1 Introduction

1.1 Thesis structure

This thesis is thematically divided into five chapters. The logical chain is depicted in Figure 1.1.

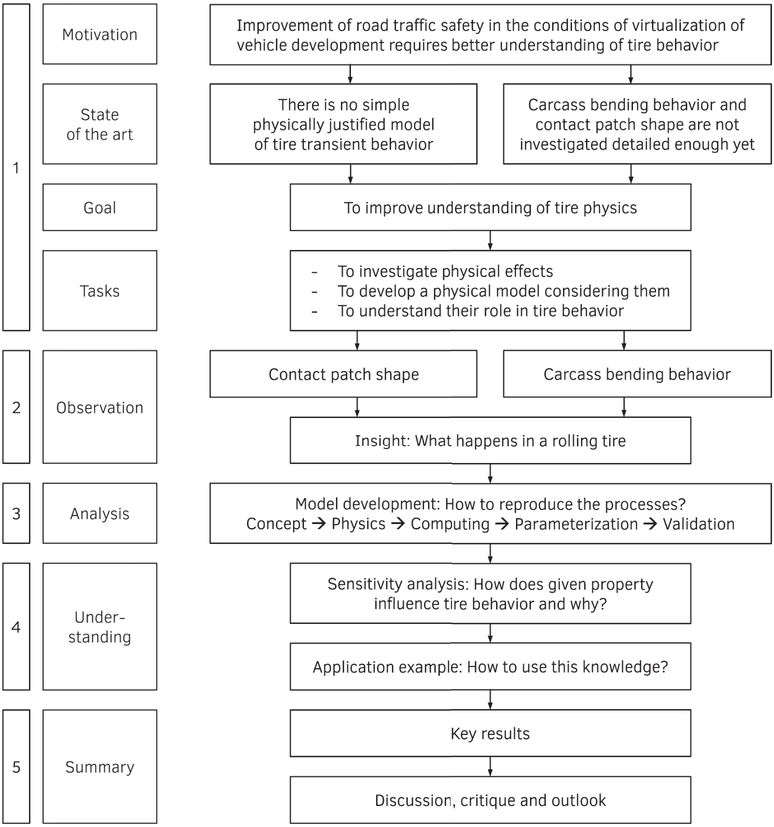


Figure 1.1. Logical chain of this thesis.

Three special symbols are used to highlight the following elements:

D	Definition: A statement of the meaning of a term used in this thesis.
?	Question: A step of logical argumentation, expressing the request of required information.
!	Insight: A clear understanding or conclusion regarding any relevant issue.

The core text of this dissertation is compressed down to the observations, arguments and conclusions necessary to achieve the aims of the study. Their background and further information are available in Appendix according to the references in the text.

1.2 Motivation

Road traffic injury is considered to be a global problem of healthcare and sustainable development: More than 1.2 million people die annually in road traffic accidents worldwide, and over 50 million are injured [WHO15]. Road traffic injuries are the main cause of death among people aged between 15 and 29 years, and are one of three leading causes among population aged between 5 and 44 years.

Due to the growing population and rising motorization rate, increasing attention is being paid to engineering solutions that can improve road traffic safety, like the seat belt and airbag did [DEK15]. Currently the highest potential for safety improvement is found in advanced driving assistance systems (ADAS, [Kno06]): These help a driver in critical situations through their sensing and acting abilities, which are not available for humans. Some of these systems have become legislatively mandatory, as occurred earlier with the seat belt.

Many driver assistance systems correct vehicle motion by adjusting wheel forces [Fen98]. The task of calculating the forces on four wheel hubs that are required to secure, for example, stability of vehicle motion, is relatively simple. However, the task to determine such an impact on the wheel that causes required force and torque response in a tire contact patch is considered to be a highly complicated problem of classical mechanics, which is not completely solved yet. Hence, improvement of road safety by means of ADAS is closely connected with tire behavior.

The ADAS, which correct vehicle motion by adjusting wheel forces in a critical situation, deal with a non-steady state. Steering angle may change stepwise during critical maneuvers. In addition to it, ADAS apply further dynamic interventions on the wheels, such as braking force (Figure 1.2).

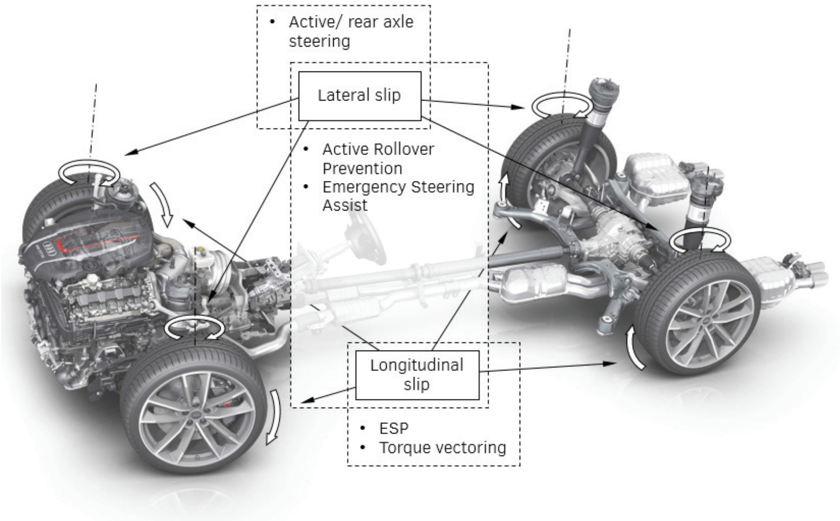


Figure 1.2. Impact of some assistance systems on wheels (background picture [AUD15]).

Electronic Stability Program (ESP, [Fen98]) impacts each wheel individually with a brake torque, modulated at up to 30 Hz, in order to stabilize the vehicle in critical situations such as the double lane change maneuver [ISO99, ISO11]. Taking into consideration that an electric vehicle with an individual drive is a realistic concept, in [Jal10, Jag15] it was proposed to substitute the individual brake torque intervention of ESP with individual drive torque for such vehicles. In this way, the maneuver can be finished faster, which means safer. Hence, both braking and driving torque can dynamically excite the tire.

Active steering systems [Lan15], which often include rear-axle steering [Har13] and active rear-axle kinematics [Wie08], combine high maneuverability at low speed with increased stability at high speed. These systems are also aimed to make vehicle reaction in critical situation predictable for driver [Don89, Köh06]. Different vehicle behavior in such situation compared to normal conditions is mainly caused by non-linear tire characteristic close to its friction limit. In [Yim15] it was proposed to adjust the slip angle of wheels individually in order to achieve the required yaw torque for vehicle stabilization with the lowest braking torque. Therefore, understanding of processes that are relevant for the non-linearity of tire characteristic (transient behavior [Hol99], rolling with combined slip and high slip values) is important for development of the active steering systems.

Active Rollover Prevention (ARP, [Sta14]) is a system that applies a full-power brake torque on a steered wheel and blocks it. In this manner the system avoids high lateral force as a cause of rollover.

Emergency Steering Assist [Har11] recognizes the possibility to avoid a crash by taking an evasive maneuver. If the driver initiates this maneuver, the system supports him/her with steering torque and individual brake interventions in order to ensure efficient evasion and stabilization of the vehicle.

Torque Vectoring systems [Saw96] manage the torque on each wheel to improve vehicle handling and its response in critical situation. The quality of vehicle state observation for optimal torque distribution is very sensitive to transient tire behavior and assumptions used for tire description in the observer [Bre95].

The possibility to use a **tire as a sensor** is emphasized by the latest developments in intelligent tire technology [Jo13]. With help of simple tire-mounted sensors (e.g., accelerometers) it is possible to estimate relevant data such as road conditions and tire wear level [Mas15]. The next goal is a real-time estimation of friction potential. Such data can significantly improve the efficiency of ADAS.

Finally, the concept of **autonomous driving** requires the vehicle to have an ability to act and react precisely and efficiently based on a number of real-time measurements. An efficient and stable control algorithm requires comprehensive understanding or at least description of a plant, which incorporates tire.

Because of increasing complexity of vehicles, early-decision-making becomes more important in vehicle development process (front loading). This leads to wider application of virtual tools and higher requirements on them. In the concept phase of development, simple and scalable simulation models are required, because chassis design data is known only at a very general level [Kva06, Wag17]. Understanding of physical processes in components and subsystems is essential for development of the corresponding simple model, aimed to an early stage of the development process [vPu17].

These facts can be summarized as observations, which raise specific requirements in the description of tire behavior (Table 1.2). The four considerations described in Table 1.2 formulate the scientific problem addressed in this research. Due to the increasing performance requirements to vehicles, virtualization of development process and rapid development of ADAS, this problem is relevant at the present day. The following section will therefore analyze the background of this problem and existing approaches to solving it.

Table 1.1. Detected challenges for tire description.

Observation	Requirements on tire description
ADAS adjust longitudinal force on the tire by means of drive or brake torque management; lateral force through steering intervention.	Consideration of combined longitudinal and lateral slip.
The highest efficiency of vehicle control corresponds to utilization of the entire friction potential of a tire.	Consideration of the entire range of slip values up to 100 %.
Electronic control systems operate at a frequency of up to 30 Hz during vehicle transient motion.	Description of transient behavior.
"Tire as a sensor" technology requires connection between simple measurements in the tire (e.g., acceleration sensor of Tire Pressure Monitoring System module) and relevant parameters such as road conditions or friction potential.	Understanding of physical processes.

1.3 State of the art

On June 10th, 1846, 23-years-old Robert William Thomson patented the "aerial wheel" [Joh17], which was the first mention of the pneumatic tire (Figure 1.3). Although he measured a 68 % rolling resistance reduction, nobody was able to develop this idea commercially at that time. In 1887, this concept appeared once again: A veterinary surgeon, John Boyd Dunlop, has fitted an inflated garden pipe to the wooden rim of his son's tricycle [Goo17]. Due to further application of this idea in cycling, pneumatic tire received recognition.

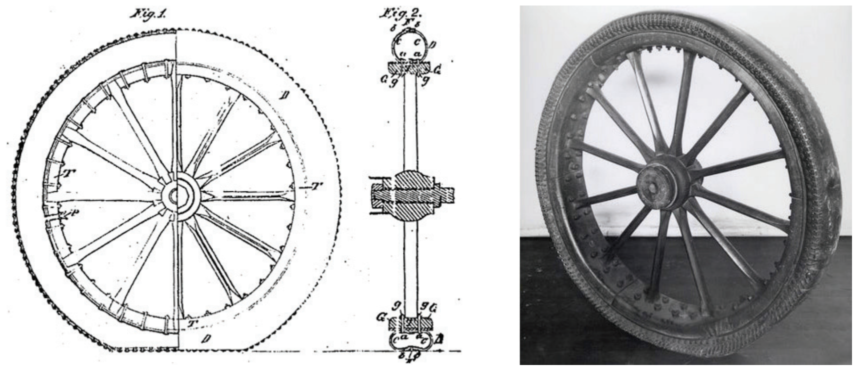


Figure 1.3. Patent US5104A by Robert William Thomson and his invention [Joh17].

The importance of the tire in the total vehicle system was recognized even during the very early periods of its development [Bro25]. Today, as one hundred years before, the tire remains the only link between a road surface and a vehicle. Still, despite its more than 150-year-long history, this physical system is not completely understood. Vehicle development process requires knowing a tire transfer function, which is usually called the "tire model".

In terms of handling, the "tire model" means a transfer function from kinematic state parameters to force parameters (Figure 1.4): Input parameters are motion laws describing wheel center coordinates and orientation angles in time. Output parameters, in terms of handling, are force laws describing longitudinal force, lateral force and aligning torque in time.

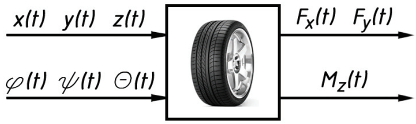


Figure 1.4. The input-output scheme of the transient handling tire model.

Because of high complexity of tire behavior, the most common approach was to describe the tire as a black box, namely using empirical methods (Magic Formula [Bak91, Pac12]). Following the increasing scope of tire motion modes, which must be described, the empirical approach was enhanced with consideration of thermal issues [TNO13], inflation pressure [Sch05] and transient lateral force generation [Ein10]. However, it was also done empirically. In the meantime, present-day trends make empirical methods less suitable for modern requirements.

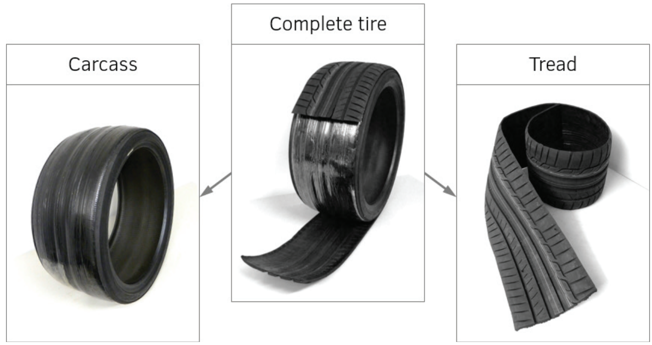
Firstly, continuously increasing performance requirements on modern vehicles lead to necessity to understand tire behavior further and to be able to use tire more efficiently. Secondly, vehicle development process experiences virtualization. An increasing share of simulation methods in vehicle development means that simulation models have to describe more complex physical systems and processes (in case of tire – combined slip, transient behavior). Comprehensive understanding is essential for this task.

Alternatively to the empirical characterization of tire handling properties, the physics behind them can be described with the help of FE-simulation [Bel00, Kal10]. Due to the highest level of detail, FE-modelling provides high accuracy, but is very time- and effort-consuming. It is reasonable to expend this effort for more complex applications, such as rolling over an uneven or deformable road surface [Cal15], vibration and comfort analysis [Bäc12], thermal processes [Bel97, Cal15b, Cal14]. Hence, for the handling analysis on rigid and flat road surfaces, an application of FE-modelling is less reasonable.

A predecessor of FE-analysis in tire dynamics is another important approach to understand the physical processes: To describe the tire with the help of a simple physical analog or mechanism. Apart from the FE-analysis, this option makes it possible to take into consideration only those physical properties and effects that are relevant to selected area of tire dynamics, and neglect the rest. This method provides an understanding of the processes and is suitable for complex motion, as long as a physical mechanism is able to respond to any correct excitation it receives. Based on these considerations, it is fair to select this approach to reach the goal of this study.

Traditionally for simple physical modelling, a tire is divided into two elements, the properties of which strongly differ: Tire tread layer (hereafter – 'tread') and tire carcass with the rest structural components (hereafter – 'carcass'). Properties, functions and constraints of these two elements are described in Table 1.3. 'Isotropy' indicates the uniformity of physical properties in different directions. If a deflection of one point of a flexible body causes deflection of other points, the body is considered to be cohesive. If a deflection of one point of the body does not cause deflection of other points (e.g. two tread blocks), such a body is considered to be non-cohesive.

Table 1.2. General separation of a tire into two structural elements.

		
Element	Tire carcass	Tire tread layer
Isotropy	Anisotropic: Composite structure	Isotropic: Homogeneous or close to homogeneous rubber
Cohesiveness	Cohesive	Non-cohesive
Function (in terms of handling)	• Longitudinal / lateral deflection • Lateral bending	• Longitudinal / lateral shear • Friction
External constraint	Flexible constraint with the rigid rim	Kinematic constraint with the road
Internal constraint	Fixed constraint with the tread	Fixed constraint with the carcass

Due to the different properties of these two elements, they are usually simulated with different simple physical structures. Because of cohesiveness and high lateral flexibility of the carcass, it is usually modeled as a body on an elastic foundation – rigid ring, flexible string or beam. The tread, on the contrary, is usually described via a brush model because of its non-cohesiveness. Following analysis emphasizes different directions of physical modelling with their advantages and disadvantages, in order to identify the most suitable method for the modern requirements.

The **string model** [Ell69] was initially considered to be a model for whole tire: The string in the free part of a tire was described using beam theory, the string in the contact patch was constrained kinematically. As a consequence, the model was unable to consider slip. An extension of this model [Böh66, Böh88] represents the tire as a beam on an elastic foundation and takes into account the mass of the carcass. Hence, this model considers inertia forces, beam bending and torsional stiffness. An analytic solution was deduced with help of Fourier transformation, but it is only available for the steady state.

The **brush model** ([Fro41, Pop93, Pac12]) describes a tire with radial bristles along its equator, which have a friction constraint with the road and can deflect in both horizontal directions (Figure 1.5). Due to isotropic brush properties, the model cannot properly describe the transient development of lateral force.

Although the string model and the brush model were initially developed to represent the whole tire, they are more suitable to describe carcass and tread respectively. This is why the most advanced physical tire models represent a combination of two structures. In [Böh85] a tire was considered as a wide string with a two-dimensional contact patch and brush elements on it. In such a manner, slip was taken into account. This model is able to consider transient behavior. However, its solution requires an expansion of functions into Taylor series, and there were used summands of only second order. This limits the accuracy and can be considered as a disadvantage of the method.

The **Brush and Ring Tire** [Gip97, Amm97] combines a rigid ring on an elastic foundation (carcass) with a brush model (tread). Based on the ring, a toroidal belt is constructed, which takes into account the two-dimensional contact patch (Figure 1.6). The elastic foundation is represented via non-linear spring-damper elements between a rigid rim and rigid ring. Brush elements of the tread model are massless, but have flexibility and damping. Still, the whole model is aimed at simulating the transient response of the tire to the vertical excitation (road unevenness). For the purpose of the simulation of a transient response to slip angle excitation, the carcass description as a rigid ring is a significant limitation: Its deflection is calculated quasi-static and deflected form is limited by a "rigid ring" assumption.

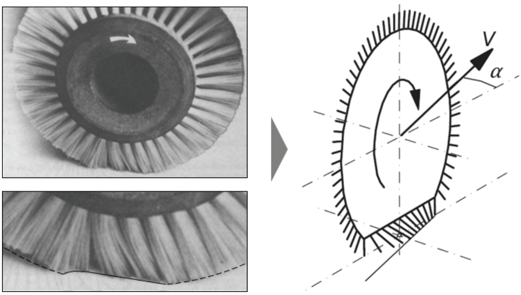


Figure 1.5. Structural scheme of brush model [Pop93, Pac12].

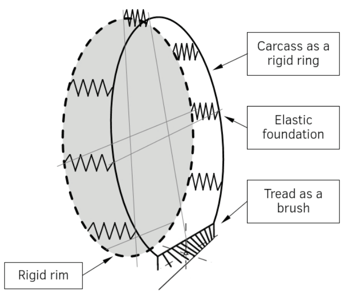


Figure 1.6. Structural scheme of the Brush and Ring Tire model in sense of lateral dynamics.

The **extended string model** [Hig97, Pac12] uses string on an elastic foundation to describe the carcass, and the brush model to simulate tread (Figure 1.7). Such a string-brush system can be multiplied in order to consider the width of tire. The entire circumference of the string is divided into two parts: The string in a contact patch and the string in a free part of the tire (Figures 1.8-1.9). These two parts are connected once on the leading (A) and once on the trailing (B) edges of the contact patch.

The model has two important assumptions. Firstly, the connection between the strings at point B is not limited by tangency. Consequently, the carcass has a kink in this point.

Secondly, the orientation of the string at point A is defined by an assumption that was described by [Böh66b]: In the middle plane of the tire there is constructed point D, which is distanced from leading edge (point L) by a relaxation length. At point D, a pivot is assumed. Next, an imaginary lever with a roller is considered, which pivots around point D. The roller always remains on the leading edge of the contact patch. This non-holonomic constraint defines the orientation of the string at point A.

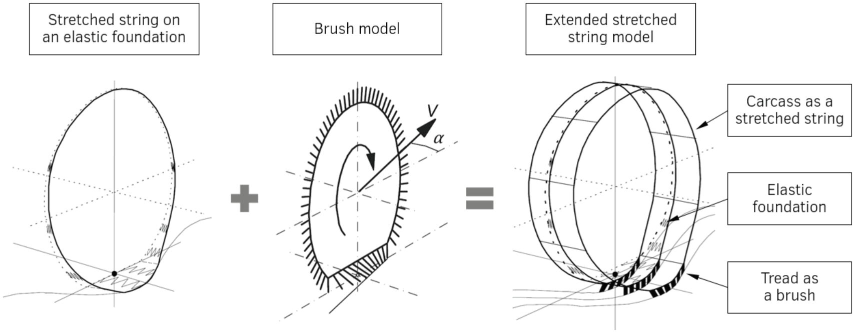


Figure 1.7. Structural scheme of the extended string model [Pac12].

These assumptions make model calculation fast. However, they greatly influence the description of the carcass, which is important for transient aligning torque generation. In addition to this, the representation of the wide carcass via several independent one-dimensional strings limits proper reproduction of carcass bending behavior.

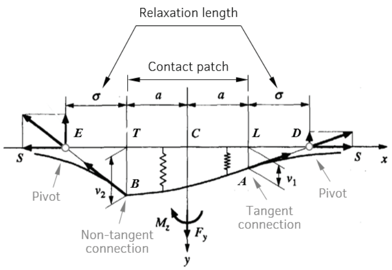


Figure 1.8. Top view on the string model, a representation of [Hig97].

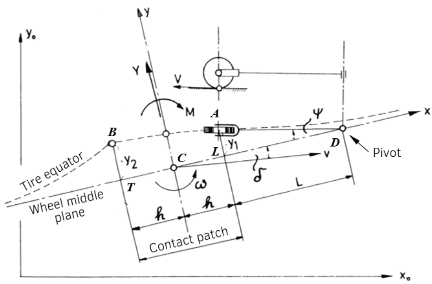


Figure 1.9. Top view on the string model, a representation of [Böh66b].

The **Treadsim** model [Pac12, Uil07, Hoo05, Fia54] considers carcass deflection only in the contact patch. Initially, this deflection was approximated by a second-order function [Pac12] (Figures 1.10-1.11). Later, it was changed to beam elements [Hoo05] (Figure 1.12). The tread is described with the brush model.

Even in its first representation, the Treadsim model had already achieved a level of complexity that made it impossible to obtain an analytical solution and required a numerical solving routine. This lead to oscillatory stability issues inherent in iterative solving process, which lead to divergence [Pac71].

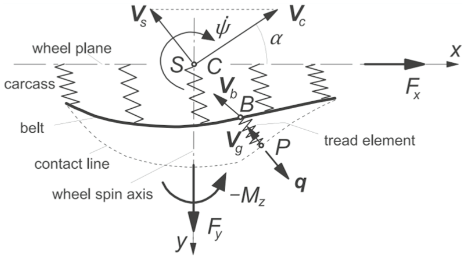


Figure 1.10. Structural scheme of the Treadsim model [Pac12].

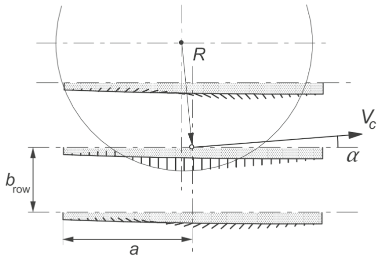


Figure 1.11. Multirow representation of the Treadsim model [Pac12].

In order to consider the width of the tire and be able to describe transient aligning torque generation, the model multiplies the beams with the brush along the tire axis (Figure 1.11). Still, these beams remain independent from each other; this fact limits precise representation of the bending behavior of the wide carcass, which is especially important for aligning torque generation. Even in a steady state, simulation error of aligning torque can be as high as 25 % [Uil07].

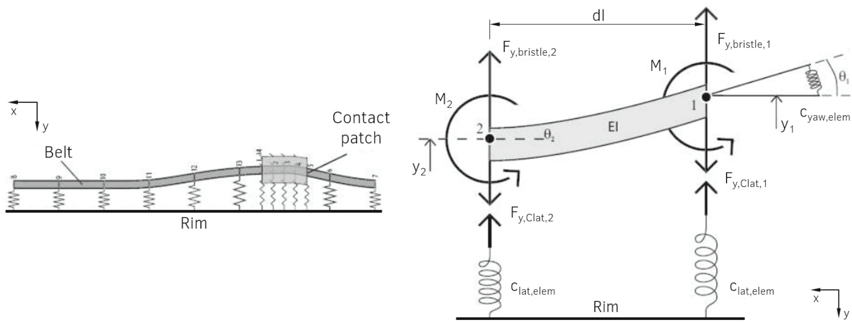


Figure 1.12. An extension of the Treadsim model with a beam-based carcass [Hoo05, Uil07].

The **TameTire** model [Fév07, Fév08, Fév10] is one of the most advanced physical models, combining mechanical description with a thermal model. The tread is described once again as a brush model. Carcass deflection is simulated with help of a second-order approximation function, based on lateral force, tire lateral flexibility and kinematic constrains (Figure 1.13).

It is noteworthy that this function has the same appearance as that of the Treadsim model. This fact confirms that the second-order function is a good compromise between simulation accuracy and computational effort. Consequently, the model is real-time capable. The price of this advantage is the simplification of the carcass deflection form and an empirical description of transient behavior.

The second-order approximation function limits carcass simulation in cases of high-frequency excitation, especially for aligning torque. The empirical description of transient behavior leads to the black-box based simulation of transient processes, which does not provide an understanding of the physical background.

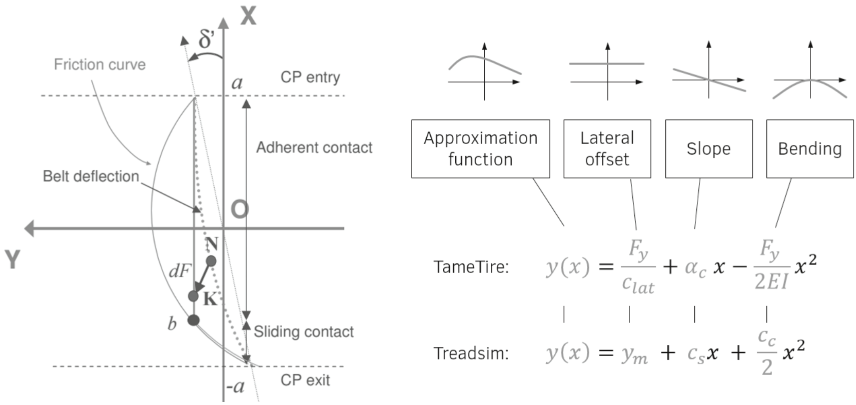


Figure 1.13. Structural scheme of the TameTire model and the composition of the carcass deflection approximation function [Fév08].

A comparison of these four described physical models emphasizes that each is aimed at different target application (Table 1.4). As long as the task of this research, which is determined by new trends in the automotive industry, differs from the target applications of the analyzed models, it is natural that they are unable to meet new requirements. However, there is a lot to be learned from them.

The goal of this investigation is to understand the physical background of the transient handling properties. In order to be able to identify a connection between the physical effects of the rolling tire and its transient handling behavior, it is important to describe the most relevant effects physically (not empirically) and physically correct (without qualitative contradiction such as a carcass kink). This is why both carcass and tread models have to be physically justified. The simplification of the wide carcass structure affects the accuracy of the aligning torque description [Uil07]. Hence, it is necessary to consider the wide common body of the carcass, analyze its bending behavior and take into account the two-dimensional array of brush elements.

A commonality in the described physical models is that each uses several important physical properties of the rolling tire to describe its behavior:

- Lateral flexibility of tire carcass, usually considered via elastic connection between tire carcass and rigid rim;
- Carcass bending, usually taken into account via flexible one-dimensional elements such as string or beam, or just approximated with a given assumed function;
- Tread shear, usually simulated via brush model;
- Friction properties between tread and road.

Due to importance of these properties for tire handling, they are considered in this study as **primary physical properties**. They make it possible to describe the transient generation of lateral force and aligning torque (partly). However, they do not provide the required understanding of the physical background, because of several simplifications.