

HTire

Handling Tire Model, Based on Magic FormulaCosin Simulation Environment
Documentation and User's Guide

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General Remarks

This documentation describes the modelization and the parameters of the Magic-Formula-based Handling Tire Model (*HTire*), being is a member of the *FTire* tire model family. For more material about this model family and related tire simulation tools, please visit www.cosin.eu.

1 Aims and Scope of *HTire*

The tire model *HTire* (Handling Tire Model) is another implementation of Pacejka's well-known **Magic-Formula tire model (MF)**, completed with an efficient contact computation, interfaces to all [cosin road models](#), and certain model enhancements regarding combined slip and dynamic tire lag behavior.

Two variants of the Magic Formula approach are made available: the widely used 1989 version (MF89) and the most recent 2002 version (MF2002). The latter is comprehensively documented in chapter 4 of: *Pacejka, H.B.: Tyre and Vehicle Dynamics. Butterworth Heinemann, Oxford 2002* (referred as [PAC] in the sequel). The cited book also contains the complete set of all equations implemented with the MF2002 horizontal forces sub-model.

HTire is meant to complete the *FTire* tire model family in situations where speed of computation is more important than accuracy in dynamic situations or prediction capabilities of a physically based tire model.

2 Modeling Approach

2.1 Rolling Kinematics

HTire performs all tire kinematics calculations necessary to generate all input signals to the Magic Formula part of the model. On basis of all rim position and velocity states, and on basis of road surface geometry and velocity, it computes and makes available to MF

- tire deflection and tire deflection velocity,
- longitudinal slip,
- side-slip angle,
- turn slip, and
- camber angle.

2.2 Contact Computation and Coupling to *cosin/road*

Tire deflection and tire deflection velocity are determined using the point contact approach with a certain built-in low-pass filter effect. This effect is achieved by choosing a large step-size in applying numerical differentiation for the road tangent plane computation. The large step-size will smooth sharp changes in road inclination.

2.3 Alternative Non-Linear Radial Stiffness Model and Bottoming

As an alternative to the standard constant radial stiffness approach, *HTire* allows to specify arbitrary data pairs for the deflection-load characteristic, which are interpolated by a smooth spline.

By extending these data into the region of extreme deflection, also bottoming effects in misuse situations can easily be taken into account.

2.4 Zero Velocity Capability

Moreover, *HTire* uses a certain numerical modification of the slip quantities at very small forward speed, to deal with the well-known slip singularities in such operating points. At even smaller speed, *HTire*

switches smoothly to a model variant for standing condition, being able to keep the vehicle completely standing even on inclined roads, if park brake is engaged.

Thanks to these modifications, *HTire* does not show any numerical instability during stand-still. However, the modification might result in a certain small but non-zero sliding velocity when the vehicle is parking on an inclined road, even if wheels are blocked.

2.5 Combined Slip Modifications

The 1989 version of Magic Formula initially did not comprise a combined slip approach. However, a respective modification had been added to the equations in *HTire*, making use of a simple friction ellipse approach.

The same approach can, as an option, also be used in the 2002 variant, eventually replacing the detailed combined-slip model suggested by Pacejka. This replacement might be helpful if only limited measurement data are available, which might be insufficient for a respective data fit.

2.6 Tire Lag and Relaxation Length

Both MF variants are completed with a non-linear first order transient force lagging approach. With the kind of non-linearity used, it is taken into account that the decrease in contact forces might take place faster than a respective increase. This effect introduces a certain frequency-dependency of the mean tire force decrease, if wheel load variations apply.

Mathematically, the non-linear tire lag is described by the following non-linear first order differential equation, used for side force, longitudinal force, and aligning torque:

$$T = \min \left(T_{max}, \frac{l}{v} \right)$$

$$\dot{F} = \begin{cases} \frac{1}{T} (F_{stat} - F) & \text{if } F_{stat} - F > 0 \\ \frac{1}{rT} (F_{stat} - F) & \text{if } F_{stat} - F \leq 0 \end{cases}$$

The following parameters and signals are used here:

- l is the constant **relaxation length**
- v is the time dependent **rolling speed**
- T_{max} is the constant **upper bound** for the resulting **time constant**
- r is a **reduction factor**, describing the relation between time constant for force increase and time constant for force decrease
- F_{stat} is the **stationary value** of the respective force or torque (longitudinal force, side force, or aligning torque, respectively)
- F is the resulting **transient value** of this force or torque.

3 Implementation and Interfaces

HTire uses exactly the same program interfaces as all other members of the *FTire* Tire Model Family. If called by the *CTI* interface, the member of the *FTire* Tire Model Family to be used is determined on basis of the contents of the tire data file. If *HTire* is recognized, the Magic Formula variant to be used

is determined in a similar way, and the content of the data file is interpreted respectively. The data file is downward compatible to data files of several other Magic Formula implementations.

As with all other members of the *FTire* tire model family, two data file formats are available:

- the *cosin/io* format, and
- the *TeimOrbit* format.

In this documentation, only the *TeimOrbit* format is described.

4 *HTire* Parameters

The following chapters list *HTire* parameters for all supported variants. Note that some more parameters might be specified in *HTire* data files; these data are used by customer-specific variants of *HTire* which are not documented here.

Both *TeimOrbit* and *cosin/io* data files are subdivided into smaller entities, called **sections** for *TeimOrbit* files and **data blocks** for *cosin/io* files. The sequence of these sections is arbitrary. Some of them, however, must appear in the data file, some others are optional. Each one of the following documentation sub-chapters describes the contents of one such section.

When downloading *FTire* Tire Model Family software, sample data files will be included for all supported tire model variants. These sample files might serve as a starting point for own modifications.

4.1 Parameters Common to all MF Variants

4.1.1 Section [COSIN_HEADER]

The header section is optional and allows to specifying some comment and a file version number. If the section is not found, all tire models of the *FTire* Tire Model Family assume the file is specified in the newest ASCII format version.

4.1.2 Section [UNIT]

In this optional section, the physical units of parameters in subsequent sections are defined:

Name in input file	Unit	required	default value	Explanation
force	-	no	'N'	<p>force unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> • 'kiloNewton', 'kNewton', 'kN' • 'dekaNewton', 'daN' • 'Newton', 'N', 'kilogram_force', 'kg_force' • 'pound_force', 'poundforce', 'poundf', 'lbf' • 'kpound_force', 'kpoundforce' • 'dyne', 'dyn' • 'ounce_force', 'ounceforce'

mass	-	no	'kg'	<p>mass unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> ● 'kilogram', 'kg' ● 'gram', 'g' ● 'pound', 'lbm', 'lb', 'pound_mass', 'poundmass', 'poundm' ● 'kpound_mass', 'kpoundmass' ● 'slug' ● 'ounce_mass', 'ouncemass'
length	-	no	'm'	<p>length unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> ● 'kilometer', 'km' ● 'meter', 'meters', 'm' ● 'centimeter', 'cm' ● 'millimeter', 'mm' ● 'inch', 'in' ● 'foot', 'ft' ● 'mile'
time	-	no	's'	<p>time unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> ● 'second', 'sec', 's' ● 'millisecond', 'msec', 'ms' ● 'minute', 'min' ● 'hour', 'h'
angle	-	no	'rad'	<p>angle unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> ● 'degree', 'degrees', 'deg' ● 'grad' ● 'radian', 'rad', 'radians'

If, in subsequent data item specifications, a unit is printed in *italic* letters (being one out of force, mass, length, time, or angle), the respective unit will be chosen according to the settings in [UNIT]. Otherwise, the unit as given in the data item specification will be used independent on the setting in [UNIT].

4.1.3 Section [MODEL]

This section allows selecting the tire model and some more related settings:

Name in input file	Unit	required	default value	Explanation
property_file_format	-	yes	-	<p>tire model selection. The string is case-insensitive. Supported models are:</p> <ul style="list-style-type: none"> ● 'pac2002' ● 'pac89' ● 'htire' (the MF variant is detected automatically) ● 'rtire' ● 'ftire' ● 'fetire' <p>Note that models might be locked due to license restrictions</p>
tyreside	-	no	'asis'	<p>if necessary, mirrors or zeros side-dependent data. Possible values:</p> <ul style="list-style-type: none"> ● 'asis' (data are not modified) ● 'left' (data are mirrored, if actual tire is on right vehicle side) ● 'right' (data are mirrored, if actual tire is on right vehicle side) ● 'symmetric' (data that cause an unbalance between left and right side are modified during initialization, resulting in a symmetric behaviour) <p>By default, no data are modified ('asis')</p>

use_mode	-	no	-1	<p>activation of model features:</p> <ul style="list-style-type: none"> ● -1: activate all model features; same as use mode 24 ● 0: only use vertical force ● 1..4: use model in steady-state mode ● 11..14: use model in transient mode ● 21..24: use model in enhanced steady-state mode (at present, no difference to use modes 11..14) <p>The right-most digit selects the forces to be computed:</p> <ul style="list-style-type: none"> ● 1: only longitudinal force and rolling resistance ● 2: only lateral force and aligning torque ● 3: all forces/torques, but disregarding combined slip conditions ● 4: all forces/torques, taking into account combined slip conditions <p>By default, the most complex use mode (24) is used</p>
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seperate_animation	-	no	0	<p>requesting and specifying properties of an extra animation window for all tire model instances which are called by CTI. The value of separate_animation consists of up to 8 decimal digits (not all of them being effective for all tire model types), with the following meaning:</p> <p>select animation mode:</p> <ul style="list-style-type: none">0 no animation1 normal mode2 movie preparation3 full screen4 small window5 translucent structure7 multiple exposure <p>select contour plot type (only FTire) :</p> <ul style="list-style-type: none">0. no contour plot1. contour plot: contact pressure distribution2. contour plot: longitudinal shear stress3. contour plot: lateral shear stress4. contour plot: friction coefficient5. contour plot: sliding velocity6. contour plot: tread temperature7. contour plot: tread depth8. contour plot: power loss density <p>select running diagram type:</p> <ul style="list-style-type: none">0.. no running diagrams1.. running diagrams: forces2.. running diagrams: torques3.. running diagrams: handling signals <p>show interactive sliders, if available:</p> <ul style="list-style-type: none">0... no sliders1... show sliders <p>select camera setting:</p> <ul style="list-style-type: none"> ...0.... camera focussing rim center ...1.... camera focussing contact patch ...2.... bird's view ...3.... rim-fixed camera <p>select tire structure visualization (only FTire):</p> <ul style="list-style-type: none"> ..0..... tire structure rendered ..1..... tire structure wire-framed <p>select road visualization:</p> <ul style="list-style-type: none"> .0..... no road .1..... auto road display, defined by road type .2..... single line road .3..... grid road .4..... rendered road <p>select sound (if available):</p> <ul style="list-style-type: none"> 0..... no sound 1..... sound <p>time unit, defined by case-insensitive character string. Supported units are</p> <ul style="list-style-type: none"> ● 'second', 'sec', 's' ● 'millisecond', 'msec', 'ms' ● 'minute', 'min' ● 'hour', 'h'
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cosingl_path	-	no	working directory and more	path to the <i>cosin/gl</i> animation program cosingl (optional). By default, <i>CTI</i> will search for this program in a certain predefined list of directories. This list includes the working directory, the home directory, the root directory, and the directory specified by the environmental variable COSINGLPATH. If cosingl cannot be found, <i>CTI</i> will run anyway, but will not display the on-line animation. This does not affect any simulation results
road_grid_size	length	no	600x300 mm	approximate width and length (same value for both) of road visualization grid in animation window
road_grid_line_dist	length	no	5x50 mm	approximate grid line distance (same value for x- and y- direction) of road visualization in animation window
animation_time_sleep	time	no	same as simulation time step	approximate time step for on-line animation, to be specified in the data file's time unit. If zero or not specified, an approximate animation time step of 1 ms will be used.
animation_start	time	no	0.0	approximate simulation time to begin animation. If not specified, animation (if requested) will begin with simulation.
animation_end	time	no	unlimited	approximate simulation time to end animation. If not specified, animation will end with simulation.
force_scaling	-	no	1.0	factor that scales all kinds of force display in the animation window (sliders, forces in running diagrams, contact force vectors, etc.). Default value is 1.0

4.1.4 Section [DIMENSION]

This section collects all data needed to specify the tire size:

Name in input file	Unit	required	default value	Explanation
width	length	yes	-	maximum width of unloaded tire
aspect_ratio	-	yes	-	tire aspect ratio. Note that this value is not specified in %, but in a value between 0 and 1
rim_radius	length	yes	-	rim (bead seat) radius
rim_width	length	yes, in case of 2002 variant	estimated	rim (bead seat) width. By default, estimated on basis of tire dimension
rolling_circumference	length	no	estimated	rolling circumference. By default, estimated on basis of tire dimension

4.1.5 Section [PARAMETER] or [VERTICAL]

This section collects data needed to specify the tire radial stiffness and damping properties, and some more stiffness-related data:

Name in input file	Unit	required	default value	Explanation
vertical_stiffness	force/length	(yes)	-	mean radial stiffness (required if no section [DEFLECTION_LOAD_CURVE] is specified)
vertical_damping	force · time/length	no	0	mean radial damping coefficient
step_size_contact_plane	length	no	50 mm	numerical step-size to approximate the road normal vector by numerical differentiation. Should be roughly half the contact patch width
Fnomin	N	yes, in case of 2002 variant	LI load	nominal wheel load
breff	-	yes, in case of 2002 variant	9	parameter Breff in determination of effective rolling radius (eq. (A3.7), p. 617 in [PAC])
dreff	-	yes, in case of 2002 variant	0.23	parameter Dreff in determination of effective rolling radius (eq. (A3.7), p. 617 in [PAC])
freff	-	yes, in case of 2002 variant	0.01	parameter Freff in determination of effective rolling radius (eq. (A3.7), p. 617 in [PAC])
lateral_stiffness	force/length	no	infinity	lateral stiffness of the non-rolling tire; used for contact patch shift estimation due to tire forces
longitudinal_stiffness	force/length	no	infinity	longitudinal stiffness of the non-rolling tire; used for contact patch shift estimation due to tire forces and for the influence of wheel load on overturning torque
rolling_resistance	-	no	0.012	dimensionless rolling resistance coefficient
relaxation_length_Fx	length	no	0	relaxation length of longitudinal force
max_time_constant_Fx	time	no	0.3 s	time constant upper bound for longitudinal force lag
relaxation_length_reduction_Fx		no	0.7	relaxation length reduction of longitudinal force decrease relative to force increase
relaxation_length_Fy	length	no	0	relaxation length of side force
max_time_constant_Fy	time	no	0.3 s	time constant upper bound for side force lag
relaxation_length_reduction_Fy		no	0.7	relaxation length reduction of side force decrease relative to force increase
relaxation_length_Mz	length	no	0	relaxation length of allignment torque

max_time_constant_Mz	time	no	0.3 s	time constant upper bound for allignung torque lag
relaxation_length_reduction_Mz		no	0.7	relaxation length reduction of allignung torque decrease relative to force increase
model_switch_ref_speed	length /time	no	0.2	forward speed at which model will be smoothly switched from 'slip-based' to 'displacement-based'. The latter mode is a simplified approach for the standing tire. The reference speed is used if the calling integrator time-step is 1ms; shorter or longer time-steps will decrease or increase the switching velocity, respectively

4.1.6 Section [DEFLECTION_LOAD_CURVE]

This optional section provides an alternative to `vertical_stiffness`. If specified, the x/y data in the section define a smooth spline, representing the tire's non-linear deflection/load characteristic. Arbitrarily many x/y data of tire deflection (length) and radial load (force) can be specified, one or more in a line. Deflection values must be monotonously increasing. TeimOrbit-compatible comment lines are allowed between the data lines.

This is an example of a valid [DEFLECTION_LOAD_CURVE] section:

```
[DEFLECTION_LOAD_CURVE]
0      0.0
5      400.0
10     1250.0
20     4000.0
30     8500.0
```

4.2 Additional Parameters for the MF1989 Variant

4.2.1 Section [LATERAL_COEFFICIENTS]

This section specifies the MF 89 side force parameters for purely lateral slip:

Name in input file	Unit	required	default value	Explanation
a0 .. a13	-	yes	-	a0 to a13

4.2.2 Section [LONGITUDINAL_COEFFICIENTS]

This section specifies the MF 89 longitudinal force parameters for purely longitudinal slip:

Name in input file	Unit	required	default value	Explanation
b0 .. b13	-	yes	-	b0 to b13

4.2.3 Section [ALIGNING_COEFFICIENTS]

This section specifies the MF 89 aligning torque parameters for purely lateral slip:

Name in input file	Unit	required	default value	Explanation
c0 .. c13	-	yes	-	c0 to c13

4.3 Additional Parameters for the MF 2002 Variant

4.3.1 Section [PARAMETER] or [VERTICAL]

In this section, one additional data item is searched for in the case of the 2002 variant:

Name in input file	Unit	required	default value	Explanation
longv1	length/ time	yes	-	reference velocity, used in rolling resistance torque computation

4.3.2 Section [LONG_SLIP_RANGE]

This section specifies bounds for the effective longitudinal slip as it is used in the MF 2002 equations:

Name in input file	Unit	required	default value	Explanation
kpumin	-	no	-1	lower bound for effective longitudinal slip
kpumax	-	no	1	upper bound for effective longitudinal slip

4.3.3 Section [SLIP_ANGLE_RANGE]

This section specifies bounds for the effective slip angle as it is used in the MF 2002 equations:

Name in input file	Unit	required	default value	Explanation
alpmin	angle	no	-1 rad	lower bound for effective slip angle
alpmax	angle	no	1 rad	upper bound for effective slip angle

4.3.4 Section [INCLINATION_ANGLE_RANGE]

This section specifies bounds for the effective camber angle as it is used in the MF 2002 equations:

Name in input file	Unit	required	default value	Explanation
cammin	angle	no	-0.2 rad	lower bound for effective camber angle
cammax	angle	no	0.2 rad	upper bound for effective camber angle

4.3.5 Section [VERTICAL_FORCE_RANGE]

This section specifies bounds for the effective wheel load as it is used in the MF 2002 equations:

Name in input file	Unit	required	default value	Explanation
fzmin	force	no	0 N	lower bound fort effective wheel load
fzmax	force	no	10000 N	upper bound fort effective wheel load

4.3.6 Section [LATERAL_COEFFICIENTS]

This section specifies the MF 2002 side force parameters:

Name in input file	Unit	required	default value	Explanation
pcy1 .. pty2	-	yes	-	pcy1 to pty2, cf. [PAC], p. 614

4.3.7 Section [LONGITUDINAL_COEFFICIENTS]

This section specifies the MF 2002 longitudinal force parameters:

Name in input file	Unit	required	default value	Explanation
pcx1 .. ptx2	-	yes	-	pcx1 to ptx2, cf. [PAC], p. 614

4.3.8 Section [ALIGNING_COEFFICIENTS]

This section specifies the MF 2002 aligning torque parameters:

Name in input file	Unit	required	default value	Explanation
qbz1 .. qtz2	-	yes	-	qbz1 to qtz1, cf. [PAC], p. 614
mbelt	mass	yes	-	belt mass

4.3.9 Section [ROLLING_COEFFICIENTS]

This section specifies the MF 2002 parameters for rolling resistance torque:

Name in input file	Unit	required	default value	Explanation
qsx1 .. qsx3	-	yes	-	qsx1 to qsx3, cf. [PAC], p. 614

4.3.10 Section [OVERTURNING_COEFFICIENTS]

This section specifies the MF 2002 parameters for overturning torque:

Name in input file	Unit	required	default value	Explanation
qsy1 .. qsy4	-	yes	-	qsy1 to qsy4, cf. [PAC], p. 614

4.3.11 Section [SCALING_COEFFICIENTS]

This section specifies the MF 2002 scaling coefficients:

Name in input file	Unit	required	default value	Explanation
lfz0 .. lmy	-	no	-	lfz0 to lmy, cf. [PAC], p. 614

5 Additional TYDEX Output Signals

Complementary to the actual rim forces and moments, *HTire* provides a couple of additional output signals. A subset of these signals is bundled in the STI-compatible **TYDEX output array**, described in the table below. Due to compatibility constraints set by different calling programs, this output array is not well ordered and contains some signals repeatedly. Moreover, the availability of the TYDEX output array depends on the calling program.

It is suggested to make use of the additional **plot signal output** file instead, which is documented in chapter 6 below.

Index in TYDEX output array	Unit	Explanation
1..3	N	contact forces, expressed in TYDEX W frame
4..6	Nm	contact moments, expressed in TYDEX W frame
7	rad	side-slip angle
8	-	longitudinal slip (values between -1 and 1)
9	rad	tire camber angle (angle between road normal and tire mid-plane)
26..28	m	assumed contact point position in global coordinates
29..37	-	3x3 transformation matrix from W frame to global coordinates, stored column-wise
38..40	N	contact forces, expressed in ISO coordinate system (differs from TYDEX W frame by road inclination)
41..43	Nm	contact moments, expressed in ISO coordinate system
44	m	tire deflection
45	m/s	rim center velocity in 'vertical' direction, along road normal
46	m/s	slip velocity in longitudinal direction (nearly zero for free rolling tire)
47	m/s	slip velocity in lateral direction (nearly zero at zero side-slip angle)
48	m/s	rim center velocity in longitudinal direction
49	m	dynamic rolling radius
50	rad/s	rim angular velocity
82..84	N	rim forces, expressed in TYDEX C frame
85..87	Nm	rim moments, expressed in TYDEX C frame

Index in TYDEX output array	Unit	Explanation
91..93	N	contact forces, expressed in ISO coordinate system
94..96	Nm	contact moments, expressed in ISO coordinate system

6 Additional Plot Signals Output File

Upon request, HTire provides another ASCII output file, containing a comprehensive set of most of the available output signals. This file, provided independently on the calling program, has extension 'mtl', which reflects the fact that the file is easily loaded and analyzed in Matlab. Moreover, *FTire/tools* provide an easy-to-use plot program for this file format.

The table below lists the channels and its meaning.

Channel #	Unit	Explanation
1	mm	tire deflection
2	m/s	deflection velocity
3	%	wheel slip
4	deg	side-slip angle
5	deg	camber angle
6	deg	wheel rotation angle
7	m	traveled distance
8	deg	normalized wheel rotation angle
9	rad/s	wheel angular speed
10	m	traveled distance
11	m/s	wheel longitudinal velocity
12	m/s	wheel lateral velocity
13	m/s	wheel vertical velocity
14	%	turn slip
15	N	stationary fore-aft force
16	N	stationary side force
17	Nm	stationary aligning torque
18	1/m	road profile curvature
19..21	N	rim forces, expressed in TYDEX C frame
22..24	Nm	rim moments, expressed in TYDEX C frame
25..27	N	rim forces, expressed in TYDEX H frame
28..30	Nm	rim moments, expressed in TYDEX H frame
31..33	N	contact forces, expressed in TYDEX W frame
34..36	Nm	contact moments, expressed in TYDEX W frame
37..39	N	contact forces, expressed in ISO coordinate system
40..42	Nm	contact moments, expressed in ISO coordinate system