FTire: 10 Years of Development and Application

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Abstract

The first version of the tire simulation software *FTire* (**F**lexible Ring **Tire** Model) had been released in December 1998, development being initiated in spring 1998. Being subject to permanent improvement and several far-reaching model extensions since then, it has become today one of the most widely used and generally accepted tire models for ride comfort, handling, and road load prediction.

Strength of *FTire* is the strictly physical background, which perfectly fits both to MBS and FEM environments. Even though certain simplifications are unavoidable, this clean mechanical, thermo-dynamical, and tribological structure of the model guarantees a consistent and plausible model behavior even in situations that are not covered by respective measurements.

The modelization takes into account most of the relevant excitation sources and non-linear transfer mechanisms, up to very high frequencies and extremely short wavelengths. The model's high level of detail is accompanied by a very comfortable program interface and a numerically robust and efficient solver. This allows the simulation of even extreme maneuvers with moderate computation time. *FTire* can be used together with most of the important MBS packages and specialized vehicle dynamics programs.

This paper gives an overview on history, application, modelization, road models, parameterization, interfacing, availability, and future perspectives of *FTire*.

Keywords: Tire simulation model, FTire, road load prediction, road model, tire model parameterization, vehicle dynamics

1. Brief History of the Model Development

Certain ideas and concepts of *FTire* go back to two other tire models of the author: DNS-Tire (**D**ynamical **N**on-Linear **S**patial **Tire** Model; [1], [2], [4], [6], [20]), and BRIT (**B**rush And **Ri**ng **T**ire Model; [3], [5], [6]).

DNS-Tire, under development since 1986 and still today used for certain tire development investigations, is a coarse non-linear time-domain FE model. Initially, it was meant as research tool to study the influence of tire design details on dynamic tire forces. Many extensions and improvements of DNS-Tire had been spin-off of a research cooperation between a German OEM and a German tire manufacturer.

DNS-Tire was suitable even for extreme excitations, including misuse conditions. Despite development and usage of an optimized numerical integration scheme, in its early days DNS-Tire obviously required too much computing time to be used as standard tire model in full vehicle simulations.

Like most other physically based tire models, DNS-Tire comprises two sub-models. The first one is the structural model of belt, side-wall, carcass, and bead. This sub-model consists of lumped masses, connected to each other by a non-linear and an-isotropic network of translational springs, dampers, and bending stiffnesses. Moreover, it precisely takes into account the influence of nodal forces caused by inflation pressure. Unlike other tire models, DNS-Tire allows to select an arbitrary number of nodes both in circumferential and in lateral direction. The structural sub-model is completed by the tread model, approximating the distributed mass, damping, stiffness, and friction properties of the tread rubber. Details of the model approach can be found in [1], [2], [4], [20].

A state-of-the-art re-implementation of DNS-Tire is *FETire*, now being the most complex member of the *FTire* model family. When using reasonable mesh sizes and time steps, this code requires about 100..200 s CPU time for one second real time. Thus, it is reasonable now to use it even in full vehicle simulations during typical simulation time spans.

BRIT, the second tire model influencing the development of *FTire*, was being developed since 1990. It was meant to compromise speed of computation and model accuracy even for higher-frequent excitation. BRIT replaced DNS-Tire's time-consuming stiff non-linear finite element model of the tire structure by a simple rigid-body approach, giving the belt structure 6 degrees of freedom of motion relative to the rim. Shape of the foot-print and ground pressure distribution had been approximated mathematically now, as function of tire deflection, camber angle, and road surface geometry. This approximation used mathematically simple two-dimensional shape functions.

The contact forces in BRIT, however, had been computed using a detailed distributed dynamic road friction model, similar to the one of DNS-Tire. This is the main difference to the tire model Swift ([9]). Here, contact forces are approximated purely mathematically, applying a Magic Formula type approach.

BRIT, still today being used at a German OEM, is real-time capable. Due to the speed of computation, an accompanying tool for parameterization is very efficient. This tool is based upon a least-squares fit of measured vertical and horizontal force characteristics, together with eigenfrequencies and modal damping of the first structural rigid-body modes.

Main drawback of BRIT, however, is its limited capability to resolve short-waved road irregularities. This is a consequence of approximating the belt distortion by rigid-body motions. Even with smart filtering of the road profile, similar to Swift's approach, such a simplification is not able to predict contact forces for all existing rough road geometries sufficiently accurate.

In view of this, in 1996, the author started developing a new tire model (CTire = **C**omfort **Tire** Model, [6]), ordered by a German tire manufacturer. Goal had been to more accurately predict dynamic in-plane tire forces and moments (wheel load, longitudinal force, and rolling resistance torque) when rolling over extremely rough roads, as compared to BRIT. As far as out-of plane forces and moments are concerned, the model was expected to provide these signals only in such a way that a combination with full vehicle models was possible and meaningful. Other primary objectives had been speed of computation (less than five times real-time) and ease of parameterization.

It was decided to model the tire's in-plane behavior by a lumped-mass approach, replacing the belt structure by a chain of point masses, located along the intersecting circle between rim mid-plane and outer belt layer. These masses had been connected to each other and to the rim by non-linear springs and dampers. The respective stiffness and damping values had been determined in such a way that both the measured radial stiffness and the first in-plane eigenfrequencies (both rigid-body modes and low-order bending modes) were met exactly by the model. Again, the road contact model was quite similar to the respective ones of BRIT and DNS-Tire. However, the road contact elements were only placed in the rim mid-plane, assuming that road irregularities only occur in rolling direction, and that camber angle is negligible. All out-of-plane forces and moments were computed by a Magic Formula-type sub-model.

Though the model accuracy was quite satisfying for the intended application ([6]), it soon turned out that the assumptions were too restrictive to meet all future demands on tire simulation. As a consequence, initially ordered by a Japanese OEM, the development of *FTire* began in 1998. *FTire*'s first version added new degrees of freedom to the CTire model, allowing the belt nodes as well as the friction elements to be elongated in lateral direction as well. Consequently, the Magic Formula part of the model had been completely removed.

Though being able to compute dynamic lateral force and aligning torque now, the out-of-plane accuracy still was insufficient. This issue could be solved only after the contact elements' locations had been extended in lateral direction, being able now to cover the true two-dimensional shape of the contact patch. Moreover, new degrees of freedom of the belt elements had been introduced, describing the belt's torsional displacement about the circumferential axis, caused by camber angle. The result had been the first, fully three-dimensional version of *FTire*, completed in 2000.

Since then, several major model extensions have been implemented, comprising

- the detailed consideration of inflation pressure influence,
- a distributed thermal model,
- a distributed tread-wear model,
- new belt element degrees of freedom, precisely describing lateral belt bending,
- new radial and horizontal force elements in belt/carcass structure, to take into account dynamic stiffening and hysteresis effects,
- detailed consideration of the tread pattern geometry,
- detailed, spline-data-based description of the cross-section geometry,
- new contact elements to take into account several different misuse conditions,
- detailed consideration of most important types of tire imperfections,
- coupling to a wide variety of commonly used road models,
- a new program interface to easily connect *FTire* to all major MBS packages,
- a large and powerful set of assisting parameterization and simulation tools,

and much more.

In addition, in 2002, a new implementation of a rigid-body based model had been ordered by the same Japanese OEM already mentioned. This new real-time capable member of *FTire*'s model family was named *RTIre* (**R**igid Ring **Tire** Model). *RTire* is not meant for use in all vehicle dynamics relevant situations. Rather, it is specialized for test-rig simulations of the standing or slowly rolling tire.

Finally, as already mentioned, in 2003 the first version of DNS-Tire's re-implementation, called *FETire*, was completed. All three members of the model family, *RTire*, *FTire*, and *FETire*, are called via the same program interface, and use compatible data to the greatest possible extent. In the remainder of this paper, only the most important member, *FTire*, is discussed.

2. Range of Application

Like most other tire models compared in the TMPT benchmark, *FTire* mainly serves as a sophisticated force element in MBS and FE environments. Combined with a respective suspension or full vehicle model, it can be used for many kinds of tire-related investigations, among others concerning

- road-contact induced vibrations along all three directions, up to about 150 Hz,

- dynamic force reaction to obstacle wave lengths at least down to half the length of the foot-print, both in longitudinal and lateral direction, and for sharp-edged obstacles like high cleats,
- vibration excitation by different kinds of tire imperfections,
- moving ground and all kinds of test-bench simulations,
- generation of accurate spatial load histories for durability simulations on measured 3D road surfaces,
- traction and handling properties on even roads, as well as on mildly up to extremely uneven roads,
- steering torque amount during parking,
- assessment of the tire's influence on highly dynamic suspension control systems,
- tire forces in misuse conditions,
- distributed tread temperature prediction and influence on tire performance,
- tread wear prediction,

and more.

The most important objectives during development of *FTire* have been:

- high or at least sufficient prediction accuracy in all intended applications,
- ease of implementation, with multiple instances, into general MBS or FE software,
- computing time not more than 5..20 times real time,
- ease of parameterization,
- numerical robustness in all possible situations (standing tire, locked tire, spinning tire, large to extreme deflection, large to extreme camber angle, high to extremely high rolling speed, inflation pressure loss, curb impact, rapidly varying road friction, rim-to-road contact, and so on),
- usability in all vehicle-dynamics relevant situations, without user intervention like manual model switch, and without laborious road data pre-processing or similar special actions.

Obviously, some of these objectives were hard to meet with other existing tire models. Mainly the concurrent demands on accuracy, numerical robustness, and computing time required a careful review and improvement of numerical methods used previously.

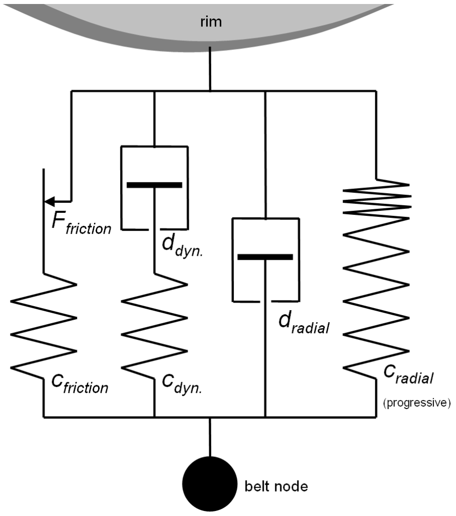

***Figure 1**. Force elements between single belt node and rim (only those in radial direction shown)*

3. Modelization: Idea, Simplifications, Assumptions

FTire comprises a mechanical model, an optional thermal model, and an optional tread wear model. The mechanical model in turn is split into a sub-model for the belt-carcass-bead structure and another one for the mechanical and tribological properties of the tread.

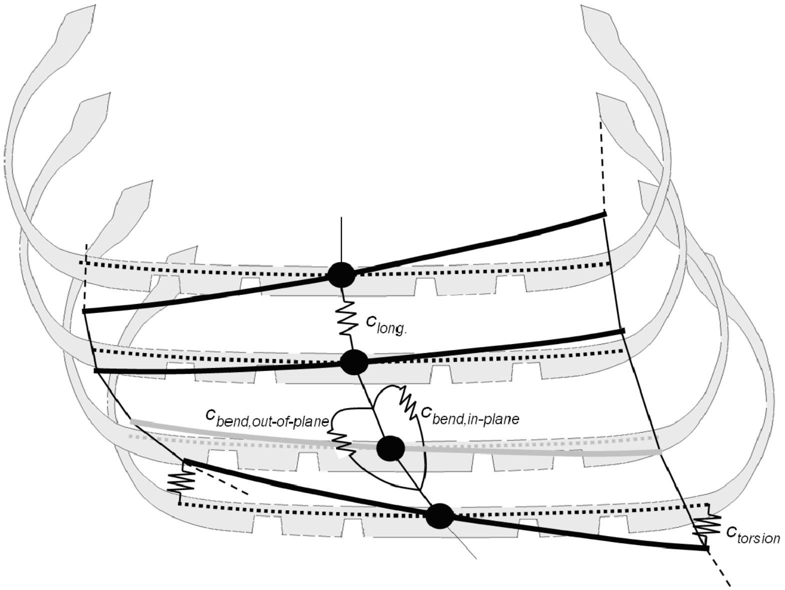

Figure 2. *Some force elements between adjacent belt elements and rim*

The mechanical model of the belt-carcass-bead structure can be interpreted as a very coarse, but highly non-linear finite element model, implemented in terms of a spring/damper/mass assembly. Within this assembly, the tire belt is described as an extensible and flexible ring, being elastically founded on the rim by distributed, partially dynamic stiffnesses in radial, tangential, and lateral direction (see figure 1). The degrees of freedom of this ring are such that rim in-plane as well as out-of-plane motions are possible. The ring is numerically approximated by a finite number (typically 100..200) of rigid 'belt elements'. These belt elements are coupled to their direct neighbors by stiff translational springs and by bending stiffnesses about both the in-plane and the out-of-plane direction, see figure 2.

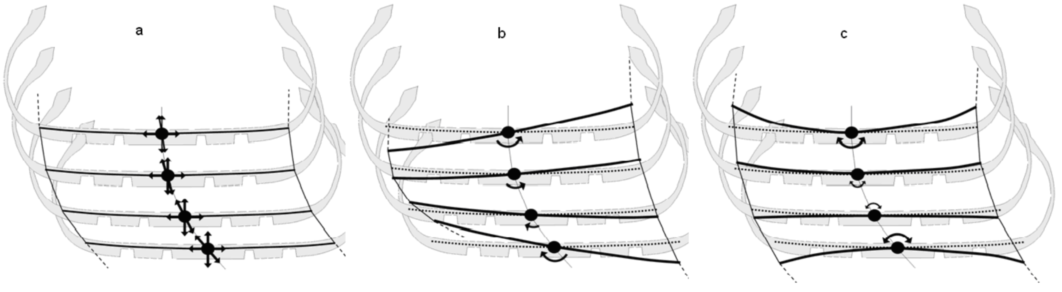

Figure 3. *Belt elements degrees of freedom*

Each belt element has

- three translational degrees of freedom,

- one rotational degree of freedom (the torsion angle about the circumferential axis), and
- a certain number of 'bending degrees of freedom', describing the shape of the belt distortion caused by bending about the circumferential axis (called 'lateral belt bending' hereafter),

see figure 3.

The torsion angles are coupled by rotational stiffnesses between two adjacent belt elements, and by another rotational stiffness for each belt element, located between belt element and rim. At the same time, a certain 'kinematic' coupling between the lateral displacement of a belt element and its torsion angle is taken into account by an appropriate coupling stiffness.

To every belt element, a certain number (10 to 100, say) of mass-less 'tread blocks' is associated, building the tread sub-model. These blocks carry nonlinear stiffness and damping properties in radial, tangential, and lateral direction. The radial deflections of the blocks depend on road profile, locus, and orientation of the associated belt elements. Tangential and lateral deflections are determined by the sliding velocity on the ground and the local values of the sliding coefficient. The latter depends on ground pressure and sliding velocity. 'Radial', 'tangential', and 'lateral' is to be understood relatively to the orientation of the belt element, whereas 'sliding velocity' is the block end point velocity, projected onto the road profile tangent plane. By polynomial interpolation, certain precautions have been undertaken not to let the ground pressure distribution mirror the polygonal shape of the 'belt chain'.

Usually, the tread blocks are located along several parallel lines. Alternatively, they can be placed randomly in lateral direction, or according to a black-and-white bitmap, showing the tread pattern geometry.

The belt elements are curvilinear in lateral direction. The respective cross-section shape of the unloaded belt and tread surface can be described either in terms of spline data or by few characteristic values, comprising mean belt curvature, tread height, and tread shoulder dimensions.

The actual lateral curvature of a belt element in loaded condition, and thus indirectly also the contact patch shape, is not only determined by the unloaded geometrical shape, but also by the belt lateral bending degrees of freedom. As mentioned, the belt's lateral bending is approximated by certain appropriate shape functions, the coefficients of which are the mentioned generalized degrees of freedom. They are determined on basis of the respective bending moments, which in turn are functions of the normal forces of the belt elements' tread blocks.

In order to determine all six components of the force/moment vector, which is virtually acting on the geometrical rim center, the distributed forces and moments in the elastic foundation of the belt are added up properly.

Stiffness, bending stiffness, and damping coefficients of the belt structure are calculated during pre-processing, fitting certain prescribed static, steady-state, and modal properties.

Optionally, *FTire* can take into account tire non-uniformity, which is a harmonic or a general variation of the vertical and/or longitudinal stiffness, as well as static and dynamic imbalance, radius variation ('run-out'), and mass variation.

Kernel of the *FTire* implementation is an implicit integration algorithm that calculates the belt shape. This integrator runs parallel but synchronized to the calling main integrator. By use of this specialized implicit BDF integrator, the belt extensibility may be chosen to be extremely small. By this, *FTire* also allows the simulation of an in-extensible belt without any numerical drawbacks.

FTire's thermal sub-model can be activated by the user, according to the current application. It consists of three components. The first one is the thermo-dynamical computation of the actual inflation pressure as function of the filling gas mass, the 'cold tire inflation pressure', the filling gas temperature, and the actual interior volume as determined by the mechanical model. The second component describes heat generation and heat transfer both in the belt/carcass structure and in the tread. This model introduces state variables for the temperature of the tire structure (including filling gas), and the individual temperature of each tread contact element. Heat generation and heat transfer is driven by the power loss distribution due to structural damping and hysteresis, as well as the sliding friction power on the road surface. Finally, the third thermal model component describes the influence of the actual tread and road surface temperatures on the friction characteristic.

The tread abrasion model ('wear model') can be activated by the user in the same way as the thermal model. If activated, *FTire* determines, individually for each tread element, the instantaneous values of sliding velocity, frictional stress, normal stress, and temperature. These signals are used as independent variables of a general multi-dimensional characteristic (the 'wear function'), predicting the instantaneous tread block's wear rate. This wear rate is integrated, resulting in the tread-block-individual state variable 'tread element height'. These state have location-dependent values, distributed along the tread circumferential and lateral coordinates.

The actual, time-dependent tread block heights will affect cross-section geometry (and thus indirectly the contact pressure distribution), radial tread stiffness, tread shear stiffness, tire mass and its distribution, and the tread's distributed heat capacity. Indirectly, tread wear affects the global tire stiffness and handling properties. Moreover, because the actual tread thickness is a function of the tread element's location, tire imperfections like 'spot wear' etc. are subject to possible investigation.

The real challenge of this approach is the determination of the wear function, which has to be approximated on basis of respective measurements (cf. [22]). By default, the following dependency for the wear rate *dh/dt* is assumed, using only the frictional power density P_{frict} (the product of sliding velocity and frictional stress):

$$\frac{dh}{dt} = -c_{wear} \cdot P_{frict}{}^{e_{wear}}$$

However, this formula can easily be replaced by a more detailed, user-defined one.

4. Internally Used Road Models and Interfaces to External Road Models

Obviously, the choice of the road model to be used with *FTire* (more precise, the format of the road surface description, together with the evaluation algorithm) depends on the kind of road data. Roughly, one can distinguish between

- geometrically simple obstacles, requiring only few values for exact specification,
- synthesized pseudo-stochastic data, using a 1D or 2D dynamic shape filter method,
- measured data on equally meshed ('regular') grids,
- measured data on irregular triangulations.

FTire supports a wide variety of respective road models of all four kinds. For many road models, *FTire* uses its own optimized evaluation procedures. These include

- most rdf-files as used by Adams™, including all 2D roads, 3D roads based on curved center-lines, and 3D triangulations,
- WaveFront triangulation files,
- all *COSIN/ev* road models ([16]), including a large set of parameterized single obstacle definitions, general cleat geometries on rotating drums, and spatial test track specifications,
- RGR roads (Regular Grid Roads, [16]),
- CRG roads (as defined by Daimler and TÜV SÜD, [21]; similar to RGR roads),
- FTR roads (as defined by vi-Grade; similar to RGR roads).

All these road models are available in all environments which are supported by *FTire*. They do not require a separate license or an extra library other than *FTire*.

In contrast, several other road models use the original evaluation routines. Obviously, these models might require installation and license of the respective software environment:

- all Adams™ xml-files,
- all Simpack™ road models (in preparation),
- all CASCaDE roads,
- all roads given in the TYDEX/STI Standard Road Description Format,
- IPG-Road (provided by IPG Automotive GmbH),
- URM roads (a very simple program interface for user-programmable road models),
- several user-specific models.

FTire, like any other high-resolution physical tire model, needs to evaluate the road surface millions of times per second, in order to achieve both the required spatial and temporal resolution, see figure 4. This is why efficiency of evaluation is one of the most critical aspects of road model selection.

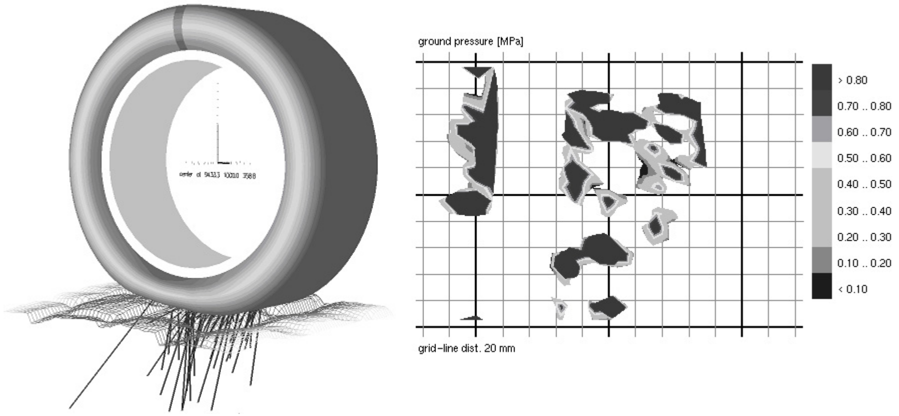

Figure 4. *FTire, rolling over Belgian block road; resulting instantaneous contact pressure distribution*

It turned out that RGR roads, an optimized representation of high resolution road surface measurements on equally spaced grids, optionally equipped with a curved center-line, are especially well suited to meet the demands on efficiency, accuracy, and flexibility. This is why RGR roads, besides geometrically simple, parameterized obstacles, are *FTire*'s preferred road description method. RGR roads provide considerable and scalable reductions in file size, in memory demand, in file loading time, and in CPU time for evaluation, as compared to the widely used irregular triangulations.

FTire provides a collection of auxiliary programs to generate, analyze, and process all road files, including RGR models. This toolbox, called *FTire/roadtools*, is free of charge for all *FTire* licensees. *FTire/roadtools* is equipped with an easy-to-use graphical user interface (GUI) and comprises

- visualization of the road in terms of 2D height profiles with arbitrary length and resolution;
- visualization of the road in terms of 3D surfaces, both as wire-frame or in rendered mode;
- generation of RGR data out of any other supported road format, including triangulations, with arbitrary patch size and resolution (but of course not higher than the one of the input data);
- reformatting of RGR data: ASCII to binary, coarsening, compressing both loss-less or lossy with prescribed tolerance, etc.;
- filtering of RGR data on basis of space-domain convolution with smoothing functions, or FFT-based smoothing in frequency domain;
- combination of several RGR patches into one; and
- splitting of an RGR file into patches with prescribed overlapping.

5. Parameterization Techniques and Tools

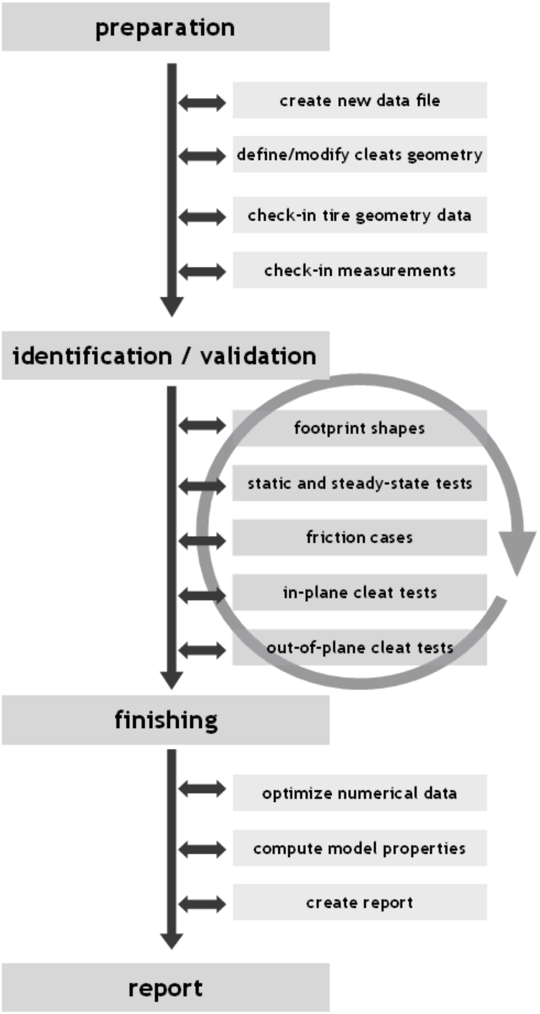

***Figure 5**. FTire/fit workflow*

Obviously, as with all detailed tire models, determination of *FTire*'s data is essential and laborious at the same time. There are several institutions that have gathered far-reaching experience in the 'turn-key' parameterization of *FTire*, see chapter 6.

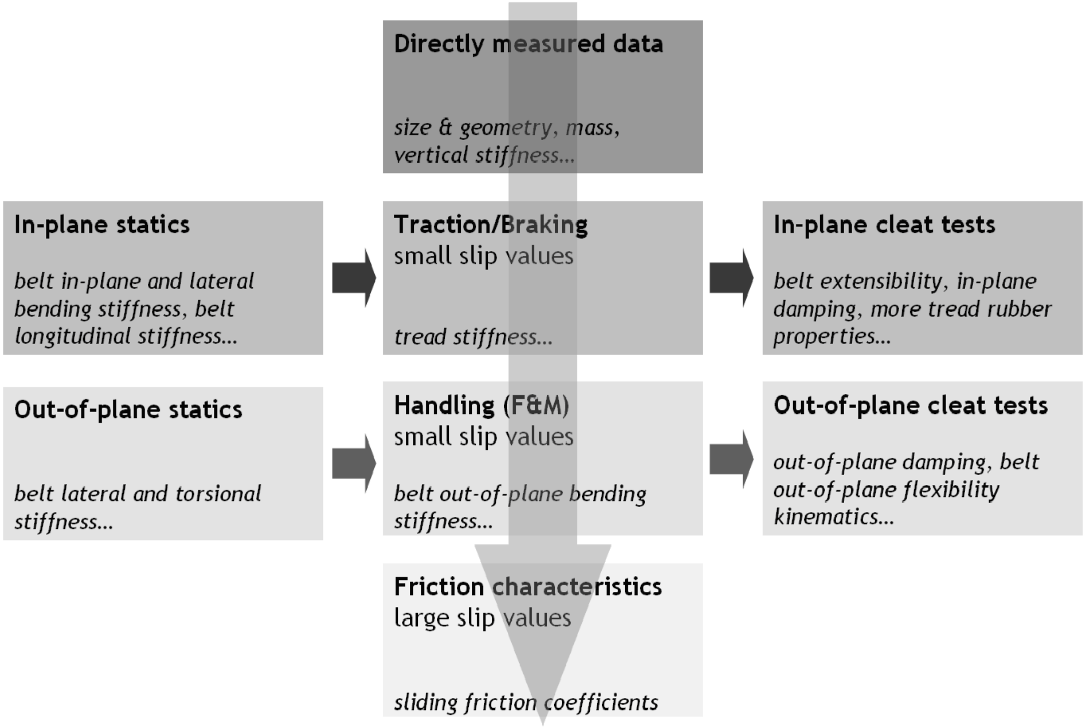

Figure 6. *FTire/fit proposed sequence of data processing in the identification step*

FTire assists users in performing this task with three different tools:

- *FTire/estim*, a tool for 'rough estimation' of *FTire* data, using parameters of a similar reference tire together with certain user-definable similarity formulae, estimating the influence of small size variations on some basic stiffness data (cf. [16]),
- *FTire/fit*, a comprehensive working environment for completely processing all kinds of measurements (cf. [16]), and
- *FTire/calc*, a tool to extract certain *FTire* data out of detailed tire design data, with the help of *FETire*, cf.[16]).

FTire/fit, being the most important one of these tools, is a user-friendly collection of programs to process, identify, and validate measured geometrical, static, steady-state, handling, dynamic, and modal data. It is equipped with

- automatic measurement data format recognition and conversion,
- automated footprint comparison,
- automated cross-section geometry import,
- automated stiffness determination (radial, longitudinal, lateral, torsion, cornering stiffness, pneumatic trail, slip stiffness),
- automated static and steady-state validation by time domain simulation,
- dynamic identification by least squares fit of cleat tests in time and frequency domain,

- fully automatic HTML-based report generator, including generation and display of many tire model characteristic properties, all foot-print comparisons, and all static/steady-state/handling simulation comparisons.

FTire/fit's GUI leads the user through the complete data processing and identification process in a very clear way, see figures 5 and 6. Ultimate goal is to completely automate the whole process, at least in cases where completeness and sufficient quality of measured data had been proven in similar projects.

6. Commercial Availability

Currently, *FTire* software is commercially available from two sources:

- from the author, for use in all simulation environments apart from MSC products (for more information, please contact info@ftire.com),
- from MSC Software Corp., USA, for use in MSC products (Adams™, MD ADAMS™, etc.; for more information, please contact your local MSC representative).

For use in Simpack™, an additional solver-side interface is required, which is available from Intec GmbH, Germany.

Moreover, all assisting tools, like *FTire/tools*, *FTire/roadtools*, *FTire/sim*, *FTire/fit*, and *FTire/calc* are available from the author; the latter three on a commercial basis. The same holds for the Simulink™ blockset *FTire/link*. Licensing can be organized either in node-locked mode, or dongle-based, or network-based. Typically, all licenses are permanently valid and include a one-year free support and update service. Special evaluation or academic conditions are available upon request.

FTire-related services, like measurement-based parameterization or simulation studies, currently are offered from several institutions, like

- RWTH Aachen University (IKA/FKA),
- Karlsruhe University (Institut für Fahrzeugtechnik und Mobile Arbeitsmaschinen),
- Helmut Schmidt University Hamburg - University of the Federal Armed Forces (Institut für Fahrzeugtechnik und Antriebssystemtechnik),
- TÜV SÜD Automotive GmbH,

and others.

7. Interfaces to MBS Software

At present, program interfaces for the following simulation environments exist for *FTire*:

- Adams™ (all versions starting with V11)
- CASCaDE
- COSIN/mbs
- DADS™, Virtual.Lab Motion™
- FEDEM™
- MATLAB/Simulink™
- Mesa Verde
- RecurDyn™
- Simpack™
- veDyna™.

More interfaces to other environments are in preparation or planned for implementation, like

- Altair MotionSolve™
- CarSim™.

FTire can be called from most major OS platforms, like

- Windows™ 2000, XP, Vista™
- Linux (Redhat™, Novell™, OpenSUSE™ and others)
- SGI IRIX™ 32n and 64 bit
- HP-UX™.

Other Unix™-type platforms can be added upon request.

Being implemented mainly in ANSI Fortran 90 (and smaller parts in ANSI C), *FTire* is compiled and tested regularly using many different compilers, like

- Lahey/Fujitsu™ Fortran 95 for Windows
- Intel Visual Fortran™ for Windows
- Intel Visual Fortran™ for Linux
- GNU gfortran for Linux
- SGI IRIX™ Fortran Compiler
- HP-UX™ Fortran Compiler

and more.

FTire's animation and sound features are implemented using the OpenGL™ and OpenAL™ APIs. The graphical user interfaces (GUIs) of *FTire*'s additional tools (*FTire/tools*, *FTire/roadtools*, *FTire/sim*, *FTire/fit* and *FTire/calc*) all are implemented platform-independent in Tcl/Tk.

8. Future Perspectives

Obviously, refinement and improvement of *FTire* and its tools will continue. Some of the next steps will be:

- interfacing *FTire* to even more simulation environments,
- refining the thermal model,
- implementing a real-time capable simplified version of *FTire*,
- closing the remaining gap between *FTire* and *FETire*, by introducing a scalable tire structural stiffness model,
- directly extracting *FTire*'s stiffness data from more detailed commercial FE models,
- implementing a standardized soft soil model interface.

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