact method.

The normal load F_z of the tire is calculated with the tire deflection ρ as follows:

$$F_z = \left\{ q_{REO} + q_{V2}|\Omega|\frac{R_o}{V_o} - \left(q_{Fcx1}\frac{F_x}{F_{z0}}\right) - \left(q_{Fcy1}\frac{F_y}{F_{z0}}\right) + q_{Fc\gamma 1}\gamma^2 \right\}$$

$$\left[q_{Fz1}\frac{\rho}{R_0} + q_{Fz2}\left(\frac{\rho}{R_0}\right)^2 + q_{Fz3}\gamma^2\frac{\rho}{R_0}\right](\{1 + q_{pFz1}dp_i\}\lambda_{Cz}F_{z0}) + K_z\dot{\rho} \quad (8)$$

Using this formula, the vertical tire stiffness increases due to increasing rotational speed Ω and decreases by longitudinal and lateral tire forces. If q_{Fz1} and q_{Fz2} are zero, q_{Fz1} will be defined as C_zR_0/F_{z0}.

Parameter q_{RE0} corrects for possible differences in between the specified unloaded radius (R_0) and the measured radius in tire testing.

When you do not provide the coefficients q_{V2}, q_{Fcx}, q_{Fcy}, q_{Fz1}, q_{Fz2} and q_{Fz3} in the tire property file, the normal load calculation is compatible with previous versions of PAC2002, because, in that case, the normal load is calculated using the linear vertical tire stiffness C_z and tire damping K_z according to:

$$F_z = C_z\rho\lambda_{Cz} + K_z\dot{\rho}$$

© 2025 Hexagon AB and/or its subsidiaries.

Instead of the linear vertical tire stiffness C_z (= $q_{Fz1}F_{z0}/R_0$), you can define an arbitrary tire deflection - load curve in the tire property file in the section [DEFLECTION_LOAD_CURVE] (see the Example of PAC2002 Tire Property File). If a section called [DEFLECTION_LOAD_CURVE] exists, the load deflection data points with a cubic spline for inter- and extrapolation are used for the calculation of the vertical force of the tire. Note that you must specify C_z in the tire property file, but it does not play any role.

Loaded and Effective Tire Rolling Radius

With the loaded tire radius Rl defined as the distance of the wheel center to the contact point of the tire with the road, the tire deflection can be calculated using the free tire radius R_0 and a correction for the tire radius growth due to the rotational tire speed Ω:

(9) $$\rho = R_0\left[q_{REO} + q_{V1}\left(\frac{\Omega R_0}{V_0}\right)^2\right] - R_1$$

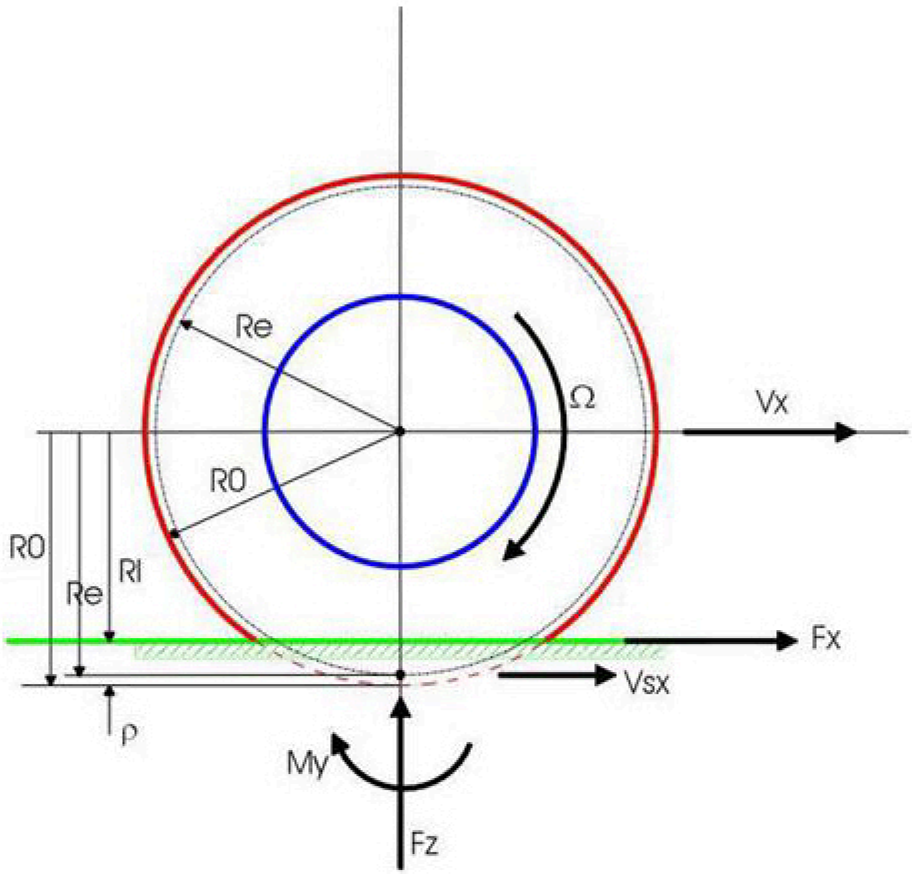
The effective rolling radius R_e (at free rolling of the tire), which is used to calculate the rotational speed of the tire, is defined by:

(10) $$R_e = \frac{V_x}{\Omega}$$

For radial tires, the effective rolling radius is rather independent of load in its load range of operation because of the high stiffness of the tire belt circumference. Only at low loads does the effective tire radius decrease with increasing vertical load due to the tire tread thickness. See the figure below.

Effective Rolling Radius and Longitudinal Slip

© 2025 Hexagon AB and/or its subsidiaries.



To represent the effective rolling radius R_e, a MF-type of equation is used:

$$R_e = R_0 \cdot q_{REO} + q_{V1} R_0 \left(\frac{\Omega R_0}{V_0}\right)^2 - \rho_{Fz0}[D_{Reff} arc\tan(B_{Reff}\rho^d) + F_{Reff}\rho^d]$$
(11)

in which ρ_{Fz0} is the nominal tire deflection:

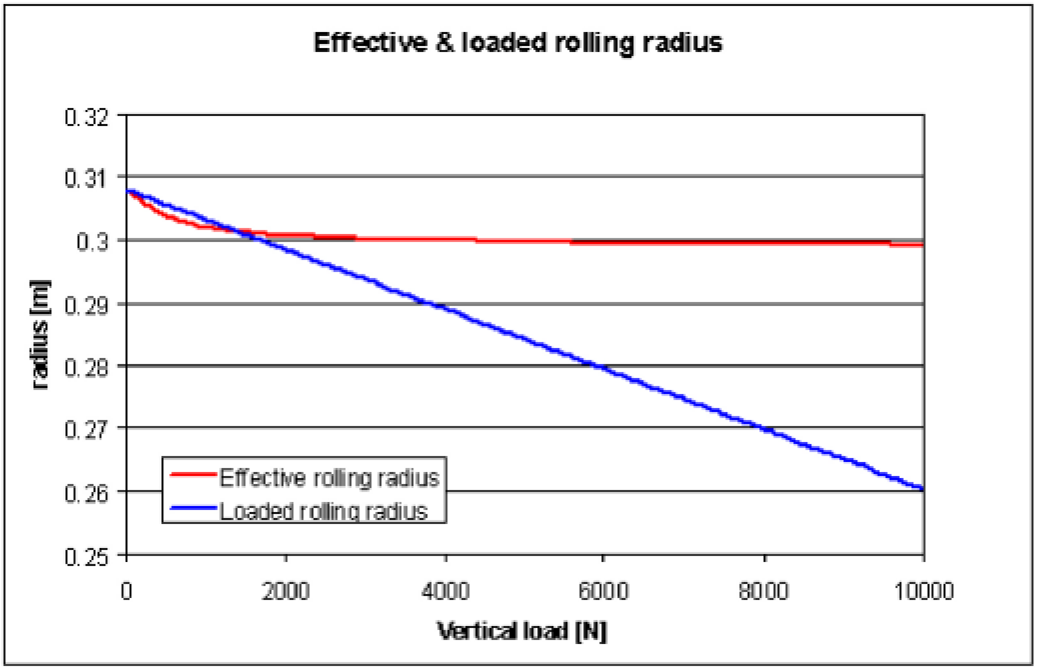
$$\rho_{Fz0} = \frac{F_{z0}}{C_z \lambda_{Cz}}$$
(12)

and ρ^d is called the dimensionless radial tire deflection, defined by:

$$\rho^d = \frac{\rho}{\rho_{F_{z0}}}$$
(13)

Example of Loaded and Effective Tire Rolling Radius as Function of Vertical Load

© 2025 Hexagon AB and/or its subsidiaries.



Normal Load and Rolling Radius Parameters

Name:	Name Used in Tire Property File:	Explanation:
F_{z0}	FNOMIN	Nominal wheel load
R_o	UNLOADED_RADIUS	Free tire radius
B_{Reff}	BREFF	Low load stiffness effective rolling radius
q_{REO}	QREO	Correction factor for measured unloaded radius
D_{Reff}	DREFF	Peak value of effective rolling radius

© 2025 Hexagon AB and/or its subsidiaries.

F_{Reff}	FREFF	High load stiffness effective rolling radius
C_Z	VERTICAL_STIFFNESS	Tire vertical stiffness (if q_{Fz1}=0)
K_Z	VERTICAL_DAMPING	Tire vertical damping
q_{Fz1}	QFZ1	Tire vertical stiffness coefficient (linear)
q_{Fz2}	QFZ2	Tire vertical stiffness coefficient (quadratic)
q_{Fz3}	QFZ3	Camber dependency of the tire vertical stiffness
q_{Fcx1}	QFCX1	Tire stiffness interaction with Fx
q_{Fcy1}	QFCY1	Tire stiffness interaction with Fy
$q_{Fc\gamma 1}$	QFCG1	Tire stiffness interaction with camber
q_{V1}	QV1	Tire radius growth coefficient
q_{V2}	QV2	Tire stiffness variation coefficient with speed

© 2025 Hexagon AB and/or its subsidiaries.

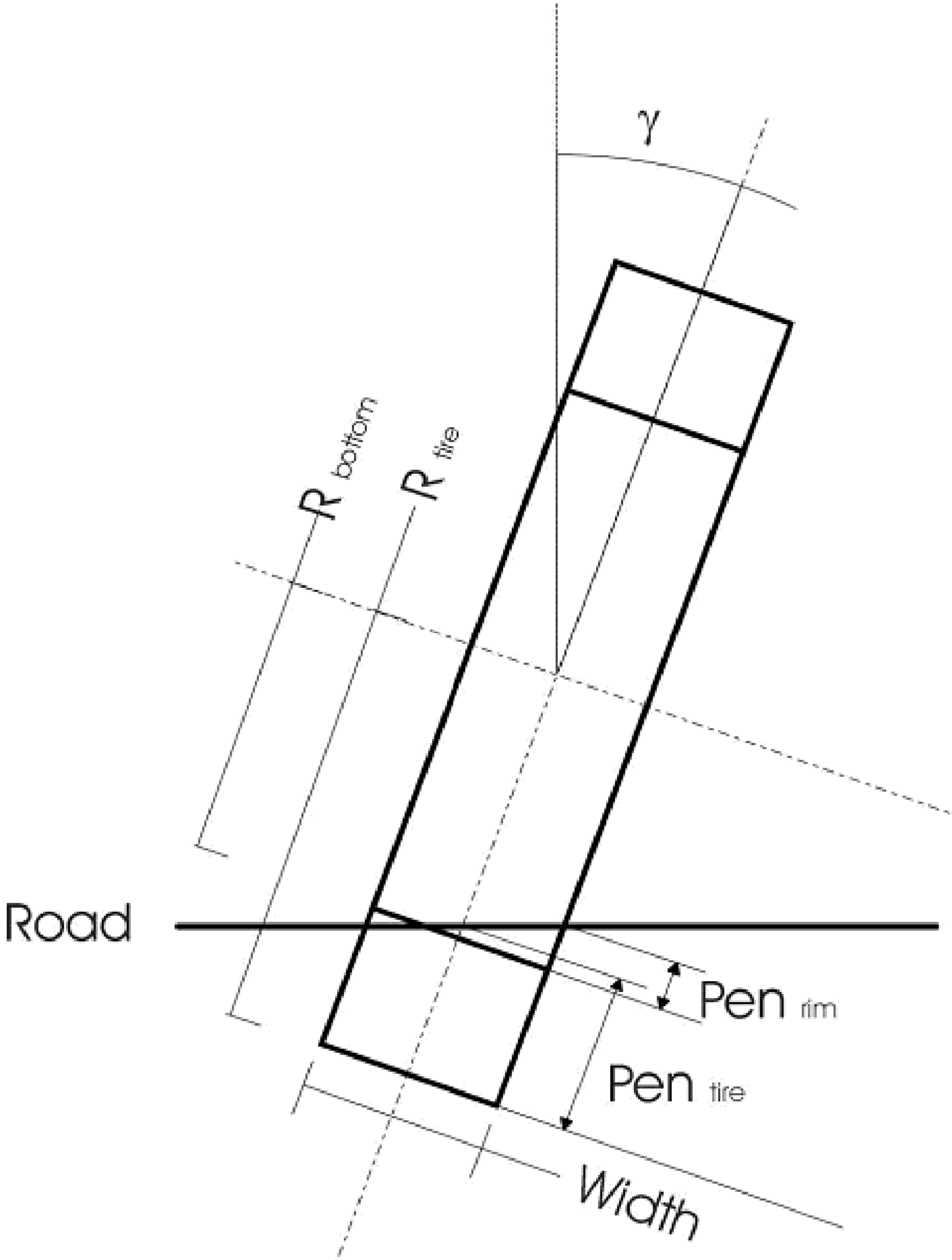
Wheel Bottoming

You can optionally supply a wheel-bottoming deflection, that is, a load curve in the tire property file in the [BOTTOMING_CURVE] block. If the deflection of the wheel is so large that the rim will be hit (defined by the BOTTOMING_RADIUS parameter in the [DIMENSION] section of the tire property file), the tire vertical load will be increased according to the load curve defined in this section.

Note that the rim-to-road contact algorithm is a simple penetration method (such as the 2D contact) based on the tire-to-road contact calculation, which is strictly valid for only rather smooth road surfaces (the length of obstacles should have a wavelength longer than the tire circumference). The rim-to-road contact algorithm is not based on the 3D-volume penetration method, but can be used in combination with the 3D Contact, which takes into account the volume penetration of the tire itself. If you omit the [BOTTOMING_CURVE] block from a tire property file, no force due to rim road contact is added to the tire vertical force.

You can choose a BOTTOMING_RADIUS larger than the rim radius to account for the tire's material remaining in between the rim and the road, while you can adjust the bottoming load-deflection curve for the change in stiffness.

© 2025 Hexagon AB and/or its subsidiaries.



© 2025 Hexagon AB and/or its subsidiaries.

If (Pen_{tire} - (R_{tire} - R_{bottom}) - ½·width ·| tan(γ) |) < 0, the left or right side of the rim has contact with the road. Then, the rim deflection Pen_{rim} can be calculated using:

δ = max(0 , ½·width ·| tan(γ) |) + Pen_{tire}- (R_{tire} - R_{bottom})Pen_{rim}= δ^2/(2 · width ·| tan(γ) |)S_{rim}= ½·width - max(width , δ/| tan(γ) |)/3

with S_{rim}, the lateral offset of the force with respect to the wheel plane.

If the full rim has contact with the road, the rim deflection is:

Pen_{rim} = Pen_{tire} - (R_{tire} - R_{bottom})

S_{rim} = width^2 · | tan(γ) | · /(12 · Pen_{rim})Using the load - deflection curve defined in the [BOTTOMING_CURVE] section of the tire property file, the additional vertical force due to the bottoming is calculated, while S_{rim} multiplied by the sign of the inclination γ is used to calculate the contribution of the bottoming force to the overturning moment. Further, the increase of the total wheel load Fz due to the bottoming (F_{zrim}) will not be taken into account in the calculation for F_x, F_y, M_y, and M_z. F_{zrim} will only contribute to the overturning moment M_x using the F_{zrim}·S_{rim}.

Note:	R_{tire} is equal to the unloaded tire radius R_0; Pen_{tire} is similar to effpen (=ρ).

Basics of the Magic Formula in PAC2002

The Magic Formula is a mathematical formula that is capable of describing the basic tire characteristics for the interaction forces between the tire and the road under several steady-state operating conditions. We distinguish:

■Pure cornering slip conditions: cornering with a free rolling tire

■Pure longitudinal slip conditions: braking or driving the tire without cornering

■Combined slip conditions: cornering and longitudinal slip simultaneously

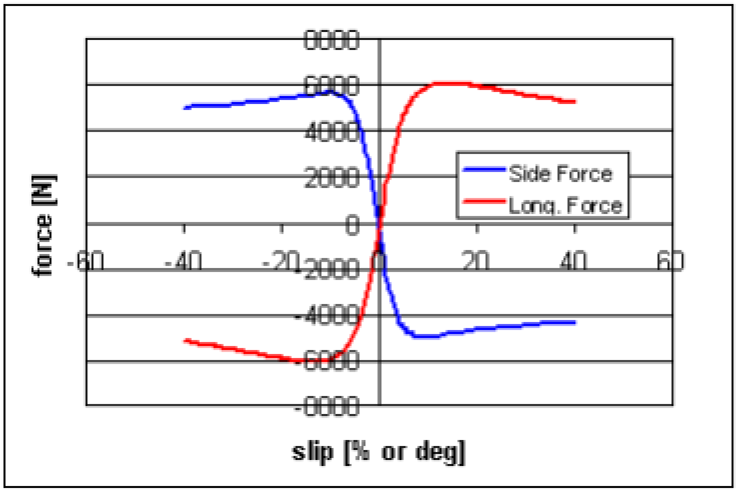
For pure slip conditions, the lateral force F_y as a function of the lateral slip α, respectively, and the longitudinal force F_x as a function of longitudinal slip κ, have a similar shape (see the figure, **Characteristic Curves for F_x and F_y Under Pure Slip Conditions**). Because of the sine - arctangent combination, the basic Magic Formula equation is capable of describing this shape:

(14) $$Y(x) = D\sin[C\arctan\{Bx - E(Bx - \arctan(Bx))\}]$$

where Y(x) is either F_x with x the longitudinal slip κ, or F_y and x the lateral slip α.

Characteristic Curves for F_x and F_y Under Pure Slip Conditions

© 2025 Hexagon AB and/or its subsidiaries.



The self-aligning moment M_z is calculated as a product of the lateral force F_y and the pneumatic trail t added with the residual moment M_{zr}. In fact, the aligning moment is due to the offset of lateral force F_y, called pneumatic trail t, from the contact point. Because the pneumatic trail t as a function of the lateral slip a has a cosine shape, a cosine version the Magic Formula is used:

(15) $Y(x) = D\cos[C\,arc\tan\{Bx - E(Bx - arc\tan(Bx))\}]$

in which Y(x) is the pneumatic trail t as function of slip angle α.

The figure, **The Magic Formula and the Meaning of Its Parameters**, illustrates the functionality of the B, C, D, and E factor in the Magic Formula:

■D-factor determines the peak of the characteristic, and is called the peak factor.

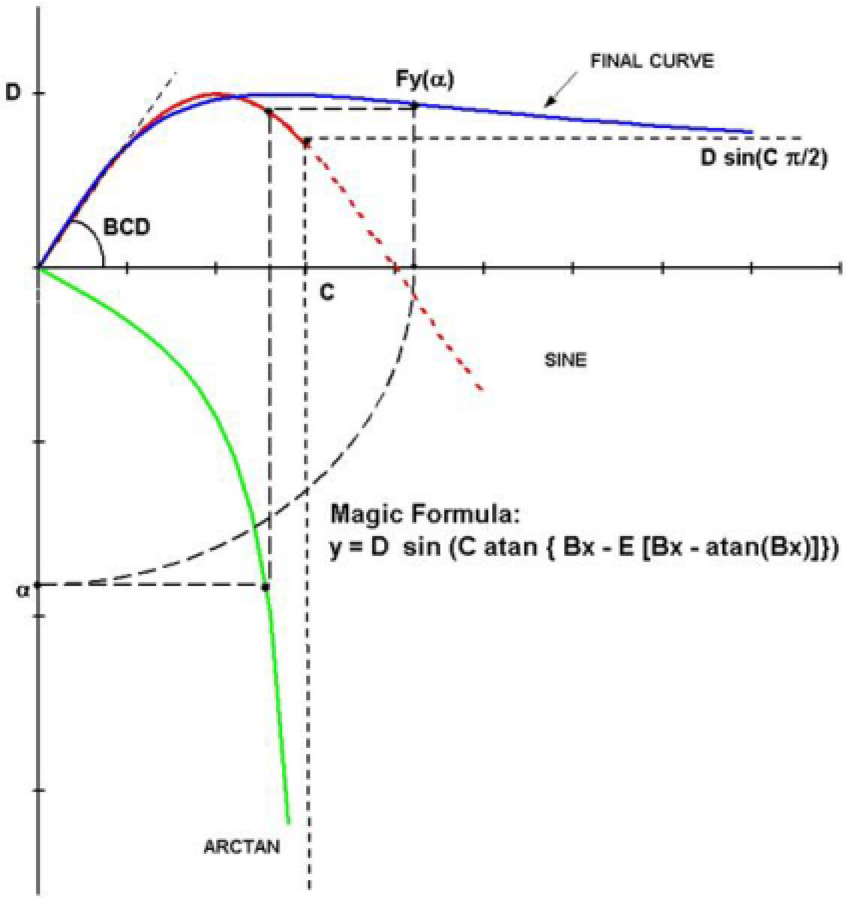
■C-factor determines the part used of the sine and, therefore, mainly influences the shape of the curve (shape factor).

■B-factor stretches the curve and is called the stiffness factor.

■E-factor can modify the characteristic around the peak of the curve (curvature factor).

The Magic Formula and the Meaning of Its Parameters

© 2025 Hexagon AB and/or its subsidiaries.



In combined slip conditions, the lateral force F_y will decrease due to longitudinal slip or the opposite, the longitudinal force F_x will decrease due to lateral slip. The forces and moments in combined slip conditions are based on the pure slip characteristics multiplied by the so-called weighing functions. Again, these weighting functions have a cosine-shaped MF equation.

The Magic Formula itself only describes steady-state tire behavior. For transient tire behavior (up to 8 Hz), the MF output is used in a stretched string model that considers tire belt deflections instead of slip velocities to cope with standstill situations (zero speed).

Input Variables

The input variables to the Magic Formula are:

Longitudinal slip	κ	[-]
Slip angle	α	[rad]

© 2025 Hexagon AB and/or its subsidiaries.

Inclination angle	γ	[rad]
Normal wheel load	F_z	[N]

Output Variables

Longitudinal force	F_x	[N]
Lateral force	F_y	[N]
Overturning couple	M_x	[Nm]
Rolling resistance moment	M_y	[Nm]
Aligning moment	M_z	[Nm]

The output variables are defined in the W-axis system of TYDEX.

Basic Tire Parameters

All tire model parameters of the model are without dimension. The reference parameters for the model are:

Name	Name used in tire property file	Unit	Explanation
F_{z0}	FNOMIN	[N]	Nominal (rated) load

© 2025 Hexagon AB and/or its subsidiaries.

R_0	UNLOADED_RADIUS	[m]	Unloaded tire radius
p_{i0}	IP_NOM	[Pa]	Nominal inflation pressure
p_i	IP	[Pa]	Actual inflation pressure
m_0	TYRE_MASS	[kg]	Tire mass (if belt dynamics is used)

As a measure for the vertical load, the normalized vertical load increment df_z is used:

(16) $$df_z = \frac{F_z - F'_{zo}}{F'_{zo}}$$

with the possibly adapted nominal load (using the user-scaling factor, $\lambda_{F_{Z0}}$):

$$F'_{zo} = F_{zo} \cdot \lambda_{F_{z0}}$$

Similarly the normalized inflation pressure dp_i is defined as:

(17) $$dp_i = \frac{p_i - p'_{i0}}{p'_{i0}}$$

With the user scaling factor for the inflation pressure:

$$p'_{i0} = \lambda_{ip} p_{i0}$$

Nomenclature of the Tire Model Parameters

In the subsequent sections, formulas are given with non-dimensional parameters a_{ijk} with the following logic:

Tire Model Parameters

© 2025 Hexagon AB and/or its subsidiaries.

Parameter:		Definition:
a =	p	Force at pure slip
	q	Moment at pure slip
	r	Force at combined slip
	s	Moment at combined slip
i =	B	Stiffness factor
	C	Shape factor
	D	Peak value
	E	Curvature factor
	K	Slip stiffness = BCD
	H	Horizontal shift
	V	Vertical shift
	s	Moment at combined slip

© 2025 Hexagon AB and/or its subsidiaries.

	t	Transient tire behavior
j =	x	Along the longitudinal axis
	y	Along the lateral axis
	z	About the vertical axis
k =	1, 2, ...	

User Scaling Factors

A set of scaling factors is available to easily examine the influence of changing tire properties without the need to change one of the real Magic Formula coefficients. The default value of these factors is 1. You can change the factors in the tire property file. The peak friction scaling factors, $\lambda_{\mu x}$ and $\lambda_{\mu y}$, are also used for the position-dependent friction in 3D Road Contact and 3D Road. An overview of all scaling factors is shown in the following tables.

Scaling Factor Coefficients for Pure Slip

Name:	Name used in tire property file:	Explanation:
λ_{Fzo}	LFZO	Scale factor of nominal (rated) load
λ_{ip}	LIP	Scale factor of nominal inflation pressure
λ_{Cz}	LCZ	Scale factor of vertical tire stiffness

© 2025 Hexagon AB and/or its subsidiaries.

λ_{Cx}	LCX	Scale factor of Fx shape factor
$\lambda_{\mu x}$	LMUX	Scale factor of Fx peak friction coefficient
λ_{Ex}	LEX	Scale factor of Fx curvature factor
λ_{Kx}	LKX	Scale factor of Fx slip stiffness
λ_{Hx}	LHX	Scale factor of Fx horizontal shift
λ_{Vx}	LVX	Scale factor of Fx vertical shift
$\lambda_{\gamma x}$	LGAX	Scale factor of inclination for Fx
λ_{Cy}	LCY	Scale factor of Fy shape factor
$\lambda_{\mu y}$	LMUY	Scale factor of Fy peak friction coefficient
λ_{Ey}	LEY	Scale factor of Fy curvature factor
λ_{Ky}	LKY	Scale factor of Fy cornering stiffness

© 2025 Hexagon AB and/or its subsidiaries.

λ_{Hy}	LHY	Scale factor of Fy horizontal shift
λ_{Vy}	LVY	Scale factor of Fy vertical shift
λ_{gy}	LGAY	Scale factor of inclination for Fy
$\lambda_{Ky\gamma}$	LKG	Scale factor of the camber stiffness $K_{y\gamma 0}$
λ_{t}	LTR	Scale factor of peak of pneumatic trail
λ_{Mr}	LRES	Scale factor for offset of residual moment
$\lambda_{\gamma z}$	LGAZ	Scale factor of inclination for Mz
λ_{Mx}	LMX	Scale factor of overturning couple
λ_{VMx}	LVMX	Scale factor of Mx vertical shift
λ_{My}	LMY	Scale factor of rolling resistance moment

Scaling Factor Coefficients for Combined Slip

© 2025 Hexagon AB and/or its subsidiaries.

Name:	Name used in tire property file:	Explanation:
$\lambda_{x\alpha}$	LXAL	Scale factor of alpha influence on Fx
$\lambda_{y\kappa}$	LYKA	Scale factor of alpha influence on Fy
$\lambda_{Vy\kappa}$	LVYKA	Scale factor of kappa-induced Fy
λ_{s}	LS	Scale factor of moment arm of Fx

Scaling Factor Coefficients for Transient Response

Name:	Name used in tire property file:	Explanation:
$\lambda_{\sigma \kappa}$	LSGKP	Scale factor of relaxation length of Fx
$\lambda_{\sigma \alpha}$	LSGAL	Scale factor of relaxation length of Fy
λ_{gyr}	LGYR	Scale factor of gyroscopic moment

Note that the scaling factors change during the simulation according to any user-introduced function. See the next section, Online Scaling of Tire Properties.

© 2025 Hexagon AB and/or its subsidiaries.

Online Scaling of Tire Properties

PAC2002 can provide online scaling of tire properties. For each scaling factor, a variable should be introduced in the Adams .adm dataset. For example:

!lfz0 scaling

! adams_view_name='TR_Front_Tires until wheel_lfz0_var'

VARIABLE/53

, IC = 1

, FUNCTION = 1.0

This lets you change the scaling factor during a simulation as a function of time or any other variable in your model. Therefore, tire properties can change because of inflation pressure, road friction, road temperature, and so on.

You can also use the scaling factors in co-simulations in MATLAB/Simulink.

For more detailed information, see Simcompanion Knowledge Base Article KB8016467.

Steady-State: Magic Formula in PAC2002

- Steady-State Pure Slip
- Steady-State Combined Slip

Steady-State Pure Slip

- Longitudinal Force at Pure Slip
- Lateral Force at Pure Slip
- Aligning Moment at Pure Slip
- Turn-slip and Parking

Formulas for the Longitudinal Force at Pure Slip

For the tire rolling on a straight line with no slip angle, the formulas are:

(18) $F_x = F_{x0}(\kappa, F_z, \gamma)$

© 2025 Hexagon AB and/or its subsidiaries.

(19) $F_{x0} = D_x \sin([C_x \arctan\{B_x\kappa_x - E_x(B_x\kappa_x - \arctan(B_x\kappa_x))\}]) + S_{Vx}$

(20) $\kappa_x = \kappa + S_{Hx}$

(21) $\gamma_x = \gamma \cdot \lambda_{\gamma x}$

with following coefficients:

(22) $C_x = p_{Cx1} \cdot \lambda_{Cx}$

(23) $D_x = \mu_x \cdot F_z \cdot \zeta_1$

(24) $\mu_x = (p_{Dx1} + p_{Dx2}df_z)(1 + p_{px3}dp_i + p_{px4}dp_i^{\ 2}) \cdot (1 - p_{Dx3} \cdot \gamma^2)\lambda_{\mu x}$

(25) $E_x = (p_{Ex1} + p_{Ex2}df_z + p_{Ex3}df_z^2) \cdot \{1 - p_{Ex4}\operatorname{sgn}(\kappa_x)\} \cdot \lambda_{Ex} \ \ with \ \ E_x \le 1$

the longitudinal slip stiffness:

(26) $K_x = F_z \cdot (p_{Kx1} + p_{Kx2}df_z) \cdot \exp(p_{Kx3}df_z)(1 + p_{px1}dp_i + p_{px2}dp_i^{\ 2})\lambda_{Kx}$

$$K_x = B_x C_x D_x = \frac{\partial F_{x0}}{\partial \kappa_{x?}} at_? \kappa_x = 0$$

(27) $B_x = K_x / (C_x D_x)$

(28) $S_{Hx} = (p_{Hx1} + p_{Hx2} \cdot df_z)\lambda_{Hx}$

(29) $S_{Vx} = F_z \cdot (p_{Vx1} + p_{Vx2} \cdot df_z)\lambda_{Vx} \cdot \lambda_{\mu x} \cdot \zeta_1$

Longitudinal Force Coefficients at Pure Slip

Name:	Name used in tire property file:	Explanation:
p_{Cx1}	PCX1	Shape factor Cfx for longitudinal force

© 2025 Hexagon AB and/or its subsidiaries.

p_{Dx1}	PDX1	Longitudinal friction Mux at Fznom
p_{Dx2}	PDX2	Variation of friction Mux with load
p_{Dx3}	PDX3	Variation of friction Mux with inclination
p_{Ex1}	PEX1	Longitudinal curvature Efx at Fznom
p_{Ex2}	PEX2	Variation of curvature Efx with load
p_{Ex3}	PEX3	Variation of curvature Efx with load squared
p_{Ex4}	PEX4	Factor in curvature Efx while driving
p_{Kx1}	PKX1	Longitudinal slip stiffness Kfx/F_Z at Fznom
p_{Kx2}	PKX2	Variation of slip stiffness Kfx/F_Z with load
p_{Kx3}	PKX3	Exponent in slip stiffness Kfx/F_Z with load

© 2025 Hexagon AB and/or its subsidiaries.

p_{Hx1}	PHX1	Horizontal shift Shx at Fznom
p_{Hx2}	PHX2	Variation of shift Shx with load
p_{Vx1}	PVX1	Vertical shift Svx/F_Z at Fznom
p_{Vx2}	PVX2	Variation of shift Svx/F_Z with load
p_{px1}	PPX1	Variation of slip stiffness Kfx/F_Z with pressure
p_{px2}	PPX2	Variation of slip stiffness Kfx/F_Z with pressure squared
p_{px3}	PPX3	Variation of friction Mux with pressure
p_{px4}	PPX4	Variation of friction Mux with pressure squared

Formulas for the Lateral Force at Pure Slip

(30) $F_y = F_{y0}(\alpha, \gamma, F_z)$

(31) $F_{y0} = D_y \sin[C_y arc\tan\{B_y\alpha_y - E_y(B_y\alpha_y - arc\tan(B_y\alpha_y))\}] + S_{Vy}$

(32) $\alpha_y = \alpha + S_{Hy}$

The scaled inclination angle:

(33) $\gamma_y = \gamma \cdot \lambda_{\gamma y}$

© 2025 Hexagon AB and/or its subsidiaries.

with coefficients:

(34) $C_y = p_{Cy1} \cdot \lambda_{Cy}$

(35) $D_y = \mu_y \cdot F_z \cdot \zeta_2$

(36) $\mu_y = (p_{Dy1} + p_{Dy2} df_z)(1 + p_{py3} dp_i + p_{py4} dp_i^2)(1 - p_{Dy3} \gamma_y^2) \lambda_{\mu y}$

(37) $E_y = (p_{Ey1} + p_{Ey2} df_z) \cdot \{1 - (p_{Ey3} + p_{Ey4} \gamma_y) \operatorname{sgn}(\alpha_y)\} \cdot \lambda_{Ey} \ with \ E_y \le 1$

The cornering stiffness:

(38) $K_{y0} = P_{Ky1} F_{z0}(1 + p_{py1} dp_i) \sin\left[2 arc\tan\left\{\frac{F_z}{P_{Ky2} F'_{z0}(1 + p_{py2} dp_i)}\right\}\right] \lambda_{F_{z0}} \lambda_{Ky}$

(39) $K_y = K_{y0} \cdot (1 - p_{Ky3} |\gamma_y|) \cdot \zeta_3$

(40) $B_y = K_y / (C_y D_y)$

(41) $S_{Hy} = (p_{Hy1} + p_{Hy2} df_z) \cdot \lambda_{Hy} + p_{Hy3} \gamma_y \cdot \lambda_{K y\gamma} \cdot \zeta_0 + \zeta_4 - 1$

(42) $S_{Vy} = F_z \cdot \{(p_{Vy1} + p_{Vy2} df_z) \cdot \lambda_{Vy} + (p_{Vy3} + p_{Vy4} df_z) \cdot \gamma_y \cdot \lambda_{Ky\gamma}\} \cdot \lambda_{\mu y} \cdot \zeta_2$

(43) $S_{Vy\gamma} = F_z \cdot \{(p_{Vy3} + p_{Vy4} df_z) \cdot \gamma_y \cdot \lambda_{Ky\gamma}\} \cdot \lambda_{\mu y} \cdot \zeta_2$

The camber stiffness is given by:

(44) $K_{y\gamma 0} = \{p_{Hy3} K_{y0} + F_z (p_{Vy3} + p_{Vy4} df_z)\} \cdot \lambda_{Ky\gamma}$

Lateral Force Coefficients at Pure Slip

Name:	Name used in tire property file:	Explanation:
p_{Cy1}	PCY1	Shape factor Cfy for lateral forces
p_{Dy1}	PDY1	Lateral friction Muy

© 2025 Hexagon AB and/or its subsidiaries.

p_{Dy2}	PDY2	Variation of friction Muy with load
p_{Dy3}	PDY3	Variation of friction Muy with squared inclination
p_{Ey1}	PEY1	Lateral curvature Efy at Fznom
p_{Ey2}	PEY2	Variation of curvature Efy with load
p_{Ey3}	PEY3	Inclination dependency of curvature Efy
p_{Ey4}	PEY4	Variation of curvature Efy with inclination
p_{Ky1}	PKY1	Maximum value of stiffness Kfy/Fznom
p_{Ky2}	PKY2	Load at which Kfy reaches maximum value
p_{Ky3}	PKY3	Variation of Kfy/Fznom with inclination
p_{Hy1}	PHY1	Horizontal shift Shy at Fznom
p_{Hy2}	PHY2	Variation of shift Shy with load

© 2025 Hexagon AB and/or its subsidiaries.

p_{Hy3}	PHY3	Variation of shift Shy with inclination
p_{Vy1}	PVY1	Vertical shift in Svy/Fz at Fznom
p_{Vy2}	PVY2	Variation of shift Svy/Fz with load
p_{Vy3}	PVY3	Variation of shift Svy/Fz with inclination
p_{Vy4}	PVY4	Variation of shift Svy/Fz with inclination and load
p_{py1}	PPY1	Variation of max. stiffness Kfy/Fznom with pressure
p_{py2}	PPY2	Variation of load at max. Kfy with pressure
p_{py3}	PPY3	Variation of friction Muy with pressure
p_{py4}	PPY4	Variation of friction Muy with pressure squared

Formulas for the Aligning Moment at Pure Slip

(45) $M'_z = M_{z0}(\alpha, \gamma, F_z)$

$$M_{z0} = -t \cdot F_{y0} + M_{zr}$$

© 2025 Hexagon AB and/or its subsidiaries.

with the pneumatic trail t:

(46) $$t(\alpha_t) = D_t \cos[C_t \arctan\{B_t\alpha_t - E_t(B_t\alpha_t - \arctan(B_t\alpha_t))\}]\cos(\alpha)$$

(47) $$\alpha_t = \alpha + S_{Ht}$$

and the residual moment M_{zr}:

(48) $$M_{zr}(\alpha_r) = D_r \cos[C_r \arctan(B_r\alpha_r)] \cdot \cos(\alpha)$$

(49) $$\alpha_r = \alpha + S_{Hf}$$

(50) $$S_{Hf} = S_{Hy} + S_{Vy}/K_y$$

The scaled inclination angle:

(51) $$\gamma_z = \gamma \cdot \lambda_{\gamma z}$$

with coefficients:

(52) $$B_t = (q_{Bz1} + q_{Bz2}df_z + q_{Bz3}df_z^2) \cdot (1 + q_{Bz4}\gamma_z + q_{Bz5}|\gamma_z|) \cdot \lambda_{Ky}/\lambda_{\mu y}$$

(53) $$C_t = q_{Cz1}$$

(54) $$D_t = F_z(q_{Dz1} + q_{Dz2}df_z)(1 - q_{pz1}dp_i)(1 + q_{Dz3}\gamma_z + q_{Dz4}\gamma_z^2)\frac{R_0}{F'_{z0}}\lambda_t\zeta_5$$

(55) $$E_t = (q_{Ez1} + q_{Ez2}df_z + q_{Ez3}df_z^2)$$

$$\left\{1 + (q_{Ez4} + q_{Ez5}\gamma_z)\left(\left(\frac{2}{\pi}\right) \cdot \arctan(B_t \cdot C_t \cdot \alpha_t)\right)\right\} \; with \; (E_t \le 1)$$

(56) $$S_{Ht} = q_{Hz1} + q_{Hz2}df_z + (q_{Hz3} + q_{Hz4} \cdot df_z)\gamma_z$$

(57) $$B_r = \left(q_{Bz9} \cdot \frac{\lambda_{Ky}}{\lambda_{\mu y}} + q_{Bz10} \cdot B_y \cdot C_y\right) \cdot \zeta_6$$

$$C_r = \zeta_7$$

(58) $$D_r = F_z[(q_{Dz6} + q_{Dz7}df_z)\lambda_r + (q_{Dz8} + q_{Dz9}df_z)(1 + q_{pz2}dp_i)\gamma_z]R_o\lambda_{\mu\gamma} + \zeta_8 - 1$$

© 2025 Hexagon AB and/or its subsidiaries.

An approximation for the aligning moment stiffness reads:

(59) $$K_z = -t \cdot K_y \qquad \left(? \approx -\frac{\partial M_z}{\partial \alpha} ? at \ \alpha\right) = 0)$$

Aligning Moment Coefficients at Pure Slip

Name:	Name used in tire property file:	Explanation:
q_{Bz1}	QBZ1	Trail slope factor for trail Bpt at Fznom
q_{Bz2}	QBZ2	Variation of slope Bpt with load
q_{Bz3}	QBZ3	Variation of slope Bpt with load squared
q_{Bz4}	QBZ4	Variation of slope Bpt with inclination
q_{Bz5}	QBZ5	Variation of slope Bpt with absolute inclination
q_{Bz9}	QBZ9	Slope factor Br of residual moment Mzr
q_{Bz10}	QBZ10	Slope factor Br of residual moment Mzr
q_{Cz1}	QCZ1	Shape factor Cpt for pneumatic trail

© 2025 Hexagon AB and/or its subsidiaries.

q_{Dz1}	QDZ1	Peak trail Dpt = Dpt*(Fz/ Fznom*R0)
q_{Dz2}	QDZ2	Variation of peak Dpt with load
q_{Dz3}	QDZ3	Variation of peak Dpt with inclination
q_{Dz4}	QDZ4	Variation of peak Dpt with inclination squared.
q_{Dz6}	QDZ6	Peak residual moment Dmr = Dmr/ (Fz*R0)
q_{Dz7}	QDZ7	Variation of peak factor Dmr with load
q_{Dz8}	QDZ8	Variation of peak factor Dmr with inclination
q_{Dz9}	QDZ9	Variation of Dmr with inclination and load
q_{Ez1}	QEZ1	Trail curvature Ept at Fznom
q_{Ez2}	QEZ2	Variation of curvature Ept with load
q_{Ez3}	QEZ3	Variation of curvature Ept with load squared

© 2025 Hexagon AB and/or its subsidiaries.

q_{Ez4}	QEZ4	Variation of curvature Ept with sign of Alpha-t
q_{Ez5}	QEZ5	Variation of Ept with inclination and sign Alpha-t
q_{Hz1}	QHZ1	Trail horizontal shift Sht at Fznom
q_{Hz2}	QHZ2	Variation of shift Sht with load
q_{Hz3}	QHZ3	Variation of shift Sht with inclination
q_{Hz4}	QHZ4	Variation of shift Sht with inclination and load
q_{pz1}	QPZ1	Variation of peak Dt with pressure
q_{pz2}	QPZ2	Variation of peak Dr with pressure

Turn-slip and Parking

For situations where turn-slip may be neglected and camber remains small, the reduction factors ζ_i that appear in the equations for steady-state pure slip, are to be set to 1:

$$\zeta_i = 1 \qquad i = 0, \qquad 1,\dots 8$$

For larger values of spin, the reduction factors are given below.

The weighting function ζ_1 is used to let the longitudinal force diminish with increasing spin,

© 2025 Hexagon AB and/or its subsidiaries.

according to:

(60) $$\zeta_l = \cos[arc\tan(B_{x\varphi}R_0\varphi)]$$

with:

(61) $$B_{x\varphi} = p_{Dx\varphi1}(1 + p_{Dx\varphi2}df_z)\cos[arc\tan(p_{Dx\varphi3}\kappa)]$$

The peak side force reduction factor ζ_2 reads:

(62) $$\zeta_2 = \cos[arc\tan\{B_{y\varphi}(R_0|\varphi| + p_{Dy\varphi4}\sqrt{R_0|\varphi|})\}]$$

with:

(63) $$B_{y\varphi} = p_{Dy\varphi1}(1 + p_{Dy\varphi2}df_z)\cos[arc\tan(p_{Dy\varphi3}\tan\alpha)]$$

The cornering stiffness reduction factor ζ_3 is given by:

(64) $$\zeta_3 = \cos[arc\tan(p_{Ky\varphi1}R_0^2\varphi^2)]$$

The horizontal shift of the lateral force due to spin is given by:

(65) $$S_{Hy\varphi} = D_{Hy\varphi}\sin[C_{Hy\varphi}arc\tan\{B_{Hy\varphi}R_o\varphi - E_{Hy\varphi}(B_{Hy\varphi}R_0\varphi - arc\tan(B_{Hy\varphi}R_0\varphi))\}]$$

The factors are defined by:

$$C_{Hy\varphi} = p_{Hy\varphi1}$$

$$D_{Hy\varphi} = (p_{Hy\varphi2} + p_{Hy\varphi3}df_z)\cdot\sin(V_x)$$

$$E_{Hy\varphi} = P_{Hy\varphi4}$$

$$BHy\varphi = \frac{K_{yR\varphi0}}{C_{Hy\varphi}D_{Hy\varphi}K_{y0}}$$

(66)

The spin force stiffness $K_{yR\phi0}$ is related to the camber stiffness K_{yy0}:

(67) $$K_{yR\varphi0} = \frac{K_{y\gamma0}}{1-\varepsilon_\gamma}$$

in which the camber reduction factor is given by:

© 2025 Hexagon AB and/or its subsidiaries.

(68) $$\varepsilon_\gamma = p_{\varepsilon\gamma\varphi 1}(1 + p_{\varepsilon\gamma\varphi 2} df_z)$$

The reduction factors ζ_0 and ζ_4 for the vertical shift of the lateral force are given by:

(69) $$\zeta_0 = 0$$ $$\zeta_4 = 1 + S_{Hy\varphi} - S_{Vy\gamma}/K_y$$

The reduction factor for the residual moment reads:

(70) $$\zeta_8 = 1 + D_{r\varphi}$$

The peak spin torque $D_{r\varphi}$ is given by:

(71) $$D_{r\varphi} = D_{Dr\varphi} \sin e[C_{Dr\varphi} arc\tan\{B_{Dr\varphi}R_0\varphi - E_{Dr\varphi}(B_{Dr\varphi}R_0\varphi - arc\tan(B_{Dr\varphi}R_0\varphi))\}]$$

The maximum value is given by:

(72) $$D_{Dr\varphi} = \frac{M_{z\varphi\infty}}{\sin\left(\frac{\pi}{2}C_{Dr\varphi}\right)}$$

The pneumatic trail reduction factor due to turn slip is given by:

(73) $$\xi_5 = \cos[arc\tan(q_{Dt\varphi 1}R_0\varphi)]$$

The moment at vanishing wheel speed at constant turning is given by:

(74) $$M_{z\varphi\infty} = q_{Cr\varphi 1}\mu_y R_0 F_z \sqrt{F_z/F_{z0}}$$

The shape factors are given by:

(75) $$C_{Dr\varphi} = q_{Dr\varphi 1}$$ $$E_{Dr\varphi} = q_{Dr\varphi 2}$$ $$B_{Dr\varphi} = \frac{K_{z\gamma r0}}{C_{Dr\varphi}D_{Dr\varphi}(1 - \varepsilon_y)}$$

in which:

(76) $$K_{z\gamma r0} = F_z R_0(q_{Dz8} + q_{Dz9} df_z)$$

© 2025 Hexagon AB and/or its subsidiaries.

The reduction factor ζ_6 reads:

(77) $$\zeta_6 = \cos[arc\tan(q_{Br\varphi 1}R_0\varphi)]$$

The spin moment at 90º slip angle is given by:

(78) $$M_{z\varphi 90} = M_{z\varphi\infty} \cdot \frac{2}{\pi} \cdot arc\tan(q_{Cr\varphi 2}R_0|\varphi|) \cdot G_{yx}(\kappa)$$

The spin moment at 90º slip angle is multiplied by the weighing function $G_{y\kappa}$ to account for the action of the longitudinal slip (see steady-state combined slip equations).

The reduction factor ζ_7 is given by:

(79) $$\zeta_7 = \frac{2}{\pi} \cdot arc\cos[M_{z\varphi 90} / |D_{Dr\varphi}|]$$

Turn-Slip and Parking Parameters

Name:	Name used in tire property file:	Explanation:
$p_{\varepsilon\gamma\phi 1}$	PECP1	Camber spin reduction factor parameter in camber stiffness.
$p_{\varepsilon\gamma\phi 2}$	PECP2	Camber spin reduction factor varying with load parameter in camber stiffness.
$p_{Dx\phi 1}$	PDXP1	Peak Fx reduction due to spin parameter.
$p_{Dx\phi 2}$	PDXP2	Peak Fx reduction due to spin with varying load parameter.
$p_{Dx\phi 3}$	PDXP3	Peak Fx reduction due to spin

© 2025 Hexagon AB and/or its subsidiaries.

		with kappa parameter.
$p_{Dy\phi 1}$	PDYP1	Peak Fy reduction due to spin parameter.
$p_{Dy\phi 2}$	PDYP2	Peak Fy reduction due to spin with varying load parameter.
$p_{Dy\phi 3}$	PDYP3	Peak Fy reduction due to spin with alpha parameter.
$p_{Dy\phi 4}$	PDYP4	Peak Fy reduction due to square root of spin parameter.
$p_{Ky\phi 1}$	PKYP1	Cornering stiffness reduction due to spin.
$p_{Hy\phi 1}$	PHYP1	Fy-alpha curve lateral shift limitation.
$p_{Hy\phi 2}$	PHYP2	Fy-alpha curve maximum lateral shift parameter.
$p_{Hy\phi 3}$	PHYP3	Fy-alpha curve maximum lateral shift varying with load parameter.
$p_{Hy\phi 4}$	PHYP4	Fy-alpha curve maximum lateral shift parameter.

© 2025 Hexagon AB and/or its subsidiaries.

$q_{Dt\phi 1}$	QDTP1	Pneumatic trail reduction factor due to turn slip parameter.
$q_{Br\phi 1}$	QBRP1	Residual (spin) torque reduction factor parameter due to side slip.
$q_{Cr\phi 1}$	QCRP1	Turning moment at constant turning and zero forward speed parameter.
$q_{Cr\phi 2}$	QCRP2	Turn slip moment (at alpha=90deg) parameter for increase with spin.
$q_{Dr\phi 1}$	QDRP1	Turn slip moment peak magnitude parameter.
$q_{Dr\phi 2}$	QDRP2	Turn slip moment peak position parameter.

The tire model parameters for turn-slip and parking are estimated automatically. In addition, you can specify each parameter individually in the tire property file (see example).

Steady-State Combined Slip

PAC2002 has two methods for calculating the combined slip forces and moments. If the user supplies the coefficients for the combined slip cosine 'weighing' functions, the combined slip is calculated according to Combined slip with cosine 'weighing' functions (standard method). If no coefficients are supplied, the so-called friction ellipse is used to estimate the combined slip forces and moments, see section Combined Slip with friction ellipse.

Combined slip with cosine 'weighing' functions

■Longitudinal Force at Combined Slip

© 2025 Hexagon AB and/or its subsidiaries.

■Lateral Force at Combined Slip

■Aligning Moment at Combined Slip

■Overturning Moment at Pure and Combined Slip

■Rolling Resistance Moment at Pure and Combined Slip

Formulas for the Longitudinal Force at Combined Slip

(80) $F_x = F_{x0} \cdot G_{x\alpha}(\alpha, \kappa, F_z)$

with $G_{x\alpha}$ the weighting function of the longitudinal force for pure slip.

We write:

(81) $F_x = D_{x\alpha} \cos[C_{x\alpha} arc\tan\{B_{x\alpha}\alpha_s - E_{x\alpha}(B_{x\alpha}\alpha_s - arc\tan(B_{x\alpha}\alpha_s))\}]$

(82) $\alpha_s = \alpha + S_{Hx\alpha}$

with coefficients:

(83) $B_{x\alpha} = r_{Bx1} \cos[arc\tan\{r_{Bx2}\kappa\}] \cdot \lambda_{x\alpha}$

(84) $C_{x\alpha} = r_{Cx1}$

(85) $D_{x\alpha} = \dfrac{F_{xo}}{\cos[C_{x\alpha} arc\tan\{B_{x\alpha}S_{Hx\alpha} - E_{x\alpha}(B_{x\alpha}S_{Hx\alpha} - arc\tan(B_{x\alpha}S_{Hx\alpha}))\}]}$

(86) $E_{x\alpha} = r_{Ex1} + r_{Ex2}df_z \;\; with \;\; E_{x\alpha} \le 1$

(87) $S_{Hx\alpha} = r_{Hx1}$

The weighting function follows as:

(88) $G_{x\alpha} = \dfrac{\cos[C_{x\alpha} arc\tan\{B_{x\alpha}\alpha_s - E_{x\alpha}(B_{x\alpha}\alpha_s - arc\tan(B_{x\alpha}\alpha_s))\}]}{\cos[C_{x\alpha} arc\tan[B_{x\alpha}S_{Hx\alpha} - E_{x\alpha}(B_{x\alpha}S_{Hx\alpha} - arc\tan(B_{x\alpha}S_{Hx\alpha}))]]}$

Longitudinal Force Coefficients at Combined Slip

Name:	Name used in tire property	Explanation:

© 2025 Hexagon AB and/or its subsidiaries.

file:		
r_{Bx1}	RBX1	Slope factor for combined slip Fx reduction
r_{Bx2}	RBX2	Variation of slope Fx reduction with kappa
r_{Cx1}	RCX1	Shape factor for combined slip Fx reduction
r_{Ex1}	REX1	Curvature factor of combined Fx
r_{Ex2}	REX2	Curvature factor of combined Fx with load
r_{Hx1}	RHX1	Shift factor for combined slip Fx reduction

Formulas for Lateral Force at Combined Slip

(89) $F_y = F_{y0} \cdot G_{y\kappa}(\alpha, \kappa, \gamma, F_z) + S_{Vy\kappa}$

with $G_{y\kappa}$ the weighting function for the lateral force at pure slip and $S_{Vy\kappa}$ the 'κ-induced' side force; therefore, the lateral force can be written as:

(90) $F_y = D_{y\kappa} \cos[C_{y\kappa} arc\tan\{B_{y\kappa}\kappa_s - E_{y\kappa}(B_{y\kappa}\kappa_s - arc\tan(B_{y\kappa}\kappa_s))\}] + S_{Vy\kappa}$

(91) $\kappa_s = \kappa + S_{Hy\kappa}$

with the coefficients:

(92) $B_{y\kappa} = r_{By1} \cos[arc\tan\{r_{By2}(\alpha - r_{By3})\}] \cdot \lambda_{y\kappa}$

© 2025 Hexagon AB and/or its subsidiaries.

(93) $C_{y\kappa} = r_{Cy1}$

$$D_{y\kappa} = \frac{F_{yo}}{\cos[C_{y\kappa} arc\tan\{B_{y\kappa}S_{Hy\kappa} - E_{y\kappa}(B_{y\kappa}S_{Hy\kappa} - arc\tan(B_{y\kappa}S_{Hy\kappa}))\}]}$$

(94)

(95) $E_{y\kappa} = r_{Ey1} + r_{Ey2}df_z \;\; with \;\; E_{y\kappa} \le 1$

(96) $S_{Hy\kappa} = r_{Hy1} + r_{Hy2}df_z$

(97) $S_{Vy\kappa} = D_{Vy\kappa}\sin[r_{Vy5} arc\tan(r_{Vy6}\kappa)] \cdot \lambda_{Vy\kappa}$

$$D_{Vy\kappa} = \mu_y F_z \cdot (r_{Vy1} + r_{Vy2}df_z + r_{Vy3}\gamma) \cdot \cos[arc\tan(r_{Vy4}\alpha)]$$

(98)

The weighting function appears is defined as:

(99) $$G_{y\kappa} = \frac{\cos[C_{y\kappa} arc\tan\{B_{y\kappa}\kappa_s - E_{y\kappa}(B_{y\kappa}\kappa_s - arc\tan(B_{y\kappa}\kappa_s))\}]}{\cos[C_{y\kappa} arc\tan\{B_{y\kappa}S_{Hy\kappa} - E_{y\kappa}(B_{y\kappa}S_{Hy\kappa} - arc\tan(B_{y\kappa}S_{Hy\kappa}))\}]}$$

Lateral Force Coefficients at Combined Slip

Name:	Name used in tire property file:	Explanation:
r_{By1}	RBY1	Slope factor for combined Fy reduction
r_{By2}	RBY2	Variation of slope Fy reduction with alpha
r_{By3}	RBY3	Shift term for alpha in slope Fy reduction

© 2025 Hexagon AB and/or its subsidiaries.

r_{Cy1}	RCY1	Shape factor for combined Fy reduction
r_{Ey1}	REY1	Curvature factor of combined Fy
r_{Ey2}	REY2	Curvature factor of combined Fy with load
r_{Hy1}	RHY1	Shift factor for combined Fy reduction
r_{Hy2}	RHY2	Shift factor for combined Fy reduction with load
r_{Vy1}	RVY1	Kappa induced side force Svyk/Muy*Fz at Fznom
r_{Vy2}	RVY2	Variation of Svyk/Muy*Fz with load
r_{Vy3}	RVY3	Variation of Svyk/Muy*Fz with inclination
r_{Vy4}	RVY4	Variation of Svyk/Muy*Fz with alpha
r_{Vy5}	RVY5	Variation of Svyk/Muy*Fz with kappa

© 2025 Hexagon AB and/or its subsidiaries.

r_{Vy6}	RVY6	Variation of Svyk/Muy*Fz with atan (kappa)

Formulas for Aligning Moment at Combined Slip

(100) $M' = -t \cdot F'_y + M_{zr} + s \cdot F_x$

with:

(101) $t = t(\alpha_{t,eq})$

(102) $? = D_t \cos[C_t arc\tan\{B_t\alpha_{t,eq} - E_t(B_t\alpha_{t,eq} - arc\tan(B_t\alpha_{t,eq}))\}]\cos(\alpha)$

(103) $F'_{y,\gamma=0} = F_y - S_{Vy\kappa}$

(104) $M_{zr} = M_{zr}(\alpha_{r,eq}) = D_r\cos[arc\tan(B_r\alpha_{r,eq})]\cos(\alpha)$

(105) $t = t(\alpha_{t,eq})$

with the arguments:

(106) $\alpha_{t,eq} = arc\tan\sqrt{\tan^2\alpha_t + \left(\frac{K_x}{K_y}\right)^2\kappa^2} \cdot \mathrm{sgn}(\alpha_t)$

(107) $\alpha_{r,eq} = arc\tan\sqrt{\tan^2\alpha_r + \left(\frac{K_x}{K_y}\right)^2\kappa^2} \cdot \mathrm{sgn}(\alpha_r)$

(108) $s = \left\{s_{sz1} + s_{sz2}\frac{F_y}{F'_{z0}} + (s_{sz3} + s_{sz4}dfz)\gamma\right\}R_0\lambda_s$

Aligning Moment Coefficients at Combined Slip

Name:	Name used in tire property file:	Explanation:

© 2025 Hexagon AB and/or its subsidiaries.

s_{sz1}	SSZ1	Nominal value of s/R0 effect of Fx on Mz
s_{sz2}	SSZ2	Variation of distance s/R0 with Fy/Fznom
s_{sz3}	SSZ3	Variation of distance s/R0 with inclination
s_{sz4}	SSZ4	Variation of distance s/R0 with load and inclination

Formulas for Overturning Moment at Pure and Combined Slip

For the overturning moment, see also reference [5.], the formula reads both for pure and combined slip conditions:

$$\begin{aligned} M_x = {} & R_o \cdot F_z \cdot \Bigg\{ q_{sx3} \cdot \frac{F_y}{F'_{z0}} \\ & + q_{sx4} \cos\left[q_{sx5} \arctan\left(\left(q_{sx6} \frac{F_z}{F'_{z0}} \right)^2 \right) \right] \sin\left[q_{sx7}\gamma + q_{sx8} \arctan\left(q_{sx9} \frac{F_y}{F'_{z0}} \right) \right] \\ & + \left[q_{sx10} \arctan\left(q_{sx11} \frac{F_z}{F'_{z0}} \right) - q_{sx2}(1 + q_{px1} dp_i) \right] \gamma + q_{sx1} \lambda_{VMx} \Bigg\} \lambda_{Mx} \end{aligned}$$

(109)

Overturning Moment Coefficients

Name:	Name used in tire property file:	Explanation:
q_{sx1}	QSX1	Lateral force induced overturning couple
q_{sx2}	QSX2	Inclination induced overturning

© 2025 Hexagon AB and/or its subsidiaries.

		couple
q_{sx3}	QSX3	Fy induced overturning couple
q_{sx4}	QSX4	Fz induced overturning couple due to lateral tire deflection
q_{sx5}	QSX5	Fz induced overturning couple due to lateral tire deflection
q_{sx6}	QSX6	Fz induced overturning couple due to lateral tire deflection
q_{sx7}	QSX7	Fz induced overturning couple due to lateral tire deflection by inclination
q_{sx8}	QSX8	Fz induced overturning couple due to lateral tire deflection by lateral force
q_{sx9}	QSX9	Fz induced overturning couple due to lateral tire deflection by lateral force
q_{sx10}	QSX10	Inclination induced overturning couple, load dependency
q_{sx11}	QSX11	load dependency inclination induced overturning couple

© 2025 Hexagon AB and/or its subsidiaries.

q_{px1}	QPX1	Variation of camber effect with pressure

Formulas for Rolling Resistance Moment at Pure and Combined Slip

The rolling resistance moment is defined by:

(110)
$$M_y = -R_0 F_z \lambda_{My}\left\{q_{sy1} + q_{sy2}\frac{F_x}{F_{z0}} + q_{sy3}\left|\frac{V_x}{V_{ref}}\right| + q_{sy4}\left(\frac{V_x}{V_{ref}}\right)^4 + q_{sy5}\gamma^2 + q_{sy6}\frac{F_z}{F_{z0}}\gamma^2\right\}\left\{\left(\frac{F_z}{F_{z0}}\right)^{qsy7}\left(\frac{p_i}{p_{i0}}\right)^{qsy8}\right\}$$

If q_{sy1} and q_{sy2} are both zero and FITTYP is equal to 5 (MF-Tyre 5.0), then the rolling resistance is calculated according to an old equation:

(111)
$$M_y = R_0(S_{Vx} + K_x \cdot S_{Hx})$$

Rolling Resistance Coefficients

Name:	Name used in tire property file:	Explanation:
q_{sy1}	QSY1	Rolling resistance moment coefficient
q_{sy2}	QSY2	Rolling resistance moment depending on Fx
q_{sy3}	QSY3	Rolling resistance moment depending on speed
q_{sy4}	QSY4	Rolling resistance moment depending on speed^4

© 2025 Hexagon AB and/or its subsidiaries.

q_{sy5}	QSY5	Rolling resistance moment depending on camber
q_{sy6}	QSY6	Rolling resistance moment depending on camber and load
q_{sy7}	QSY7	Rolling resistance moment depending on load (exponential)
q_{sy8}	QSY8	Rolling resistance moment depending on inflation pressure
V_{ref}	LONGVL	Measurement speed

Combined Slip with friction ellipse

In case the tire property file does not contain the coefficients for the 'standard' combined slip method (cosine 'weighing functions), the friction ellipse method is used, as described in this section.

Also the friction ellipse can be switched on by setting the keyword FE_METHOD in the [MODEL] section of the tire property file:

[MODEL]

FE_METHOD = 'YES'

Note that the method employed here is not part of one of the Magic Formula publications by Pacejka, but is an in-house development of MSC Software.

(112) $$\kappa_c = \kappa + S_{Hx} + \frac{S_{Vx}}{K_x}$$

(113) $$\alpha_c = \alpha + S_{Hy} + \frac{S_{Vy}}{K_y}$$

© 2025 Hexagon AB and/or its subsidiaries.

(114) $$\alpha^* = \sin(\alpha_c)$$

(115) $$\beta = \operatorname{acos}\left(\frac{|\kappa_c|}{\sqrt{\kappa_c^2 + \alpha^{*2}}}\right)$$

The following friction coefficients are defined:

(116) $$\mu_{x,\,act} = \frac{F_{x,\,0} - S_{Vx}}{F_z} \qquad \mu_{y,\,act} = \frac{F_{y,\,0} - S_{Vy}}{F_z}$$

(117) $$\mu_{x,\,max} = \frac{D_x}{F_z} \qquad \mu_{y,\,max} = \frac{D_y}{F_z}$$

(118) $$\mu_x = \frac{1}{\sqrt{\left(\frac{1}{\mu_{x,\,act}}\right)^2 + \left(\frac{\tan\beta}{\mu_{y,\,max}}\right)^2}}$$

(119) $$\mu_y = \frac{\tan\beta}{\sqrt{\left(\frac{1}{\mu_{x,\,max}}\right)^2 + \left(\frac{\tan\beta}{\mu_{y,\,act}}\right)^2}}$$

The forces corrected for the combined slip conditions are:

(120) $$F_x = \frac{\mu_x}{\mu_{x,\,act}} F_{x,\,0} \qquad F_y = \frac{\mu_y}{\mu_{y,\,act}} F_{y,\,0}$$

For aligning moment M_Z, rolling resistance M_Y and aligning moment M_Z the formulae (76) until and including (85) are used with $S_{Vyk} = 0$.

Transient Behavior in PAC2002

The previous Magic Formula equations are valid for steady-state tire behavior. When driving, however, the tire requires some response time on changes of the inputs. In tire modeling terminology, the low-frequency behavior (up to 15 Hz) is called transient behavior. For modeling transient tire behavior PAC2002 provides two methods:

- Linear transient model (validity up to 8 Hz)
- Non linear transient model (validity up to 15 Hz)

In transient mode the tire model is able to deal with zero speed (stand-still). The more advanced non-linear transient mode shows better stand-still and tire spinning up performance. In

© 2025 Hexagon AB and/or its subsidiaries.

combination with turn-slip and parking modeling, PAC2002 in non-linear transient mode is able to account for the so-called parking torque: the torque around the vertical axis due to the friction in between tire and road at stand-still when steering.

In the linear transient model, the longitudinal and lateral tire stiffness at stand-still depend on the rolling tire slip stiffness properties, while in the non-linear model the stand-still stiffness values depend on the carcass and slip stiffness properties, which is more realistic.

Linear transient model

In the linear transient model the tire contact point S' is suspended to the wheel-rim plane with a longitudinal and lateral spring, with respectively stiffness's C_{Fx} and C_{Fy}, see reference [1]. In the figure below a top view of the tire with the single contact point S' and the longitudinal (u) and lateral (v) carcass deflections is shown.

linear_transient.bmp

The contact point may move with respect to the wheel-rim plane and road. Movements relative to the road will result in tire-road interaction forces. Differences in slip velocities at point S and point S' will result in the tire carcass to deflect. The change of the longitudinal deflection u can be defined as:

(121) $$\frac{du}{dt} = -(V_{sx} - V'_{sx})$$

and the lateral deflection v as:

(122) $$\frac{dv}{dt} = -(V_{sy} - V'_{sy})$$

For small values of slip the side force F_y can be calculated using the cornering stiffness $C_{F\alpha}$ as follows:

(123) $$F_y = C_{F\alpha}\alpha' = -C_{F\alpha}\frac{V'_{sy}}{|V_x|}$$

While the lateral force on the carcass reads:

(124) $$F_y = C_{Fy}v$$

When introducing the lateral relaxation length σ_a as:

(125) $$\sigma_\alpha = \frac{C_{F\alpha}}{C_{Fy}}$$

the differential equation for the lateral deflection can be written as follows:

(126) $$\frac{dv}{dt} + \frac{1}{\sigma_\alpha}|V_x|v = |V_x|\alpha = -V_{sy}$$

For linear small slip we can define the practical slip quantity α' as:

(127) $$\alpha' = \operatorname{atan}\left(\frac{v}{\sigma_\alpha}\right)$$

With α' the equation for the lateral deflection becomes:

(128) $$\sigma_\alpha \frac{d\alpha'}{dt} + |V_x|\alpha' = -V_{sy}$$

Similar the differential equation for longitudinal direction with the longitudinal relaxation length σ_k can be derived:

(129) $$\sigma_\kappa \frac{d\kappa'}{dt} + |V_x|\kappa' = -V_{sx}$$

with the practical slip quantity κ'

(130) $$\kappa' = \frac{u}{\sigma_\kappa}$$

Both the longitudinal and lateral relaxation lengths are defined as of the vertical load:

(131) $$\sigma_\kappa = F_z \cdot (P_{Tx1} + P_{Tx2} df_z) \cdot \exp(P_{Tx3} df_z) \cdot (R_0 / F'_{z0}) \lambda_{\sigma\kappa}$$

(132) $$\sigma_\alpha = P_{Ty1} \sin\left[2 arc\tan\left\{\frac{F_z}{(P_{Ty2} F_{z0} \lambda_{F_{z0}})}\right\}\right] \cdot (1 - P_{Ky3}|\gamma_y|) \cdot R_0 \lambda_{F_{z0}} \cdot \lambda_{\sigma\alpha}$$

Using these practical slip quantities, κ'and α', the Magic Formula equations can be used to calculate the transient tire-road interaction forces and moments:

(133) $$F_x = F_x(\alpha', \kappa', F_z)$$

(134) $$F_y = F_y(\alpha', \kappa', \gamma, F_z)$$

(135) $$M'_z = -t \cdot F_y$$

(136) $$M_{zr} = M_{zr}(\alpha', \kappa', \gamma, F_z)$$

(137) $$M_z = M'_z + M_{zr} + s \cdot F_x$$

© 2025 Hexagon AB and/or its subsidiaries.

With this linear transient model the effective lateral compliance of the tire at stand-still is

(138) $$\frac{1}{C_{Fy}} = \frac{\sigma_{\alpha}}{C_{F\alpha}}$$

Similarly following applies for the longitudinal compliance:

(139) $$\frac{1}{C_{Fx}} = \frac{\sigma_{\kappa}}{C_{F\kappa}}$$

Coefficients of Linear Transient Model

Name:	Name used in tire property file:	Explanation:
p_{Tx1}	PTX1	Longitudinal relaxation length at Fznom
p_{Tx2}	PTX2	Variation of longitudinal relaxation length with load
p_{Tx3}	PTX3	Variation of longitudinal relaxation length with exponent of load
p_{Ty1}	PTY1	Peak value of relaxation length for lateral direction
p_{Ty2}	PTY2	Shape factor for lateral relaxation length

Non linear transient model

The contact mass model is based on the separation of the contact patch slip properties and the tire carcass compliance (see reference [1]). Instead of using relaxation lengths to describe compliance effects, the carcass springs are explicitly incorporated in the model. The contact patch

© 2025 Hexagon AB and/or its subsidiaries.

is given some inertia to ensure computational causality. This modeling approach automatically accounts for the lagged response to slip and load changes that diminish at higher levels of slip. The contact patch itself uses relaxation lengths to handle simulations at low speed.

non_linear_transient.bmp

The contact patch can deflect in longitudinal, lateral, and yaw directions with respect to the lower part of the wheel rim. A mass is attached to the contact patch to enable straightforward computations. Note that the yaw deflection of the contact mass yaw β is not shown in the upper figure.

The differential equations that govern the dynamics of the contact patch body are:

(140) $m_c(\dot{V}_{cx} - V_{cy}\dot{\psi}_c) + k_x\dot{u} + c_x u = F_x$

(141) $m_c(\dot{V}_{cy} - V_{cx}\dot{\psi}_c) + k_y\dot{v} + c_y v = F_y$

(142) $J_c\ddot{\psi}_c + k_\psi\dot{\beta} + c_\psi\beta = M_z$

The contact patch body with mass m_c and inertia J_c is connected to the wheel through springs c_x, c_y, and c_ψ and dampers k_x, k_y, and k_ψ in longitudinal, lateral, and yaw direction, respectively.

The additional equations for the longitudinal u, lateral v, and yaw β deflections are:

(143) $\dot{u} = V_{cx} - V_{sx}$

(144) $\dot{v} = V_{cy} - V_{sy}$

(145) $\dot{\beta} = \dot{\psi}_c - \psi$

in which V_{cx}, V_{cy} and $\dot{\psi}_c$ are the sliding velocity of the contact body in longitudinal, lateral, and yaw directions, respectively. V_{sx}, V_{sy}, and $\dot{\psi}$ are the corresponding velocities of the lower part of the wheel.

The transient slip equations for side slip, turn-slip, and camber are:

(146) $\sigma_c\frac{d\kappa'}{dt} + |V_x|\kappa' = V_{cx}$

(147) $\sigma_c\frac{d}{dt}\alpha' + |V_x|\alpha' = V_{cy} - V_x\beta + |V_x|\beta_{st}$

(148) $\sigma_c\frac{d\alpha'_t}{dt} + |V_x|\alpha'_t = |V_x|\alpha'$

© 2025 Hexagon AB and/or its subsidiaries.

(149) $\sigma_c \frac{d\varphi'_c}{dt} + |V_x|\varphi'_c = \dot{\psi}_c$

(150) $\sigma_{F2} \frac{d\varphi'_{F2}}{dt} + |V_x|\varphi'_{cF2} = \dot{\psi}_c$

(151) $\sigma_{\varphi 1} \frac{d\varphi'_1}{dt} + |V_x|\varphi'_1 = \dot{\psi}_c$

(152) $\sigma_{\varphi 2} \frac{d\varphi'_2}{dt} + |V_x|\varphi'_2 = \dot{\psi}_c$

where the calculated deflection angle has been used:

(153) $\beta_{st} = \frac{M_z}{c_\phi}$

The tire total spin velocity is:

(154) $\dot{\psi}_\gamma = \psi_c - (1 - \varepsilon_\gamma)\Omega \sin\gamma$

With the transient slip equations, the composite transient turn-slip quantities are calculated:

(155) $\varphi'_F = 2\varphi'_c - \varphi'_{F2}$

(156) $\varphi'_M = \varepsilon_\varphi \varphi'_c + \varepsilon_{\varphi 12}(\varphi'_1 - \varphi'_2)$

The tire forces are calculated with φ'_F and the tire moments with φ'_M.

The relaxation lengths are reduced with slip:

(157) $\sigma_c = b_{\varphi 3} \cdot a \cdot (1 - b_{\varphi 4}\theta \cdot \zeta)$

(158) $\sigma_2 = \frac{t_0}{a}\sigma_c$

In which t_0 is the pneumatic trail at zero slip angle.

(159) $\sigma_{F2} = b_{F2}\sigma_c$

(160) $\sigma_{\varphi 1} = b_{\varphi 1}\sigma_c$

(161) $\sigma_{\varphi 2} = b_{\varphi 2}\sigma_c$

© 2025 Hexagon AB and/or its subsidiaries.

Here a is half the contact length according to:

(162) $$a = p_{A1} R_0 \left(\frac{\rho_z}{R_0} + p_{A2} \sqrt{\frac{\rho_z}{R_0}} \right)$$

The composite tire parameter reads:

(163) $$\theta = \frac{K_{y0}}{3 \mu_y F_y}$$

and the equivalent slip ζ is calculated with the tire width b:

(164) $$\zeta = \frac{1}{1 + \kappa'} \sqrt{\{ |\alpha'| + a \varepsilon_{\varphi 12} |\varphi'_1 - \varphi'_2| \}^2 + \left(\frac{K_{x0}}{K_{y0}} \right)^2 \left\{ |\kappa'| + \frac{2}{3} b |\varphi'_c| \right\}^2}$$

With the contact relaxation length σ_C equal to half the contact length (a), this advanced non-linear model will yield an effective lateral compliance C_{Fy} of the tire at stand-still equal to:

(165) $$\frac{1}{C_{Fy}} = \frac{1}{C_y} + \frac{a}{C_{F\alpha}}$$

The effective tire relaxation length for lateral slip (at zero lateral slip) results in:

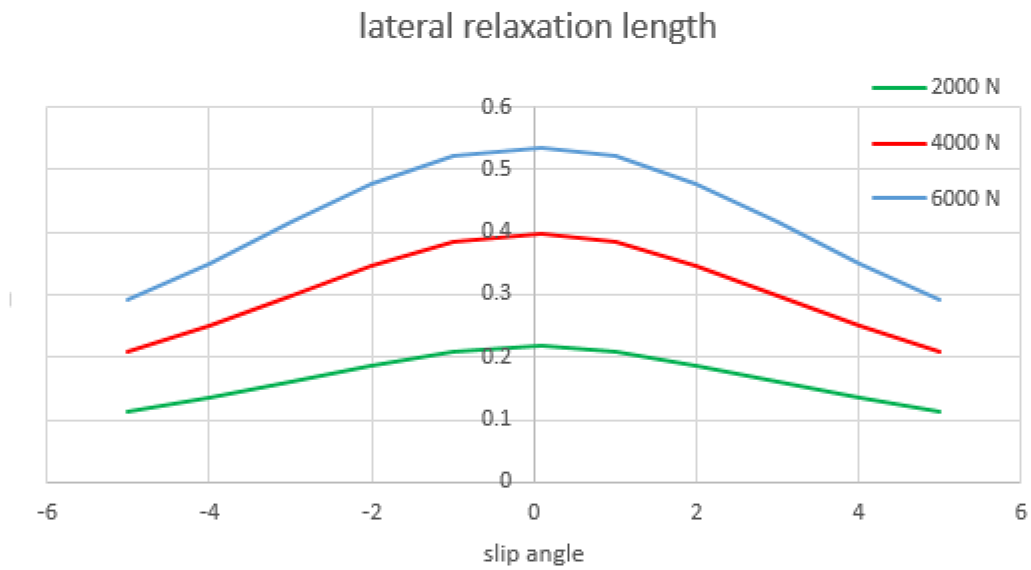
(166) $$\sigma_\alpha = \frac{C_{F\alpha}}{C_{Fy}} = \frac{C_{F\alpha}}{C_y} + a$$

Similarly following applies for longitudinal direction (at zero longitudinal slip):

(167) $$\sigma_\kappa = \frac{C_{F\kappa}}{C_{Fx}} = \frac{C_{F\kappa}}{C_x} + a$$

One advantage of the non-linear transient above the linear transient model is the dependency of relaxation to the amount of slip: if the slip increases, the relaxation will decrease, see the plot below:

© 2025 Hexagon AB and/or its subsidiaries.



In order to have a better agreement with measurement data the longitudinal and lateral stiffness can be defined to be a function of load and slip:

(168) $$C_x = c_x\left\{1 + c_{xz1}df_z + c_{xz2}df_z^2 + c_{xx1}\left(\frac{\kappa F_{z0}}{F_z}\right)^2\right\}$$

(169) $$C_y = c_y\left\{1 + c_{yz1}df_z + c_{yz2}df_z^2 + c_{yy1}\left(\frac{\alpha F_{z0}}{F_z}\right)^2\right\}$$

(170) $$C_\Psi = c_\Psi\{1 + c_{pz1}df_z\}$$

Coefficients of Non Linear Transient Model

Name:	Name used in tire property file:	Explanation:
m_C	MC	Contact body mass
I_C	IC	Contact body moment of inertia

© 2025 Hexagon AB and/or its subsidiaries.

k_x	KX	Longitudinal damping
k_y	KY	Lateral damping
k_ψ	KP	Yaw damping
c_x	CX	Longitudinal stiffness
c_y	CY	Lateral stiffness
c_ψ	CP	Yaw stiffness
c_{xz}	CXZ1	Longitudinal stiffness linear dependency on load
c_{xz2}	CXZ2	Longitudinal stiffness quadratic dependency on load
c_{xx1}	CXX1	Longitudinal stiffness dependency on long. slip
c_{yz1}	CYZ1	Lateral stiffness linear dependency on load
c_{yz2}	CYZ2	Lateral stiffness quadratic dependency on load
c_{yy1}	CYY1	Lateral stiffness dependency

© 2025 Hexagon AB and/or its subsidiaries.

		on lat. slip
p_{A1}	PA1	Half contact length with vertical tire deflection
p_{A2}	PA2	Half contact length with square root of vertical tire deflection
ε_{φ}	EP	Composite turn-slip (moment)
$\varepsilon_{\varphi 12}$	EP12	Composite turn-slip (moment) increment
b_{F2}	BF2	Second relaxation length factor
$b_{\phi 1}$	BP1	First moment relaxation length factor
$b_{\phi 2}$	BP2	Second moment relaxation length factor
$b_{\phi 3}$	BP3	Third moment relaxation factor
$b_{\phi 4}$	BP4	Fourth moment relaxation factor

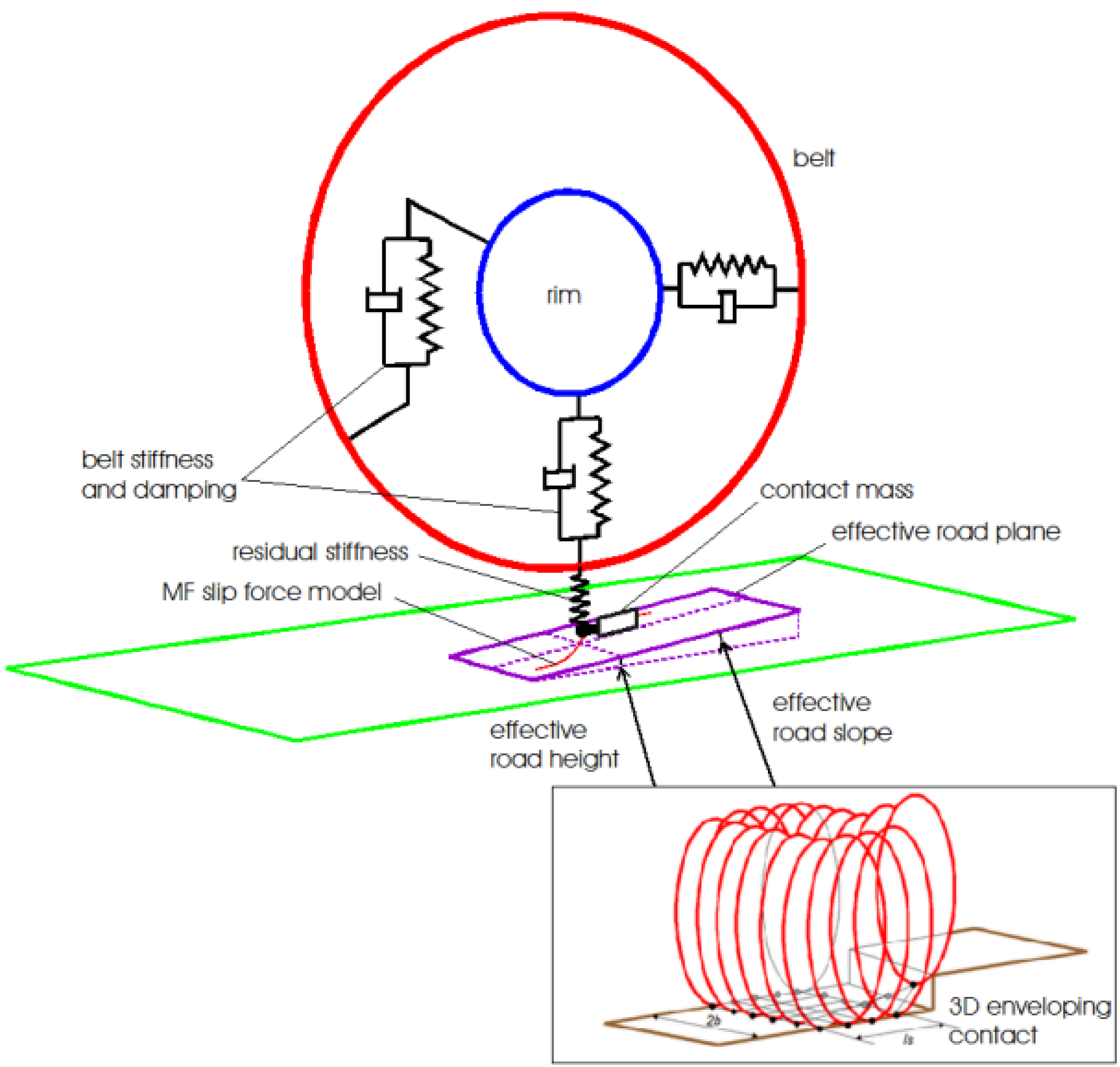
The remaining contact mass model parameters are estimated automatically based on longitudinal and lateral stiffness specified in the tire property file.

© 2025 Hexagon AB and/or its subsidiaries.

PAC2002 with Belt Dynamics

The 'basic' PAC2002 tire model with the linear transient model (USE_MODE 11 - 14) is valid up to approximately 8 Hz. By switching to the (non-linear) advanced transient mode (USE_MODE 21 - 25) the validity of the tire model can be increased to 15 Hz.

However, for having accurate tire response for frequencies higher than the 15 Hz, for example in case of vehicle ride analysis or vehicle behavior with chassis control systems, the dynamics of the tire belt starts to play a role. PAC2002 also offers a feature to describe the lowest eigen modes of the belt by assuming the belt as a rigid ring (rigid body part). The modeling approach has been published by Pacejka and others [1,6-8] and comes down to the following:



The wheel - tire assembly exists of a rim part and a belt part. In between the rim and the belt, a six

© 2025 Hexagon AB and/or its subsidiaries.

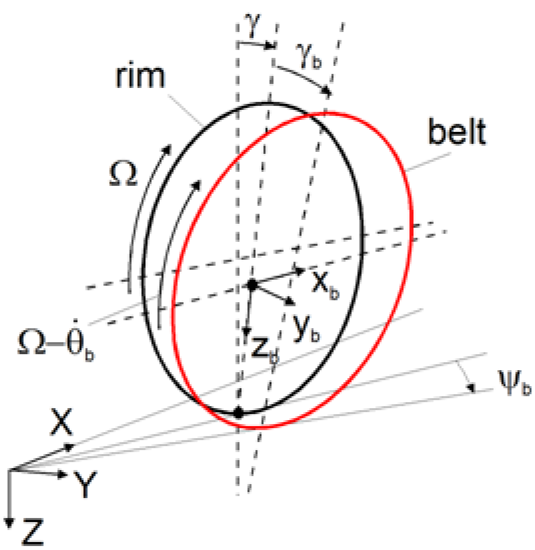
degree of freedom bushing with stiffness and damping will allow the belt to move with respect to the rim. In between the belt and the road, the residual stiffness will contribute to a correct vertical overall stiffness of the tire.

The input from the road to the tire in terms of the effective road height, road angle and road camber is supplied by the 3D Enveloping Contact. The road-belt friction interaction forces are calculated with the Non linear transient model (contact mass approach) in combination the Magic Formula equations for the tire's Force & Moment response.

Running the PAC2002 with the belt dynamics option will leverage the validity range of the tire model towards appr. 70 - 80 Hz.

Rim - Belt bushing

The interaction forces and torques in between the rim part and the wheel part are defined by a bushing with stiffness and damping forces in all 6 directions, x, y, z, γ, θ and ψ:



(171) $F_{xb} = k_{bx}\dot{x}_b + c_{bx}x_b$

(172) $F_{yb} = k_{by}\dot{y}_b + c_{by}y_b$

(173) $F_{zb} = k_{bz}\dot{z}_b + c_{bz}z_b$

(174) $T_{\gamma b} = k_{b\gamma}\dot{\gamma}_b + c_{b\gamma}\gamma_b$

(175) $T_{\theta b} = k_{b\theta}\dot{\theta}_b + c_{b\theta}\theta_b$

© 2025 Hexagon AB and/or its subsidiaries.

(176) $$T_{\psi b} = k_{b\psi}\dot{\psi}_b + c_{b\psi}\psi_b$$

For introducing an effect of the belt deflection and the wheel rotational speed on the sidewall stiffness the variable quantity Q_V is defined:

(177) $$Q_v = \frac{|\Omega|}{V_0}\sqrt{(x_b)^2 + (z_b)^2}$$

with

(178) $$c_{bx} = c_{bx0}(1 - q_{bVx}\sqrt{Q_v})$$

(179) $$c_{bz} = c_{bz0}(1 - q_{bVz}\sqrt{Q_v})$$

(180) $$c_{b\theta} = c_{b\theta 0}(1 - q_{bV\theta}\sqrt{Q_v})$$

The non-dimensional belt stiffness rates q_{cbx}, q_{cby}, q_{cbz}, $q_{cb\gamma}$, $q_{cb\theta}$ and $q_{cb\psi}$, to be supplied in the tire property file, are given by:

(181) $$c_{bx0,y,z0} = q_{cbx,y,z}F_{z0}/R_0$$

(182) $$c_{b\gamma,\theta o,\psi} = q_{cb\gamma,\theta,\psi}F_{z0}R_0$$

Because of the wheel symmetry following is valid:

$q_{cbxz} = q_{cbx} = q_{cbz}$ and $q_{cb\gamma\psi} = q_{cb\gamma} = q_{cb\psi}$

Similar, the non-dimensional q_{kbx}, q_{kby}, q_{kbz}, $q_{kb\gamma}$, $q_{kb\theta}$ and $q_{kb\psi}$, damping rates have following relation to the parameters in the bushing force equations:

(183) $$k_{bx,y,z} = 2q_{kbx,y,z}\sqrt{m_0F_{z0}/R_0}$$

(184) $$k_{b\gamma,\theta,\psi} = 2q_{kb\gamma,\theta,\psi}\sqrt{m_0F_{z0}R_0^3}$$

in which

- R_0 is the unloaded rolling radius of the tire.
- m_0 is the mass of the tire.
- F_{z0} is the nominal tire load.

© 2025 Hexagon AB and/or its subsidiaries.

Note that the in-plane damping parameters are equal due to the wheel symmetry:

$q_{kbxz} = q_{kbx} = q_{kbz}$ and $q_{kb\gamma\psi} = q_{kb\gamma} = q_{kb\psi}$

The mass of the belt is defined with parameter q_{mb}:

(185) $m_b = q_{mb} m_0$

and for the inertia of the belt q_{Ibxz} and q_{Iby} is used:

(186) $I_{bx} = I_{bz} = q_{Ibxz} m_0 R_0^2$

(187) $I_{by} = q_{Iby} m_0 R_0^2$

Normal load calculation

Knowing the deflection of the belt the vertical residual stiffness is calculated so that the tire overall normal load is still equal to the load defined in Equation (8) of the section "Contact Methods and Normal Load Calculation":

$$F_z = \left\{ q_{REO} + q_{V2}|\Omega|\frac{R_o}{V_o} - \left(q_{Fcx1}\frac{F_x}{F_{z0}}\right) - \left(q_{Fcy1}\frac{F_y}{F_{z0}}\right) + q_{Fc\gamma 1}\gamma^2 \right\}$$

(188) $$\left[q_{Fz1}\frac{\rho}{R_0} + q_{Fz2}\left(\frac{\rho}{R_0}\right)^2 + q_{Fz3}\gamma^2\frac{\rho}{R_0}\right](\{1 + q_{pFz1}dp_i\}\lambda_{Cz}F_{z0}) + K_z\dot{\rho}$$

Belt - Contact Mass

As mentioned, in the contact between the belt and the road, the non-linear transient model (see also section Non linear transient model, Equation (140) up to and including Equation (142)) is used, but with following parameters for the stiffness and damping:

(189) $m_c(\dot{V}_{cx} - V_{cy}\dot{\psi}_c) + k_{cx}\dot{u} + c_{cx}u = F_x$

(190) $m_c(\dot{V}_{cy} - V_{cx}\dot{\psi}_c) + k_{cy}\dot{v} + c_{cy}v = F_y$

(191) $I_c\ddot{\psi}_c + k_{c\psi}\dot{\beta} + c_{c\psi}\beta = M_z$

with

(192) $c_{cx} = q_{ccx}F_{z0} / R_0$

© 2025 Hexagon AB and/or its subsidiaries.

(193) $c_{cy} = q_{ccy} F_{z0} / R_0$

(194) $c_{c\psi} = q_{cc\psi} F_{z0} R_0$

(195) $k_{cx} = 2 q_{kcx} \sqrt{m_0 F_{z0} / R_0}$

(196) $k_{cy} = 2 q_{kcy} \sqrt{m_0 F_{z0} / R_0}$

(197) $k_{c\psi} = 2 q_{kc\psi} \sqrt{m_0 F_{z0} R_0^3}$

The contact mass is defined with parameter q_{mc}:

(198) $m_c = q_{mc} m_0$

And the contact mass inertia is defined with q_{Ic}:

(199) $I_c = q_{Ic} m_0 R_0^2$

Belt parameters

Name:	Name used in tire property file:	Explanation:
m_0	TYRE_MASS	Mass of the tire
q_{mb}	QMB	Mass parameter of the tire belt
q_{mc}	QMC	Mass parameter of the tire contact mass
q_{Ibxz}	QIBXZ	Ixx/Izz inertia parameter of the tire belt
q_{Iby}	QIBY	Iyy inertia parameter of the tire

© 2025 Hexagon AB and/or its subsidiaries.

		belt
q_{Ic}	QIC	Inertia parameter of the contact mass
q_{cbxz}	QCBXZ	Radial belt - wheel stiffness factor
q_{cby}	QCBY	Axial belt - wheel stiffness factor
$q_{cb\gamma y}$	QCBGM	Rotational belt - wheel stiffness factor
$q_{cb\theta}$	QCBTH	Torsional belt - wheel stiffness factor
q_{kbxz}	QKBXZ	Radial belt - wheel damping factor
q_{kby}	QKBY	Axial belt - wheel damping factor
$q_{kb\gamma y}$	QKBGM	Rotational belt - wheel damping factor
$q_{kb\theta}$	QKBTH	Torsional belt - wheel damping factor
q_{bVxz}	QBVXZ	Speed effect on radial belt -

© 2025 Hexagon AB and/or its subsidiaries.

		wheel stiffness
$q_{bV\theta}$	QBVTH	Speed effect on torsional belt - wheel stiffness
q_{ccx}	QCCX	Longitudinal stiffness factor belt - contact mass
q_{ccy}	QCCY	Lateral stiffness factor belt - contact mass
$q_{cc\psi}$	QCCFI	Yaw stiffness factor belt - contact mass
q_{kcx}	QKCX	Longitudinal damping factor belt - contact mass
q_{kcy}	QKCY	Lateral damping factor belt - contact mass
$q_{kc\psi}$	QKCFI	Yaw damping factor belt - contact mass

PAC2002 Belt Parameters

The required parameters for running pac2002 with the belt dynamics option are:

■The Magic Formula parameters (steady state tire behavior). In the tire property file these are the sections LONGITUDINAL_COEFFICIENTS, OVERTURNING_COEFFICIENTS, LATERAL_COEFFICIENTS, ROLLING_COEFFICIENTS and ALIGNING_COEFFICIENTS.

■The parameters related to turn slip modeling, section TURNSLIP_COEFFICIENTS.

■The parameters related to the 3D Enveloping contact, section CONTACT_COEFFICIENTS. If

© 2025 Hexagon AB and/or its subsidiaries.

these are not supplied, default values will be taken.

■And as last the new BELT_PARAMETERS. These define the parameters for the belt-rim bushing, and the contact mass (part of the non-linear transient model).

The belt dynamics feature can be switched on by the keyword BELT_DYNAMICS in the [MODEL] section of the tire property file, for example:

$--model

[MODEL]

PROPERTY_FILE_FORMAT = 'PAC2002'

USE_MODE = 14 $Tire use switch (IUSED)

LONGVL = 10.0 $Measurement speed at test bench (V0)

TYRESIDE = 'LEFT' $Mounted side at tire test bench

BELT_DYNAMICS = 'YES'

CONTACT_MODEL = '3D_ENVELOPING'

$---dimensions

..

Though the USE_MODE is set to 14, internally the model will switch to USE_MODE 24.

When using a handling tire model in Adams, the tire-road interaction forces are applied on a (rotating) multi-body wheel part defined in the Adams Dataset. PAC2002 with belt dynamics needs one more multi-body part in the Adams Dataset: the belt part. Now the tire-road interaction forces will act on the belt part.

The Adams View and Adams Car preprocessors will recognize when PAC2002 is using the belt dynamics feature, and generate the multi-body belt part in the Adams Dataset.

In addition the total mass and inertia of the rim & wheel assembly as specified in the preprocessor will be distributed over the rim and belt part with the information from the PAC2002 tire property file.

An example tire property file with belt parameters is shown in the section Example of PAC2002 Tire Property Files.

© 2025 Hexagon AB and/or its subsidiaries.

Tire testing for belt parameters

The tire belt parameters should be identified out of tire test data performed under realistic tire operating conditions: for the belt parameters this means exciting the tire belt mode by rolling over road obstacles.

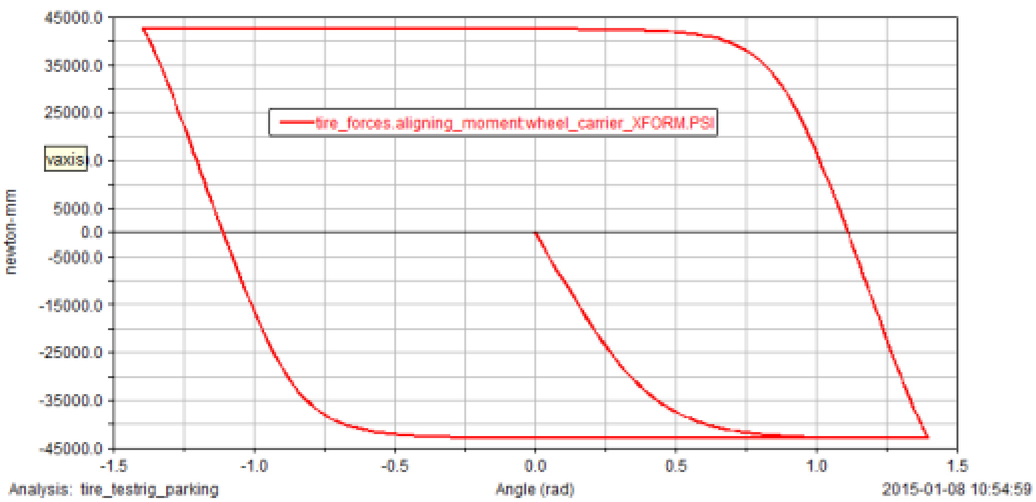
Most practical approach is using an external drum test bench, and roll the tire over a cleat at fixed axle height for various rotational speeds. The SAE standard J2730 [9] describes a proven concept for such a test program.

For identification of the PAC2002 belt parameters, the Adams Car Tire Test Rig can be used to reproduce the forces measured at cleat tests.

Parking Torque

The non-linear transient model in combination with the turn-slip / parking modeling (USE_MODE = 25) is able to account for the so-called parking torque at stand-still.

When applying a sine steering excitation to a standing tire in the non-linear (advanced) transient mode, the parking torque is generated around the vertical axis, as shown below.



The maximum parking torque is mainly determined by parameter $q_{Cr\phi 1}$, while the stiffness is due to the yaw stiffness c_ψ value.

Gyroscopic Couple in PAC2002

When having fast rotations about the vertical axis in the wheel plane, the inertia of the tire belt may lead to gyroscopic effects. When using PAC2002 without the belt dynamics (USEMODE 10 - 25), there is still a simple approach to account for the gyroscopic effect. To cope with this additional moment, the following contribution is added to the total aligning moment:

© 2025 Hexagon AB and/or its subsidiaries.

(200) $$M_{z,gyr} = c_{gyr} m_{belt} V_{r} l \frac{dv}{dt} \cos[\arctan(B_r \alpha_{r,eq})]$$

with the parameter (in addition to the basic tire parameter m_{belt}):

(201) $$c_{gyr} = q_{Tz1} \cdot \lambda_{gyr}$$

and:

(202) $$\cos[\arctan(B_r \alpha_{r,eq})] = 1$$

The total aligning moment now becomes:

(203) $$M_z = M'_z + M_{z,gyr}$$

Name:	Name used in tire property file:	Explanation:
q_{Tz1}	QTZ1	Gyroscopic moment constant
M_{belt}	MBELT	Belt mass of the wheel

Coefficients of the Gyrocopic Couple

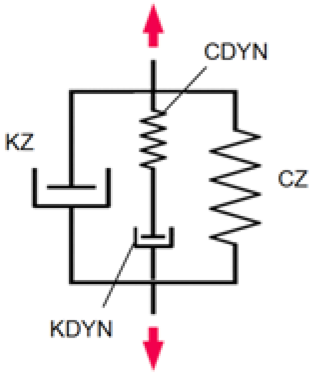
Non-rolling vertical tire stiffness and damping properties

In general the vertical stiffness and damping rates for a non-rolling tire differ from the stiffness and damping when rolling. In addition the non-rolling stiffness may depend on frequency. In the PAC2002 tire model a Maxwell element can be added to improve the non-rolling tire properties, for example for vehicle four poster simulations.

For using the Maxwell element the [VERTICAL] section of the tire property file should contain the keywords: USE_DYNAMIC_STIFFNESS, DYNAMIC_STIFFNESS and DYNAMIC_DAMPING, see the example snippet of a tire property file.

With USE_DYNAMIC_STIFFNESS = 'YES', the Maxwell element is switched on, with a 'NO' switched off.

© 2025 Hexagon AB and/or its subsidiaries.



Snippet of the [VERTICAL] section of a tire property file using the Maxwell element:

[VERTICAL]

VERTICAL_STIFFNESS = 2.1e+005

VERTICAL_DAMPING = 50

BREFF = 8.4

DREFF = 0.27

FREFF = 0.07

FNOMIN = 4850

USE_DYNAMIC_STIFFNESS = YES

DYNAMIC_STIFFNESS = 1.9E+003

DYNAMIC_DAMPING = 221

Left and Right Side Tires

In general, a tire produces a lateral force and aligning moment at zero slip angle due to the tire construction, known as conicity and plysteer. In addition, the tire characteristics cannot be symmetric for positive and negative slip angles.

A tire property file with the parameters for the model results from testing with a tire that is mounted in a tire test bench comparable either to the left or the right side of a vehicle. If these coefficients are used for both the left and the right side of the vehicle model, the vehicle does not drive straight at zero steering wheel angle.

The latest versions of tire property files contain a keyword TYRESIDE in the [MODEL] section that

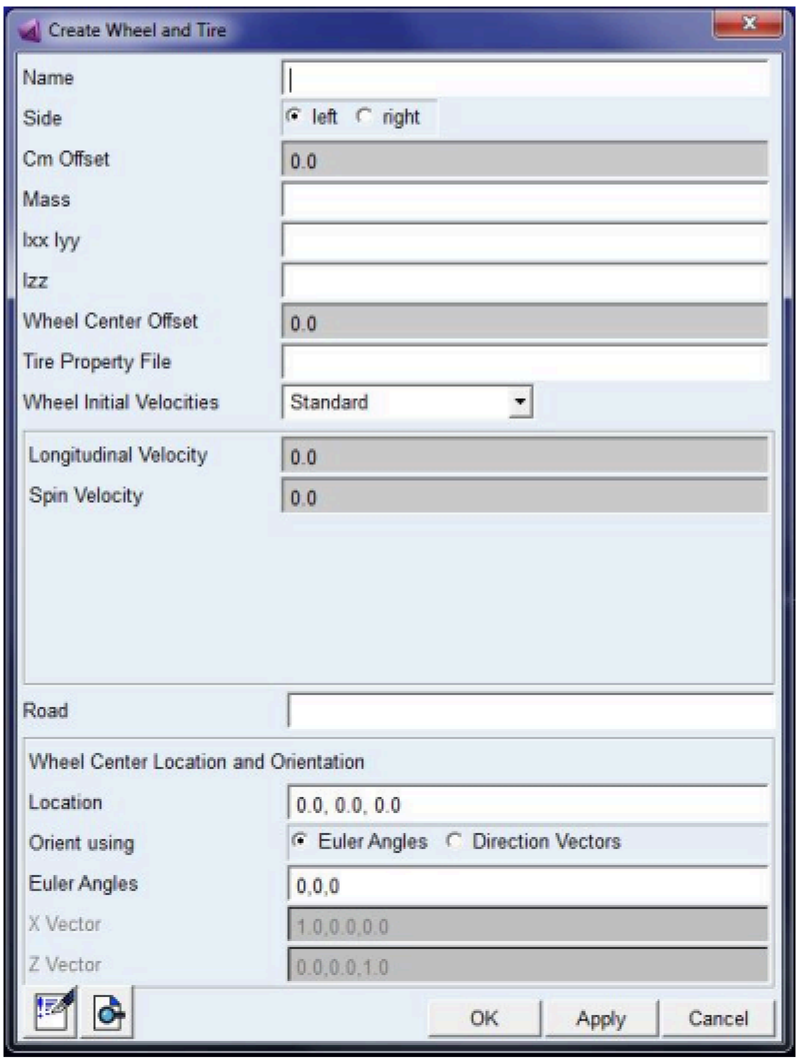
© 2025 Hexagon AB and/or its subsidiaries.

indicates for which side of the vehicle the tire parameters in that file are valid (TYRESIDE = 'LEFT' or TYRESIDE = 'RIGHT').

If this keyword is available, Adams Car corrects for the conicity and plysteer and asymmetry when using a tire property file on the opposite side of the vehicle. In fact, the tire characteristics are mirrored with respect to slip angle zero. In Adams View, this option can only be used when the tire is generated by the graphical user interface: select **Build -> Forces -> Special Force: Tire**.

Next to the LEFT and RIGHT side option of TYRESIDE, you can also set SYMMETRIC: then the tire characteristics are modified during initialization to show symmetric performance for left and right side corners and zero conicity and plysteer (no offsets).Also, when you set the tire property file to SYMMETRIC, the tire characteristics are changed to symmetric behavior.

Create Wheel and Tire Dialog Box in Adams View



Next to defining the mirroring via the GUI dialog window, also the USE_MODE parameter can be used: when the USE_MODE is negative, the tire characteristics will be mirrored as well.

© 2025 Hexagon AB and/or its subsidiaries.

When mirroring is done, following parameters will change sign:

RHX1, QSX1, PEY3, PHY1, PHY2, PVY1, PVY2, RBY3, RVY1, RVY2, QBZ4, QDZ3, QDZ6, QDZ7, QEZ4, QHZ1, QHZ2, SSZ1.

USE_MODES of PAC2002: from Simple to Complex

The parameter USE_MODE in the tire property file allows you to switch the output of the PAC2002 tire model from very simple (that is, steady-state cornering) to complex (transient combined cornering and braking).

The options for the USE_MODE and the output of the model have been listed in the table below.

USE_MODE Values of PAC2002 and Related Tire Model Output

USE_MODE:	State:	Slip conditions:	PAC2002 output (forces and moments):
0	Steady state	Acts as a vertical spring & damper	0, 0, F_z, 0, 0, 0
1	Steady state	Pure longitudinal slip	F_x, 0, F_z, 0, M_y, 0
2	Steady state	Pure lateral (cornering) slip	0, F_y, F_z, M_x, 0, M_z
3	Steady state	Longitudinal and lateral (not combined)	F_x, F_y, F_z, M_x, M_y, M_z
4	Steady state	Combined slip	F_x, F_y, F_z, M_x, M_y, M_z
11	Transient	Pure longitudinal slip	F_x, 0, F_z, 0, M_y, 0

© 2025 Hexagon AB and/or its subsidiaries.

12	Transient	Pure lateral (cornering) slip	0, F_y, F_z, M_x, 0, M_z
13	Transient	Longitudinal and lateral (not combined)	F_x, F_y, F_z, M_x, M_y, M_z
14	Transient	Combined slip	F_x, F_y, F_z, M_x, M_y, M_z
21	Advanced transient	Pure longitudinal slip	F_x, 0, F_z, M_y, 0
22	Advanced transient	Pure lateral (cornering slip)	0, F_y, F_z, M_x, 0, M_z
23	Advanced transient	Longitudinal and lateral (not combined)	F_x, F_y, F_z, M_x, M_y, M_z
24	Advanced transient	Combined slip	F_x, F_y, F_z, M_x, M_y, M_z
25	Advanced transient	Combined slip and turn-slip/parking	F_x, F_y, F_z, M_x, M_y, M_z

In addition to the use mode, the BELT_DYNAMICS switch can be used for using the Belt Dynamics option. In that case the tire model will switch to USE_MODE 24 or 25 internally.

The local Tire Solver for increasing simulation speed

By default the differential states of the Adams Tire models are calculated by the General State Equation (GSE) as part of the Standard Tire Interface (STI). PAC2002 offers the option to calculate the state internally instead of passing this calculation to the Adams solver via the GSE. In particular when the number of states is large (advanced transient or belt dynamics), this will reduce the work load for the Adams Solver and will in many cases reduce the required CPU of the solver and thus increase simulation speed.

The use of this 'tire solver' is meant for simulations with rather small maximum time step: 0.005 s.

© 2025 Hexagon AB and/or its subsidiaries.

The use of the 'tire solver' can switched on by setting the LOCAL_SOLVER key word in the [MODEL] section of the tire property file:

$--model

[MODEL]

LOCAL_SOLVER = 'YES' $tire model is using a local calculation for the tire model states

The combination of the 3D Enveloping Contact in combination with local tire solver is not supported (yet).

If the local tire solver is activated in combination with zero tire states in the GSE (ac_tire UDE -> n_tire_states), the GSE will be de-activated in dynamics. For this purpose, environment variable *MSC_ADAMS_INACTIVE_DYNAMICS*, *value="GSE, id_gse"* is introduced in the Adams dataset.

High Performance switch in Adams Car

In the Adams Car tire subsystem file, the keyword 'HIGH_PERFORMANCE' can be set for the tire model. The default value for the keyword (when not present) is 'NO'. When the HIGH_PERFORMANCE is set to 'YES', the PAC2002 is set to a high performance mode which should reduce the required cpu of the simulation.

When HIGH_PERFORMANCE = 'YES', the keywords with extension _HP are taken instead of the base keyword, these are:

[MODEL]

LOCAL_SOLVER_HP = 'YES'

[CONTACT_COEFFICIENTS]

N_WIDTH_HP = 2

N_LENGTH_HP = 2

ROAD_SPACING_HP = 0.002 (mm)

Thus the LOCAL_SOLVER_HP setting will replace the LOCAL_SOLVER setting and so on. When the _HP settings are not defined, the upper mentions values are used by default.

One must take care to ensure that the proper balance between performance and accuracy is achieved when employing this new high performance mode.

Note that the LOCAL_SOLVER will be accurate for solver steps equal or smaller than 0.005 sec.

© 2025 Hexagon AB and/or its subsidiaries.

Examples:

1.The property file lists:

[MODEL]

LOCAL_SOLVER = 'YES'

[CONTACT_COEFFICIENTS]

ROAD_SPACING_HP = 0.002 (mm)

In this case the LOCAL_SOLVER will be used with high performance 'YES' and 'NO', the ROAD_SPACING will be set to 0.002 during high performance 'YES' only

2.The property file lists:

[MODEL]

LOCAL_SOLVER_HP = 'NO'

LOCAL_SOLVER_HP = 'YES'

In this case the LOCAL_SOLVER will be used with high performance 'YES' only.

PAC2002 support for DOE

PAC2002 offers the user to define a set of DOE parameters in the PAC2002 property file. Adams Car supports this functionality by creating an array for each tire containing these parameters and which are then referenced by Adams View Design Variables. These Design Variables can be used in for example, Adams Insight to changePAC2002 properties in design of experiments studies.

An example tire property file (acar/shared_car_database.cdb/tires.tbl/ pac2002_235_60R16_doe.tir) is included in the Adams Car tire database. The section [DOE_PARAM_DEF] in the PAC2002 property file contains the names of the parameters which are chosen as DOE parameters, as shown below:

…

$---doe_param_def

[DOE_PARAM_DEF]

P1   = 'LKY'

P2   = 'PDY1'

© 2025 Hexagon AB and/or its subsidiaries.

P3   = 'RCY1'

$---doe_param

[DOE_PARAM]

P1 = 1.0

P2 = 0.95

P3 = 1.04

…

When creating a tire in Adams Car, Creating a tire in Adams Car, the ac_tire UDE creates Adams View Design Variables based on the [DOE_PARAMETERS] section in the tire property file. For each tire, an array is created which references the Design Variables. The actual values of the DOE parameters defined in the [DOE_PARAM] are passed via this array (referenced by the 17th element of the tire input array) to the PAC2002 model.

Example doe array:

Object Name	: .MDI_Demo_Vehicle.TR_Front_Tires.til_wheel.doe_array
Object Type	: Numbers ADAMS_Array
Parent Type	: ac_tire
Adams ID	: 902
Numbers	: 1.0 (.MDI_Demo_Vehicle.TR_Front_Tires.til_wheel.doe_p01)

The design variables (for example, .MDI_Demo_Vehicle.TR_Front_Tires.til_wheel.doe_p01) can be used in for example, Adams Insight to perform studies varying PAC2002 properties.

© 2025 Hexagon AB and/or its subsidiaries.

Quality Checks for the Tire Model Parameters

Because PAC2002 uses an empirical approach to describe tire - road interaction forces, incorrect parameters can easily result in non-realistic tire behavior. Below is a list of the most important items to ensure the quality of the parameters in a tire property file:

- Rolling Resistance
- Camber (Inclination) Effects
- Validity Range of the Tire Model Input

Note:	**Do not change F_{z0} (FNOMIN) and R_0 (UNLOADED_RADIUS)** in your tire property file. It will change the complete tire characteristics because these two parameters are used to make all parameters without dimension.

Rolling Resistance

For a realistic rolling resistance, the parameter q_{sy1} must be positive. For car tires, it can be in the order of 0.006 - 0.01 (0.6% - 1.0%); for heavy commercial truck tires, it can be around 0.006 (0.6%).

Tire property files with the keyword FITTYP=5 determine the rolling resistance in a different way (see equation (111)). To avoid the ‘old’ rolling resistance calculation, remove the keyword FITTYP and add a section like the following:

$---rolling resistance[ROLLING_COEFFICIENTS]

QSY1 = 0.01

QSY2 = 0

QSY3 = 0

QSY4 = 0

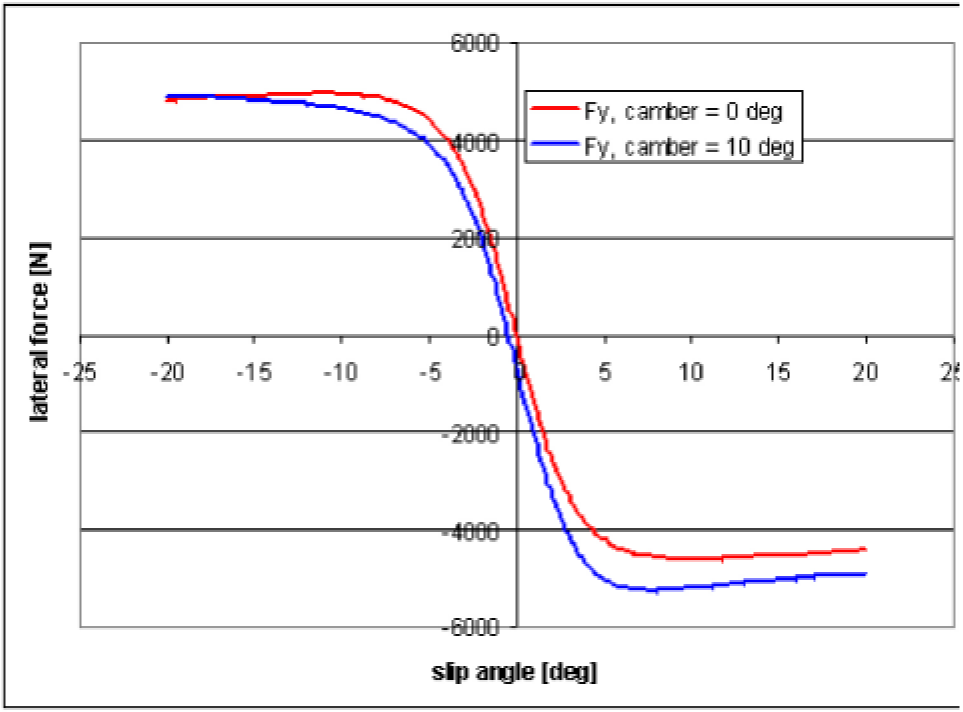
Camber (Inclination) Effects

Camber stiffness has not been explicitly defined in PAC2002; however, for car tires, positive inclination should result in a negative lateral force at zero slip angle. If positive inclination results in an increase of the lateral force, the coefficient may not be valid for the ISO but for the SAE

© 2025 Hexagon AB and/or its subsidiaries.

coordinate system. Note that PAC2002 only uses coefficients for the TYDEX W-axis (ISO) system.

Effect of Positive Camber on the Lateral Force in TYDEX W-axis (ISO) System



The table below lists further checks on the PAC2002 parameters.

Checklist for PAC2002 Parameters and Properties

Parameter/property:	Requirement:	Explanation:
LONGVL	1 m/s	Reference velocity at which parameters are measured
VXLOW	Approximately 1 m/s	Threshold for scaling down forces and moments
D_x	> 0	Peak friction (see equation (23))

© 2025 Hexagon AB and/or its subsidiaries.

p_{Dx1}/p_{Dx2}	< 0	Peak friction F_x must decrease with increasing load
K_x	> 0	Long slip stiffness (see equation (26))
D_y	> 0	Peak friction (see equation (35))
p_{Dy1}/p_{Dy2}	< 0	Peak friction F_x must decrease with increasing load
K_y	< 0	Cornering stiffness (see equation (38))
q_{sy1}	> 0	Rolling resistance, in the range of 0.005 - 0.015

Validity Range of the Tire Model Input

In the tire property file, a range of the input variables has been given in which the tire properties are supposed to be valid. These validity range parameters are (the listed values can be different):

$---long_slip_range

[LONG_SLIP_RANGE]

KPUMIN = -1.5 $Minimum valid wheel slip

KPUMAX = 1.5 $Maximum valid wheel slip

$---slip_angle_range

[SLIP_ANGLE_RANGE]

ALPMIN = -1.5708 $Minimum valid slip angle

© 2025 Hexagon AB and/or its subsidiaries.

ALPMAX = 1.5708 $Maximum valid slip angle

$--inclination_slip_range

[INCLINATION_ANGLE_RANGE]

CAMMIN = -0.26181 $Minimum valid camber angle

CAMMAX = 0.26181 $Maximum valid camber angle

$---vertical_force_range

[VERTICAL_FORCE_RANGE]

FZMIN = 225 $Minimum allowed wheel load

FZMAX = 10125 $Maximum allowed wheel load

If one of the input parameters exceeds a minimum or maximum validity value, the calculation in the tire model is performed with the minimum or maximum value of this range to avoid non-realistic tire behavior. In that case, a message appears warning you that one of the inputs exceeds a validity value.

Standard Tire Interface (STI) for PAC2002

Because all Adams products use the Standard Tire Interface (STI) for linking the tire models to Adams Solver, below is a brief background of the STI history (see also reference [4]).

At the First International Colloquium on Tire Models for Vehicle Dynamics Analysis on October 21-22, 1991, the International Tire Workshop working group was established (TYDEX).

The working group concentrated on tire measurements and tire models used for vehicle simulation purposes. For most vehicle dynamics studies, people used to develop their own tire models. Because all car manufacturers and their tire suppliers have the same goal (that is, development of tires to improve dynamic safety of the vehicle) it aimed for standardization in tire behavior description.

In TYDEX, two expert groups, consisting of participants of vehicle industry (passenger cars and trucks), tire manufacturers, other suppliers and research laboratories, had been defined with following goals:

- The first expert group's (Tire Measurements - Tire Modeling) main goal was to specify an interface between tire measurements and tire models. The result was the TYDEX-Format [2] to describe tire measurement data.

- The second expert group's (Tire Modeling - Vehicle Modeling) main goal was to specify an interface between tire models and simulation tools, which resulted in the Standard Tire Interface

© 2025 Hexagon AB and/or its subsidiaries.

(STI) [3]. The use of this interface should ensure that a wide range of simulation software can be linked to a wide range of tire modeling software.

Definitions

- General
- Tire Kinematics
- Slip Quantities
- Force and Moments

General

General Definitions

Term:	Definition:
Road tangent plane	Plane with the normal unit vector (tangent to the road) in the tire-road contact point C.
C-axis system	Coordinate system mounted on the wheel carrier at the wheel center according to TYDEX, ISO orientation.
Wheel plane	The plane in the wheel center that is formed by the wheel when considered a rigid disc with zero width.
Contact point C	Contact point between tire and road, defined as the intersection of the wheel plane and the projection of the wheel axis onto the road plane.
W-axis system	Coordinate system at the tire contact point C,

© 2025 Hexagon AB and/or its subsidiaries.

	according to TYDEX, ISO orientation.

Tire Kinematics

Tire Kinematics Definitions

Parameter:	Definition:	Units:
R_0	Unloaded tire radius	[m]
R	Loaded tire radius	[m]
R_e	Effective tire radius	[m]
ρ	Radial tire deflection	[m]
ρ^d	Dimensionless radial tire deflection	[-]
ρ_{FZ0}	Radial tire deflection at nominal load	[m]
m_{belt}	Tire belt mass	[kg]
Ω	Rotational velocity of the wheel	[radian^{-1}]

Slip Quantities

Slip Quantities Definitions

© 2025 Hexagon AB and/or its subsidiaries.

Parameter:	Definition:	Units:
V	Vehicle speed	[ms^{-1}]
V_{sx}	Slip speed in x direction	[ms^{-1}]
V_{sy}	Slip speed in y direction	[ms^{-1}]
V_s	Resulting slip speed	[ms^{-1}]
V_x	Rolling speed in x direction	[ms^{-1}]
V_y	Lateral speed of tire contact center	[ms^{-1}]
V_r	Linear speed of rolling	[ms^{-1}]
κ	Longitudinal slip	[-]
α	Slip angle	[radian]
γ	Inclination angle	[radian]

Forces and Moments

Force and Moment Definitions

© 2025 Hexagon AB and/or its subsidiaries.

Abbreviation:	Definition:	Units:
F_z	Vertical wheel load	[N]
F_{z0}	Nominal load	[N]
df_z	Dimensionless vertical load	[-]
F_x	Longitudinal force	[N]
F_y	Lateral force	[N]
M_x	Overturning moment	[Nm]
M_y	Braking/driving moment	[Nm]
M_z	Aligning moment	[Nm]

References

1.H.B. Pacejka, Tyre and Vehicle Dynamics, 2002, Butterworth-Heinemann, ISBN 0 7506 5141 5.

2.H.-J. Unrau, J. Zamow, TYDEX-Format, Description and Reference Manual, Release 1.1, Initiated by the International Tire Working Group, July 1995.

3.A. Riedel, Standard Tire Interface, Release 1.2, Initiated by the Tire Workgroup, June 1995.

4.J.J.M. van Oosten, H.-J. Unrau, G. Riedel, E. Bakker, TYDEX Workshop: Standardisation of Data Exchange in Tyre Testing and Tyre Modelling, Proceedings of the 2nd International Colloquium on Tyre Models for Vehicle Dynamics Analysis, Vehicle System Dynamics, Volume 27, Swets & Zeitlinger, Amsterdam/Lisse, 1996.

© 2025 Hexagon AB and/or its subsidiaries.

5.L. Merkx, Overturning moment analysis using the Flat plank tyre tester, DCT 2004-78, Department of Mechanical Engineering, University of Technology Eindhoven.

6.A.J.C. Schmeitz, "A semi-empirical three-dimensional model of the pneumatic tyre rolling over arbitrary uneven road surfaces," Ph.D. thesis, Delft University of Technology, Delft, 2004.

7.Maurice, J.P., "Short Wavelength and Dynamic Tyre Behaviour under Later and Combined Slip Conditions", PhD Thesis, Delft University of Technology, Delft, 2000.

8.Zegelaar, P.W.A., "The Dynamic Response of Tyres to Brake Torque Variations and Road Unevenesses", PhD Thesis, Delft University of Technology, Delft, 1998.

9."Dynamic Cleat Test with Perpendicular and Inclined Cleats", SAE Standard J2730.

Example of PAC2002 Tire Property Files

Example of a tire property file with linear transient (USE_MODE = 14):

```
[MDI_HEADER]

FILE_TYPE           ='tir'

FILE_VERSION        =3.0

FILE_FORMAT         ='ASCII'

! : TIRE_VERSION :    PAC2002

! : COMMENT :         Tire             235/60R16

! : COMMENT :         Manufacturer

! : COMMENT :         Nom. section with  (m)  0.235

! : COMMENT :         Nom. aspect ratio  (-)  60

! : COMMENT :         Infl. pressure    (Pa)  200000

! : COMMENT :         Rim radius         (m)  0.19

! : COMMENT :         Measurement ID

! : COMMENT :         Test speed       (m/s)  16.6

! : COMMENT :         Road surface

! : COMMENT :         Road condition          Dry
```

© 2025 Hexagon AB and/or its subsidiaries.

! : FILE_FORMAT :   ASCII

! : Copyright (C) 2004-2011 MSC Software Corporation

!

! USE_MODE specifies the type of calculation performed:

!   0: Fz only, no Magic Formula evaluation

!   1: Fx,My only

!   2: Fy,Mx,Mz only

!   3: Fx,Fy,Mx,My,Mz uncombined force/moment calculation

!   4: Fx,Fy,Mx,My,Mz combined force/moment calculation

!   +10: including relaxation behaviour

!   15: Fx,Fy,Mx,My,Mz combined force/moment calculation, relaxation behaviour, including turn-slip torque

!   +20: including advanced transient (contact mass approach)

!   25: Fx,Fy,Mx,My,Mz combined force/moment calculation, advanced transient including turn-slip torque & parking torque

!   *-1: mirroring of tyre characteristics

!

!   example: USE_MODE = -12 implies:

!   -calculation of Fy,Mx,Mz only

!   -including relaxation effects

!   -mirrored tyre characteristics

!

$---units

[UNITS]

LENGTH   ='meter'

© 2025 Hexagon AB and/or its subsidiaries.

```
FORCE                 ='newton'

ANGLE                 ='radian'

MASS                  ='kg'

TIME                  ='second'

$------------------------------------------------------------model

[MODEL]

PROPERTY_FILE_FORMAT    ='PAC2002' $Tire property type

USE_MODE              = 14                         $Tyre use switch (IUSED)

VXLOW                 = 1                          $Below this speed forces are scaled down

LONGVL                = 16.6                       $Measurement speed

FE_METHOD             = 'NO'                       $For switching to Friction ellipse for combined
slip

TYRESIDE              = 'LEFT'                     $Mounted side of tyre at vehicle/test bench

$-------------------------------------------------------dimensions

[DIMENSION]

UNLOADED_RADIUS       = 0.344                      $Free tyre radius

WIDTH                 = 0.235                      $Nominal section width of the tyre

ASPECT_RATIO          = 0.6                        $Nominal aspect ratio

RIM_RADIUS            = 0.19                       $Nominal rim radius

RIM_WIDTH             = 0.16                       $Rim width

$-------------------------------------------------------load_curve

$ For a non-linear tire vertical stiffness

$ Maximum of 100 points

[DEFLECTION_LOAD_CURVE]

{pen       fz}
```

© 2025 Hexagon AB and/or its subsidiaries.

```
0.000      0.0
0.001    212.0
0.002    428.0
0.003    648.0
0.005   1100.0
0.010   2300.0
0.020   5000.0
0.030   8100.0
$----------------------------------------------------------RIMPACT_CURVE
$ Maximum of 100 points
[BOTTOMING_CURVE]
{pen          fz}
0.0           0.0
0.09           0.0
0.1        100000.0
0.2        200000.0
0.3        300000.0
0.4        400000.0
0.5        500000.0
0.6        600000.0
6.0        6000000.0
$-----------------------------------------------------------parameter
[VERTICAL]
VERTICAL_STIFFNESS                = 2.1e+005        $Tyre vertical stiffness
```

© 2025 Hexagon AB and/or its subsidiaries.

VERTICAL_DAMPING = 50 $Tyre vertical damping

BREFF = 8.4 $Low load stiffness e.r.r.

DREFF = 0.27 $Peak value of e.r.r.

FREFF = 0.07 $High load stiffness e.r.r.

FNOMIN = 4850 $Nominal wheel load

$--long_slip_range

[LONG_SLIP_RANGE]

KPUMIN = -1.5 $Minimum valid wheel slip

KPUMAX = 1.5 $Maximum valid wheel slip

$---slip_angle_range

[SLIP_ANGLE_RANGE]

ALPMIN = -1.5708 $Minimum valid slip angle

ALPMAX = 1.5708 $Maximum valid slip angle

$---inclination_slip_range

[INCLINATION_ANGLE_RANGE]

CAMMIN = -0.26181 $Minimum valid camber angle

CAMMAX = 0.26181 $Maximum valid camber angle

$---vertical_force_range

[VERTICAL_FORCE_RANGE]

FZMIN = 225 $Minimum allowed wheel load

FZMAX = 10125 $Maximum allowed wheel load

$---scaling

[SCALING_COEFFICIENTS]

LFZO = 1 $Scale factor of nominal (rated) load

© 2025 Hexagon AB and/or its subsidiaries.

```
LCX      = 1   $Scale factor of Fx shape factor
LMUX     = 1   $Scale factor of Fx peak friction coefficient
LEX      = 1   $Scale factor of Fx curvature factor
LKX      = 1   $Scale factor of Fx slip stiffness
LHX      = 1   $Scale factor of Fx horizontal shift
LVX      = 1   $Scale factor of Fx vertical shift
LGAX     = 1   $Scale factor of camber for Fx
LCY      = 1   $Scale factor of Fy shape factor
LMUY     = 1   $Scale factor of Fy peak friction coefficient
LEY      = 1   $Scale factor of Fy curvature factor
LKY      = 1   $Scale factor of Fy cornering stiffness
LHY      = 1   $Scale factor of Fy horizontal shift
LVY      = 1   $Scale factor of Fy vertical shift
LGAY     = 1   $Scale factor of camber for Fy
LTR      = 1   $Scale factor of Peak of pneumatic trail
LRES     = 1   $Scale factor for offset of residual torque
LGAZ     = 1   $Scale factor of camber for Mz
LXAL     = 1   $Scale factor of alpha influence on Fx
LYKA     = 1   $Scale factor of alpha influence on Fx
LVYKA    = 1   $Scale factor of kappa induced Fy
LS       = 1   $Scale factor of Moment arm of Fx
LSGKP    = 1   $Scale factor of Relaxation length of Fx
LSGAL    = 1   $Scale factor of Relaxation length of Fy
LGYR     = 1   $Scale factor of gyroscopic torque
```

© 2025 Hexagon AB and/or its subsidiaries.

LMX = 1 $Scale factor of overturning couple

LVMX = 1 $Scale factor of Mx vertical shift

LMY = 1 $Scale factor of rolling resistance torque

$---longitudinal

[LONGITUDINAL_COEFFICIENTS]

PCX1 = 1.6411 $Shape factor Cfx for longitudinal force

PDX1 = 1.1739 $Longitudinal friction Mux at Fznom

PDX2 = -0.16395 $Variation of friction Mux with load

PDX3 = 0 $Variation of friction Mux with camber

PEX1 = 0.46403 $Longitudinal curvature Efx at Fznom

PEX2 = 0.25022 $Variation of curvature Efx with load

PEX3 = 0.067842 $Variation of curvature Efx with load squared

PEX4 = -3.7604e-005 $Factor in curvature Efx while driving

PKX1 = 22.303 $Longitudinal slip stiffness Kfx/Fz at Fznom

PKX2 = 0.48896 $Variation of slip stiffness Kfx/Fz with load

PKX3 = 0.21253 Exponent in slip stiffness Kfx/Fz with load

PHX1 = 0.0012297 $Horizontal shift Shx at Fznom

PHX2 = 0.0004318 $Variation of shift Shx with load

PVX1 = -8.8098e-006 $Vertical shift Svx/Fz at Fznom

PVX2 = 1.862e-005 $Variation of shift Svx/Fz with load

RBX1 = 13.276 $Slope factor for combined slip Fx reduction

RBX2 = -13.778 $Variation of slope Fx reduction with kappa

RCX1 = 1.2568 $Shape factor for combined slip Fx reduction

REX1 = 0.65225 $Curvature factor of combined Fx

© 2025 Hexagon AB and/or its subsidiaries.

```
REX2            = -0.24948          $Curvature factor of combined Fx with load
RHX1            = 0.0050722          $Shift factor for combined slip Fx reduction
PTX1            = 2.3657          $Relaxation length SigKap0/Fz at Fznom
PTX2            = 1.4112          $Variation of SigKap0/Fz with load
PTX3            = 0.56626          $Variation of SigKap0/Fz with exponent of load
$-----------------------------------------------------overturning
[OVERTURNING_COEFFICIENTS]
QSX1            = 0          $Lateral force induced overturning moment
QSX2            = 0          $Camber induced overturning couple
QSX3            = 0          $Fy induced overturning couple
$---------------------------------------------------------lateral
[LATERAL_COEFFICIENTS]
PCY1            = 1.3507          $Shape factor Cfy for lateral forces
PDY1            = 1.0489          $Lateral friction Muy
PDY2            = -0.18033          $Variation of friction Muy with load
PDY3            = -2.8821          $Variation of friction Muy with squared camber
PEY1            = -0.0074722          $Lateral curvature Efy at Fznom
PEY2            = -0.0063208          $Variation of curvature Efy with load
PEY3            = -9.9935          $Zero order camber dependency of curvature Efy
PEY4            = -760.14          $Variation of curvature Efy with camber
PKY1            = -21.92          $Maximum value of stiffness Kfy/Fznom
PKY2            = 2.0012          $Load at which Kfy reaches maximum value
PKY3            = -0.024778          $Variation of Kfy/Fznom with camber
PHY1            = 0.0026747          $Horizontal shift Shy at Fznom
```

© 2025 Hexagon AB and/or its subsidiaries.

PHY2 = 8.9094e-005 $Variation of shift Shy with load

PHY3 = 0.031415 $Variation of shift Shy with camber

PVY1 = 0.037318 $Vertical shift in Svy/Fz at Fznom

PVY2 = -0.010049 $Variation of shift Svy/Fz with load

PVY3 = -0.32931 $Variation of shift Svy/Fz with camber

PVY4 = -0.69553 $Variation of shift Svy/Fz with camber and load

RBY1 = 7.1433 $Slope factor for combined Fy reduction

RBY2 = 9.1916 $Variation of slope Fy reduction with alpha

RBY3 = -0.027856 $Shift term for alpha in slope Fy reduction

RCY1 = 1.0719 $Shape factor for combined Fy reduction

REY1 = -0.27572 $Curvature factor of combined Fy

REY2 = 0.32802 $Curvature factor of combined Fy with load

RHY1 = 5.7448e-006 $Shift factor for combined Fy reduction

RHY2 = -3.1368e-005 $Shift factor for combined Fy reduction with load

RVY1 = -0.027825 $Kappa induced side force Svyk/Muy*Fz at Fznom

RVY2 = 0.053604 $Variation of Svyk/Muy*Fz with load

RVY3 = -0.27568 $Variation of Svyk/Muy*Fz with camber

RVY4 = 12.12 $Variation of Svyk/Muy*Fz with alpha

RVY5 = 1.9 $Variation of Svyk/Muy*Fz with kappa

RVY6 = -10.704 $Variation of Svyk/Muy*Fz with atan(kappa)

PTY1 = 2.1439 $Peak value of relaxation length SigAlp0/R0

PTY2 = 1.9829 $Value of Fz/Fznom where SigAlp0 is extreme

$--rolling resistance

[ROLLING_COEFFICIENTS]

© 2025 Hexagon AB and/or its subsidiaries.

```
QSY1         = 0.01          $Rolling resistance torque coefficient
QSY2         = 0          $Rolling resistance torque depending on Fx
QSY3         = 0          $Rolling resistance torque depending on speed
QSY4         = 0          $Rolling resistance torque depending on speed ^4
$---------------------------------------------------------aligning
[ALIGNING_COEFFICIENTS]
QBZ1         = 10.904          $Trail slope factor for trail Bpt at Fznom
QBZ2         = -1.8412          $Variation of slope Bpt with load
QBZ3         = -0.52041          $Variation of slope Bpt with load squared
QBZ4         = 0.039211          $Variation of slope Bpt with camber
QBZ5         = 0.41511          $Variation of slope Bpt with absolute camber
QBZ9         = 8.9846          $Slope factor Br of residual torque Mzr
QBZ10         = 0          $Slope factor Br of residual torque Mzr
QCZ1         = 1.2136          $Shape factor Cpt for pneumatic trail
QDZ1         = 0.093509          $Peak trail Dpt" = Dpt*(Fz/Fznom*R0)
QDZ2         = -0.0092183          $Variation of peak Dpt" with load
QDZ3         = -0.057061          $Variation of peak Dpt" with camber
QDZ4         = 0.73954          $Variation of peak Dpt" with camber squared
QDZ6         = -0.0067783          $Peak residual torque Dmr" = Dmr/(Fz*R0)
QDZ7         = 0.0052254          $Variation of peak factor Dmr" with load
QDZ8         = -0.18175          $Variation of peak factor Dmr" with camber
QDZ9         = 0.029952          $Variation of peak factor Dmr" with camber and load
QEZ1         = -1.5697          $Trail curvature Ept at Fznom
QEZ        = 0.33394          $Variation of curvature Ept with load
```

© 2025 Hexagon AB and/or its subsidiaries.

```
QEZ3        = 0         $Variation of curvature Ept with load squared
QEZ4        = 0.26711         $Variation of curvature Ept with sign of Alpha-t
QEZ5        = -3.594         $Variation of Ept with camber and sign Alpha-t
QHZ1        = 0.0047326         $Trail horizontal shift Sht at Fznom
QHZ2        = 0.0026687         $Variation of shift Sht with load
QHZ3        = 0.11998         $Variation of shift Sht with camber
QHZ4        = 0.059083         $Variation of shift Sht with camber and load
SSZ1        = 0.033372         $Nominal value of s/R0: effect of Fx on Mz
SSZ2        = 0.0043624         $Variation of distance s/R0 with Fy/Fznom
SSZ3        = 0.56742         $Variation of distance s/R0 with camber
SSZ4        = -0.24116         $Variation of distance s/R0 with load and camber
QTZ1        = 0.2         $Gyration torque constant
MBELT         = 5.4         $Belt mass of the wheel
$---------------------------------------------turn-slip parameters
[TURNSLIP_COEFFICIENTS]
PECP1         = 0.7         $Camber stiffness reduction factor
PECP2         = 0.0         $Camber stiffness reduction factor with load
PDXP1         = 0.4         $Peak Fx reduction due to spin
PDXP2         = 0.0         $Peak Fx reduction due to spin with load
PDXP3         = 0.0         $Peak Fx reduction due to spin with longitudinal slip
PDYP1         = 0.4         $Peak Fy reduction due to spin
PDYP2         = 0.0         $Peak Fy reduction due to spin with load
PDYP3         = 0.0         $Peak Fy reduction due to spin with lateral slip
PDYP4         = 0.0         $Peak Fy reduction with square root of spin
```

© 2025 Hexagon AB and/or its subsidiaries.

PKYP1 = 1.0 $Cornering stiffness reduction due to spin

PHYP1 = 1.0 $Fy lateral shift shape factor

PHYP2 = 0.15 $Maximum Fy lateral shift

PHYP3 = 0.0 $Maximum Fy lateral shift with load

PHYP4 = -4.0 $Fy lateral shift curvature factor

QDTP1 = 10.0 $Pneumatic trail reduction factor

QBRP1 = 0.1 $Residual torque reduction factor with lateral slip

QCRP1 = 0.2 $Turning moment at constant turning with zero speed

QCRP2 = 0.1 $Turning moment at 90 deg lateral slip

QDRP1 = 1.0 $Maximum turning moment

QDRP2 = -1.5 $Location of maximum turning moment

$---contact patch parameters

[CONTACT_COEFFICIENTS]

PA1 = 0.4147 $Half contact length dependency on sqrt(Fz/Fz0)

PA2 = 1.9129 $Half contact length dependency on Fz

$---contact patch slip model

[DYNAMIC_COEFFICIENTS]

MC = 1.0 $Contact mass

IC = 0.05 $Contact moment of inertia

KX = 409.0 $Contact longitudinal damping

KY = 320.8 $Contact lateral damping

KP = 11.9 $Contact yaw damping

CX = 4.350e+005 $Contact longitudinal stiffness

CY = 1.665e+005 $Contact lateral stiffness

© 2025 Hexagon AB and/or its subsidiaries.

CP = 20319 $Contact yaw stiffness

EP = 1.0

EP12 = 4.0

BF2 = 0.5

BP1 = 0.5

BP2 = 0.67

$---loaded radius

[LOADED_RADIUS_COEFFICIENTS]

QV1 = 0.000071 $Tire radius growth coefficient

QV2 = 2.489 $Tire stiffness variation coefficient with speed

QFCX1 = 0.1 $Tire stiffness interaction with Fx

QFCY1 = 0.3 $Tire stiffness interaction with Fy

QFCG1 = 0.0 $Tire stiffness interaction with camber

QFZ1 = 0.0 $Linear stiffness coefficient, if zero, VERTICAL_STIFFNESS is taken

QFZ2 = 14.35 $Tire vertical stiffness coefficient (quadratic)

Example of a tire property file with belt dynamics:

[MDI_HEADER]

FILE_TYPE ='tir'

FILE_VERSION =3.0

FILE_FORMAT ='ASCII'

! : TIRE_VERSION : PAC2002

! : COMMENT : Tire 205/55 R16

! : COMMENT : Manufacturer -

! : COMMENT : Nom. section width (m) 0.205

© 2025 Hexagon AB and/or its subsidiaries.

```
! : COMMENT :          Nom. aspect ratio  (-)  55
! : COMMENT :          Infl. pressure    (Pa)  250000
! : COMMENT :          Rim radius        (m)  0.203
! : COMMENT :          Measurement ID
! : COMMENT :          Test speed       (m/s)  30
! : COMMENT :          Road surface
! : COMMENT :          Road condition
! : FILE_FORMAT :       ASCII
! : Copyright (C) 2004-2011 MSC Software Corporation
!
! USE_MODE specifies the type of calculation performed:
!       0: Fz only, no Magic Formula evaluation
!       1: Fx,My only
!       2: Fy,Mx,Mz only
!       3: Fx,Fy,Mx,My,Mz uncombined force/moment calculation
!       4: Fx,Fy,Mx,My,Mz combined force/moment calculation
!     +10: including relaxation behaviour
!      15: Fx,Fy,Mx,My,Mz combined force/moment calculation, relaxation behaviour, including turn-slip torque
!     +20: including advanced transient (contact mass approach)
!      25: Fx,Fy,Mx,My,Mz combined force/moment calculation, advanced transient including turn-slip torque & parking torque
!     *-1: mirroring of tire characteristics
!
!    when beltdynamics is switched on the usemode will be 24 or 25
```

© 2025 Hexagon AB and/or its subsidiaries.

```
!
!    example: USE_MODE = -12 implies:
!       -calculation of Fy,Mx,Mz only
!       -including relaxation effects
!       -mirrored tire characteristics
!
$---------------------------------------------------------------units
[UNITS]
LENGTH        ='meter'
FORCE         ='newton'
ANGLE         ='radian'
MASS          ='kg'
TIME          ='second'
$---------------------------------------------------------------model
[MODEL]
PROPERTY_FILE_FORMAT   = 'PAC2002'
USE_MODE        = 14           $Tire use switch (IUSED)
LONGVL          = 10.0         $Measurement speed at test bench (V0)
TYRESIDE        = 'LEFT'       $Mounted side at tire test bench                          LEFT/
RIGHT/SYMMETRIC
BELT_DYNAMICS        = 'YES'
CONTACT_MODEL        = '3D_ENVELOPING'
$----------------------------------------------------------dimensions
[DIMENSION]
UNLOADED_RADIUS             = 0.3169          $Free tire radius
```

© 2025 Hexagon AB and/or its subsidiaries.

```
WIDTH = 0.205 $Nominal section width of the tire
ASPECT_RATIO = 0.55 $Nominal aspect ratio
RIM_RADIUS = 0.203 $Nominal rim radius
RIM_WIDTH = 0.165 $Rim width
$---------------------------------------------------------------shape
[SHAPE]
{radial width}
1.0 0.0
1.0 0.4
1.0 0.9
0.9 1.0
$-----------------------------------------------------------parameter
[VERTICAL]
VERTICAL_STIFFNESS = 209200.0 $Tire vertical stiffness
VERTICAL_DAMPING = 500 $Tire vertical damping
BREFF = 4.90 $Low load stiffness e.r.r.
DREFF = 0.41 $Peak value of e.r.r.
FREFF = 0.09 $High load stiffness e.r.r.
FNOMIN = 4700 $Nominal wheel load
$-----------------------------------------------------long_slip_range
[LONG_SLIP_RANGE]
KPUMIN = -1.5 $Minimum valid wheel slip
KPUMAX = 1.5 $Maximum valid wheel slip
$----------------------------------------------------slip_angle_range
```

© 2025 Hexagon AB and/or its subsidiaries.

[SLIP_ANGLE_RANGE]

ALPMIN = -1.5708 $Minimum valid slip angle

ALPMAX = 1.5708 $Maximum valid slip angle

$--inclination_slip_range

[INCLINATION_ANGLE_RANGE]

CAMMIN = -0.26181 $Minimum valid camber angle

CAMMAX = 0.26181 $Maximum valid camber angle

$--vertical_force_range

[VERTICAL_FORCE_RANGE]

FZMIN = 140 $Minimum allowed wheel load

FZMAX = 10800 $Maximum allowed wheel load

$---scaling

[SCALING_COEFFICIENTS]

LFZO = 1 $Scale factor of nominal (rated) load

LCX = 1 $Scale factor of Fx shape factor

LMUX = 1 $Scale factor of Fx peak friction coefficient

LEX = 1 $Scale factor of Fx curvature factor

LKX = 1 $Scale factor of Fx slip stiffness

LHX = 1 $Scale factor of Fx horizontal shift

LVX = 1 $Scale factor of Fx vertical shift

LGAX = 1 $Scale factor of camber for Fx

LCY = 1 $Scale factor of Fy shape factor

LMUY = 1 $Scale factor of Fy peak friction coefficient

LEY = 1 $Scale factor of Fy curvature factor

© 2025 Hexagon AB and/or its subsidiaries.

LKY = 1 $Scale factor of Fy cornering stiffness

LHY = 1 $Scale factor of Fy horizontal shift

LVY = 1 $Scale factor of Fy vertical shift

LGAY = 1 $Scale factor of camber for Fy

LTR = 1 $Scale factor of Peak of pneumatic trail

LRES = 1 $Scale factor for offset of residual torque

LGAZ = 1 $Scale factor of camber for Mz

LXAL = 1 $Scale factor of alpha influence on Fx

LYKA = 1 $Scale factor of alpha influence on Fx

LVYKA = 1 $Scale factor of kappa induced Fy

LS = 1 $Scale factor of Moment arm of Fx

LSGKP = 1 $Scale factor of Relaxation length of Fx

LSGAL = 1 $Scale factor of Relaxation length of Fy

LGYR = 1 $Scale factor of gyroscopic torque

LMX = 1 $Scale factor of overturning couple

LVMX = 1 $Scale factor of Mx vertical shift

LMY = 1 $Scale factor of rolling resistance torque

$--longitudinal

[LONGITUDINAL_COEFFICIENTS]

PCX1 = 1.3178 $Shape factor Cfx for longitudinal force

PDX1 = 1.0455 $Longitudinal friction Mux at Fznom

PDX2 = 0.063954 $Variation of friction Mux with load

PDX3 = 0 $Variation of friction Mux with camber

PEX1 = 0.15798 $Longitudinal curvature Efx at Fznom

© 2025 Hexagon AB and/or its subsidiaries.

```
PEX2            = 0.41141         $Variation of curvature Efx with load
PEX3            = 0.1487          $Variation of curvature Efx with load squared
PEX4            = 3.0004          $Factor in curvature Efx while driving
PKX1            = 23.181          $Longitudinal slip stiffness Kfx/Fz at Fznom
PKX2            = -0.037391          $Variation of slip stiffness Kfx/Fz with load
PKX3            = 0.80348         $Exponent in slip stiffness Kfx/Fz with load
PHX1            = -0.00058264          $Horizontal shift Shx at Fznom
PHX2            = -0.0037992          $Variation of shift Shx with load
PVX1            = 0.045118          $Vertical shift Svx/Fz at Fznom
PVX2            = 0.058244          $Variation of shift Svx/Fz with load
RBX1            = 13.276          $Slope factor for combined slip Fx reduction
RBX2             = -13.778          $Variation of slope Fx reduction with kappa
RCX1            = 1.0          $Shape factor for combined slip Fx reduction
REX1            = 0          $Curvature factor of combined Fx
REX2            = 0          $Curvature factor of combined Fx with load
RHX1            = 0          $Shift factor for combined slip Fx reduction
PTX1            = 0.85683          $Relaxation length SigKap0/Fz at Fznom
PTX2            = 0.00011176          $Variation of SigKap0/Fz with load
PTX3            = -1.3131          $Variation of SigKap0/Fz with exponent of load
$-----------------------------------------------------overturning
[OVERTURNING_COEFFICIENTS]
QSX1            = 0          $Lateral force induced overturning moment
QSX2            = 0          $Camber induced overturning couple
QSX3            = 0          $Fy induced overturning couple
```

© 2025 Hexagon AB and/or its subsidiaries.

$---lateral

[LATERAL_COEFFICIENTS]

PCY1 = 1.2676 $Shape factor Cfy for lateral forces

PDY1 = 0.90031 $Lateral friction Muy

PDY2 = -0.16748 $Variation of friction Muy with load

PDY3 = -0.43989 $Variation of friction Muy with squared camber

PEY1 = -0.3442 $Lateral curvature Efy at Fznom

PEY2 = -0.10763 $Variation of curvature Efy with load

PEY3 = 0.11513 $Zero order camber dependency of curvature Efy

PEY4 = -6.9663 $Variation of curvature Efy with camber

PKY1 = -25.714 $Maximum value of stiffness Kfy/Fznom

PKY2 = 3.2658 $Load at which Kfy reaches maximum value

PKY3 = -0.0054467 $Variation of Kfy/Fznom with camber

PHY1 = 0.0031111 $Horizontal shift Shy at Fznom

PHY2 = 2.1666e-005 $Variation of shift Shy with load

PHY3 = 0.036592 $Variation of shift Shy with camber

PVY1 = 0.0064945 $Vertical shift in Svy/Fz at Fznom

PVY2 = -0.0052059 $Variation of shift Svy/Fz with load

PVY3 = 0.013713 $Variation of shift Svy/Fz with camber

PVY4 = -0.0092737 $Variation of shift Svy/Fz with camber and load

RBY1 = 7.1433 $Slope factor for combined Fy reduction

RBY2 = 9.1916 $Variation of slope Fy reduction with alpha

RBY3 = -0.027856 $Shift term for alpha in slope Fy reduction

© 2025 Hexagon AB and/or its subsidiaries.

RCY1 = 1.0 $Shape factor for combined Fy reduction

REY1 = 0 $Curvature factor of combined Fy

REY2 = 0 $Curvature factor of combined Fy with load

RHY1 = 0 $Shift factor for combined Fy reduction

RHY2 = 0 $Shift factor for combined Fy reduction with load

RVY1 = 0 $Kappa induced side force Svyk/Muy*Fz at Fznom

RVY2 = 0 $Variation of Svyk/Muy*Fz with load

RVY3 = 0 $Variation of Svyk/Muy*Fz with camber

RVY4 = 0 $Variation of Svyk/Muy*Fz with alpha

RVY5 = 1.9 $Variation of Svyk/Muy*Fz with kappa

RVY6 = 0 $Variation of Svyk/Muy*Fz with atan(kappa)

PTY1 = 4.1114 $Peak value of relaxation length SigAlp0/R0

PTY2 = 6.1149 $Value of Fz/Fznom where SigAlp0 is extreme

$---rolling resistance

[ROLLING_COEFFICIENTS]

QSY1 = 0.01 $Rolling resistance torque coefficient

QSY2 = 0 $Rolling resistance torque depending on Fx

QSY3 = 0 $Rolling resistance torque depending on speed

QSY4 = 0 $Rolling resistance torque depending on speed ^4

$--aligning

[ALIGNING_COEFFICIENTS]

QBZ1 = 5.6008 $Trail slope factor for trail Bpt at Fznom

QBZ2 = -1.9968 $Variation of slope Bpt with load

© 2025 Hexagon AB and/or its subsidiaries.

QBZ3 = -0.58685 $Variation of slope Bpt with load squared

QBZ4 = -0.20922 $Variation of slope Bpt with camber

QBZ5 = 0.2973 $Variation of slope Bpt with absolute camber

QBZ9 = 3.2333 $Slope factor Br of residual torque Mzr

QBZ10 = 0 $Slope factor Br of residual torque Mzr

QCZ1 = 1.0913 $Shape factor Cpt for pneumatic trail

QDZ1 = 0.082536 $Peak trail Dpt" = Dpt*(Fz/Fznom*R0)

QDZ2 = -0.011631 $Variation of peak Dpt" with load

QDZ3 = -0.18704 $Variation of peak Dpt" with camber

QDZ4 = 0.18698 $Variation of peak Dpt" with camber squared

QDZ6 = 0.00071228 $Peak residual torque Dmr" = Dmr/(Fz*R0)

QDZ7 = 0.0010419 $Variation of peak factor Dmr" with load

QDZ8 = -0.11886 $Variation of peak factor Dmr" with camber

QDZ9 = -0.011967 $Variation of peak factor Dmr" with camber
and load

QEZ1 = -35.25 $Trail curvature Ept at Fznom

QEZ2 = -34.746 $Variation of curvature Ept with load

QEZ3 = 0 $Variation of curvature Ept with load squared

QEZ4 = 0.62393 $Variation of curvature Ept with sign of
Alpha-t

QEZ5 = -2.6405 $Variation of Ept with camber and sign

Alpha-t

QHZ1 = 0.0023279 $Trail horizontal shift Sht at Fznom

QHZ2 = -0.0010156 $Variation of shift Sht with load

QHZ3 = 0.030508 $Variation of shift Sht with camber

© 2025 Hexagon AB and/or its subsidiaries.

QHZ4 = 0.058344 $Variation of shift Sht with camber and load

SSZ1 = 0.0097546 $Nominal value of s/R0: effect of Fx on Mz

SSZ2 = 0.0043624 $Variation of distance s/R0 with Fy/Fznom

SSZ3 = 0 $Variation of distance s/R0 with camber

SSZ4 = 0 $Variation of distance s/R0 with load and camber

QTZ1 = 0 $Gyration torque constant

MBELT = 0 $Belt mass of the wheel

$---turn-slip parameters

[TURNSLIP_COEFFICIENTS]

PECP1 = 0.7 $Camber stiffness reduction factor

PECP2 = 0.0 $Camber stiffness reduction factor with load

PDXP1 = 0.4 $Peak Fx reduction due to spin

PDXP2 = 0.0 $Peak Fx reduction due to spin with load

PDXP3 = 0.0 $Peak Fx reduction due to spin with longitudinal slip

PDYP1 = 0.4 $Peak Fy reduction due to spin

PDYP2 = 0.0 $Peak Fy reduction due to spin with load

PDYP3 = 0.0 $Peak Fy reduction due to spin with lateral slip

PDYP4 = 0.0 $Peak Fy reduction with square root of spin

PKYP1 = 1.0 $Cornering stiffness reduction due to spin

PHYP1 = 1.0 $Fy lateral shift shape factor

PHYP2 = 0.15 $Maximum Fy lateral shift

PHYP3 = 0.0 $Maximum Fy lateral shift with load

PHYP4 = -4.0 $Fy lateral shift curvature factor

© 2025 Hexagon AB and/or its subsidiaries.

QDTP1 = 10.0 $Pneumatic trail reduction factor

QBRP1 = 0.1 $Residual torque reduction factor with lateral slip

QCRP1 = 0.2 $Turning moment at constant turning with zero speed

QCRP2 = 0.1 $Turning moment at 90 deg lateral slip

QDRP1 = 1.0 $Maximum turning moment

QDRP2 = -1.5 $Location of maximum turning moment

$---contact patch parameters

[CONTACT_COEFFICIENTS]

PA1 = 0.4147 $Half contact length dependency on sqrt(defl/ unloaded radius)

PA2 = 1.9129 $Half contact length dependency on deflection

PB1 = 0.8989 $Half contact width dependency on sqrt(defl/ unloaded radius)

PB2 = 1.1424 $Half contact width dependency on defl/ unloaded radius

PB3 = -3.2629 $Half contact width dependency on defl/ unloaded radius*sqrt(defl/unloaded radius)

PAE = 0.82 $Half ellipse length/unloaded radius

PBE = 1.0 $Half ellipse height/unloaded radius

PCE = 2.0 $Ellipse exponent

PLS = 0.8 $Tandem base length factor

N_WIDTH = 6 $Number of cams across tire contact width

N_LENGTH = 5 $Number of cams along tire contact length

$---belt_dynamics_parameters

[BELT_PARAMETERS]

© 2025 Hexagon AB and/or its subsidiaries.

TYRE_MASS = 9.3 $Total mass of tire

QMB = 0.763 $Mass parameter of the tire belt

QMC = 0.108 $Mass parameter of the tire contact mass

QIBY = 0.687 $Iyy inertia parameter of the tire belt

QIBXZ = 0.427 $Ixx/Izz inertia parameter of the tire belt

QIC = 0.053 $Inertia parameter of the contact mass

QCBXZ = 121.4 $Radial belt - wheel stiffness factor

QCBY = 40.05 $Axial belt - wheel stiffness factor

QCBTH = 20.33 $Torsional belt - wheel stiffness factor

QCBGM = 61.96 $Rotational belt - wheel stiffness factor

QKBXZ = 0.228 $Radial belt - wheel damping factor

QKBY = 0.284 $Axial belt - wheel damping factor

QKBTH = 0.18 Torsional belt - wheel damping factor

QKBGM = 0.09 $Rotational belt - wheel damping factor

QBVXZ = 0.0 $Speed effect on radial belt - wheel stiffness

QBVTH = 0.0 $Speed effect on torsional belt - wheel stiffness

QCCX = 391.9 $Longitudinal stiffness factor belt - contact mass

QCCY = 62.7 $Lateral stiffness factor belt - contact mass

QCCFI = 55.82 $Yaw stiffness factor belt - contact mass

QKCX = 0.91 $Longitudinal damping factor belt - contact mass

QKCY = 0.91 $Lateral damping factor belt - contact mass

QKCFI = 0.834 $Yaw damping factor belt - contact mass

© 2025 Hexagon AB and/or its subsidiaries.