

Tire Model Application and Parameter Identification-A Literature Review

Bin Li
Texas Tech University

Xiaobo Yang
Oshkosh Corp.

James Yang
Texas Tech University

ABSTRACT

A tire may be one of the most critical and complex components in vehicle dynamics and road loads analyses because it serves as the only interface between the road surface and the vehicle. Extensive research and development activities about vehicle dynamics and tire models have been published in the past decades, but it is still not clear about the applications and parameter identification associated with all of these tire models. In this literature review study, various published tire models used for vehicle dynamics and road loads analyses are compared in terms of their modeling approaches, applications and parameters identification process and methodologies. It is hoped that the summary of this literature review work can help clarify and guide the future research and development direction about tire modeling.

KEYWORDS: Tire model, vehicle dynamics, vehicle handling and stability, ride comfort, road load, parameter identification

CITATION: Li, B., Yang, X., and Yang, J., "Tire Model Application and Parameter Identification-A Literature Review," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(1):2014, doi:10.4271/2014-01-0872.

INTRODUCTION

A pneumatic tire is usually the only component interfacing with the road from a vehicle, thus it plays an important role in the vehicle dynamics system. The pneumatic tire has three fundamental functions: (i) generating proper forces during vehicle cornering or traction/braking, (ii) absorbing the shock and vibration caused by road irregularity, and (iii) supporting the vehicle weight on various terrains (Wong, 2001). From this point of view, it can be concluded that the design of a pneumatic tire is vital to vehicle performance. To achieve a proper tire design that meets all three function requirements, it is essential to understand the tire dynamics characteristics experimentally and/or analytically. Experimental approach is ultimately considered to be necessary, direct and reliable, but expensive, time consuming and practically impossible to cover all operating conditions. Alternatively, analytical method via modeling and simulation becomes more and more popular for its significant advantages in many ways.

Like any other virtual models, the accuracy and predictability of a tire model is most important. Ideally if one tire model could be applied accurately for all operating conditions, it would be highly accepted by users. Unfortunately such an "ideal" tire model may not be viable in engineering practice. Therefore in the past decades, various tire models have been developed for

different applications, such as handling and stability analysis, ride comfort analysis, and road load analysis, etc.

In general, we have divided tire models into two groups: the on-road tire model and the off-road tire model. The on-road one refers to the paved road such as the highway and the local city roads with hard surfaces; while the off-road case refers to the road which is unpaved such as sand, mud, snow road. The main purposes for tire models to be used for driving/braking and handling analysis are to predict the longitudinal force during braking/traction and/or the lateral force and self-align torque during cornering at on-road situation. For these types of analyses, the road is usually assumed to be flat and rigid and the tire model is required to be valid up to around 8 Hz (Pacejka and Bakker, 1992). In general, two approaches were employed to construct this type of tire models: the analytical approach and the empirical approach (Pacejka, 2005). Brush model is one of the earliest analytical tire models, and it is an origin of many other analytical models, e.g. Fiala's theory (Fiala, 1954), Pacejka's physical-based analytical model (Pacejka and Sharp, 1991), Gim's analytical model (Gim and Nikravesh, 1990; 1991), Levin's tire model (Levin, 1994) and CF-SAT system model (Miyashita and Kabe, 2005). Other important analytical tire models include Sakai's tire model (Sakai, 1981), Sharp's multi-lateral-spoke tire model (Sharp

and El-Nashar, 1986), Mastinu's FEM tire model (Mastinu and Fainello, 1992), and Maurice pragmatic tire model (Maurice et al., 1999). As for the empirical tire models, Pacejka's Magic Formula tire model (Pacejka and Besselink, 1992) is the most popular one and is still undergoing development. The latest version of MF tire model is TNO MF-SWIFT (Schmeitz et al., 2007; Besselink et al., 2010). Other empirical tire models include TMeasy tire model (Hirschberg et al., 2002) and Svendentius's Semi-empirical tire model (Svendentius and Gafvert, 2006). The handling and stability type of tire modeling has been well developed and the models can satisfy all requirements for almost all actual situations in terms of accuracy and efficiency.

The second group of tire models is the ride comfort tire models. The major concern is the human comfort and the tire acts as a filter which is able to absorb the shock generated by the obstacle between the road and tire. Human body sensitive frequency range is less than 20 Hz (ISO 2631-1, 1997). Therefore, this type of tire models has to be valid up to around 20 Hz. In particular, we mainly pay attention on vertical direction forces for ride comfort study. Related research work includes Bandel's 'black box' model (Bandel and Monguzzi, 1988), Takayama's tire model (Takayama and Yamagishi, 1984), Oertel's model (Oertel, 1997), Eichler's ride comfort tire model (Eichler, 1997). More recent ride comfort tire models include Belluzzo's road-noise model (Belluzzo et al., 2002), Kim's 2D analytical tire model (Kim et al., 2007), Hegazy's quarter and half vehicle model (Hegazy and Sandu, 2010) and Diglio's rack model (Diglio, 2009). This type of tire models can also satisfy requirements in terms of accuracy and efficiency.

Tire models for load analysis are typically more complex. This type of models is required to be valid up to around 50 Hz (Zegelaar and Pacejka, 1996) and is primarily applied for predicting the vehicle durability road loads. In this case, forces at all three directions (longitudinal, lateral and vertical) should be studied. Tire models used for load analysis include Mousseau's rigid on elastic foundation model (Mousseau and Clark, 1994), Zegelaar's rigid ring model and flexible ring model (Zegelaar and Pacejka, 1996) and Kao's BAT Tire Model (Kao, 2000). In particular, since tire models for road load analysis have higher valid frequency, this type of tire models can also handle the ride comfort situation. Four powerful commercial tire models which can be used for both ride comfort and durability cases are MF-SWIFT (Lugner et al., 2005), RMOD-K tire model (Oertel and Fandre, 1999), FTire (Gipser, 2005) and CDTire (Gallrein and Backer, 2007). However, the accuracy of current available tire models is only around 85% (Gallrein and Backer, 2007) and some of models are difficult to determine models' parameters.

Based on above discussions, various tire models for three types of applications have been proposed during the past 4 decades. However, few studies can be found in literature about the summary of various tire models' advantages, disadvantages, accuracy, efficiency, parameter identification. Therefore, it is difficult to select appropriate tire models for specific applications. This paper attempts to summarize these characteristics for various tire models based on their applications and parameter identification. In additional, this paper aims to collect all available

field/lab test data for parameter identification to facilitate tire model users to use these data.

TIRE MODEL APPLICATIONS

In this section, we divide all available tire models into three groups based on their applications. For each group of tire models, we compare their application limitations, advantages and disadvantages, simulation time, accuracy, how easy to diverge, how easy to model.

Tire Models for Handling and Stability Analysis

In this section, we reviewed various tire models suitable for the handling and stability analysis, and compare them as shown in Table 1. As we discussed before, the main purpose for handling and stability analysis model is to analyze the longitudinal/lateral force and self-align torque due to longitudinal/lateral slip and tire deformation in both steady state case and the non-steady state case. The tire models we summarized covers almost all the situations for handling and stability analysis including the pure steady slip case, combined steady slip case, and the combined non-steady state case. In general, the empirical tire models, e.g. TMeasy Tire Model (Hirschberg and Weinfurter, 2002), etc., can accurately predict the tire behavior for standard handling analysis case. However, they cannot handle the large slip or high tire deformation cases. Meanwhile, the analytical approach tire models, e.g. CF-SAT System Model (Miyashita and Kabe, 2005), etc., are more consistent between the steady state case and non-steady state case. However, their accuracy is low compared with the empirical tire models (Reinalter et al., 2007).

In Table 1, sixteen tire models used for handling and stability analysis are summarized and compared. Among these tire models, the following models can be applied only for purely steady state situation, and the rest models can be applied for both steady state and transient state situation: Fiala's theory (Fiala, 1954), Sakai's tire model (Saikai, 1981), analytical tire model (Gim et al., 1990, 1991), physical based analytical model (Pacejka and Sharp, 1991), Levin's model (Levin, 1994), TMeasy tire model (Hirschberg and Weinfurter, 2002), CF-SAT system model (Miyashita and Kabe, 2005), friction model (Velenis, 2005) and Ph.An.Ty.M.H.A tire model (Capone et al., 2009). Among all the steady state tire models, Fiala's theory (Fiala, 1954), TMeasy tire model (Hirschberg and Weinfurter, 2002), and CF-SAT system model (Miyashita and Kabe, 2005) are only valid at pure slip situation. And the rest steady state tire models can be used for combined slip situation. The following models are based on the 'brush concept' include: the Fiala's theory (Fiala, 1954), analytical tire model (Gim et al., 1990, 1991), physical based analytical model (Pacejka and Sharp, 1991), Levin's model (Levin, 1994), and CF-SAT system model (Miyashita and Kabe, 2005). The accuracies for most tire models are satisfactory except Fiala's theory (Fiala, 1954). However, Fiala's theory (Fiala, 1954) is very important since many tire models are developed based on this theory. As for the computational loads, the multi-radial-spoke tire model (Sharp and El-Nashar, 1986; Zhou et al., 1999) is the only one which has high computational costs among all the summarized handling and stability tire models due to its multi-spoke modeling approach.

Table 1. Comparison among various tire models used primarily for handling and stability analysis

Tire Models	Advantage/ Disadvantage	Accuracy	Capability	Complexity	Parameter Identifications
Fiala's Theory (Fiala, 1954)	Advantages: 1) Easy to construct and apply; 2) one of the default tire models in MSC ADAMS. Disadvantages: 1) Narrow application range.	The trend of the simulation results matches the experimental results.	Only valid at 1) pure steady state side slip case; 2) normal load distribution	Easy to construct and easy to apply	Only have 10 parameters, each parameter can be determined from experiment
Sakai's tire model (Sakai, 1981)	Advantages: This method can be applied to calculate the six components of the force and moments.	This paper presents the simulation results of the side force up to 60° side slip angle, and the slip ratio up to 0.08. And the results match the experimental data.	Valid for steady state case, can be used for combined slip situation	The calculation of the forces and moments involving integration of these component over the contact region	Parameters are identified through experiments.
Multi-radial-spoke Tire Model (Sharp and El-Nashar, 1986; Zhou et al., 1999)	Advantages: 1) High accuracy and only small amount of parameters need to be determined; 2) easy to apply; 3) wide range of application. Disadvantages: High computational load.	It is possible to select the model parameters such that the theoretical results are sufficiently accurate in certain cases.	Can be applied in both steady state and non-steady state case	Hard to construct compared to some other approaches	Small amount of parameters need to be determined
Analytical Tire Model (Gim et al., 1990, 1991)	Advantages: 1) Can be used for traction and braking simulation; 2) can be used in both on and off road conditions; 3) can be used in both pure and combined slip case. Disadvantage: Only valid at steady state case.	For both pure slip and combined slip cases, the force results satisfy the experimental results; but the Self-aligning torque doesn't fully fit the experimental data when the normal loads get higher.	Can be used for combined slip case including the camber angle; only valid at steady state case	Based on brush tire model, divide the contact region into two adhesion region and sliding region	This model maximize the parameters dependent on the tire geometry and minimize the parameters dependent on the experiments
Physical based Analytical Model (Pacejka and Sharp, 1991)	Advantages: Easy to construct, and simple; Disadvantages: 1) Only valid at steady state case; 2) doesn't fit the experimental data at combined slip case.	For pure slip case, the forces match the measured results; the moment doesn't fully match the experiment	Only valid at steady state case.	Based on the brush model, the transition region are introduced	Parameters are identified from experimental tests
MF Tire Model (Pacejka and Bakker, 1992)	Advantages: 1) Easy to construct and apply; 2) high accuracy and efficiency; 3) one of the most widely used empirical tire models, still undergoing development; 4) can capture the nonlinearity in tire behavior at very low to very high slip conditions.	High accuracy up to 10 Hz	1) Can be used in both steady state and transient state conditions; 2) can be used to analyze more complex tire behavior in combination with some other tire models.	Easy to construct and apply	More than 50 parameters need to be determined, and all the constructing parameters have physical background.
Levin's Model (Levin, 1994)	Advantages: 1) Use to examine the steady state tire behavior at large velocities; 2) includes the vertical load distribution influences. Disadvantages: Can't be used at transient condition.	Qualitatively matches the experimental data, additional verification is need for racing and aircraft tires	This model is used for analysis the steady state tire behavior for large velocities	Based on brush model, easy to construct	Some parameters are determined by direct measurements and some parameters are determined from experiments.
Semi-Analytical Tire Model (Mastinu and Gaiazzi, 1997)	Advantages: 1) can be used for vehicle dynamics and tire design; 2) can be used in both steady state and transient state conditions. Disadvantages: 1) The results of the moment don't fully fit the experimental data even for steady state conditions; 2) valid up to 10-15 Hz.	Valid up to 10 to 15 Hz, not fully accurate for the moment results	Used in both steady state and transient state conditions, also can be used for tire design	Not easy compared to some other empirical models	Parameters includes the geometrical parameters, tire structure parameters and the tire ground parameters, they are obtained by experiments
Pragmatic Tire Model (Maurice et	Advantages: 1) Easy to apply and easy to construct; 2) the results of the force fit the experiment well.	Valid at large slip variations. The results of self-align moment vs.	Used to analysis the transient tire behavior	The relaxation length is introduced for model construction, easy to	The parameters are determined from estimation

Table 1 (cont).

al., 1999)	Disadvantage: 1) The results of self-align moment vs. slip don't match well with the experimental data; 2) the model can't be used at high frequency situations.	slip don't match well with the experimental data.		construct the model	equations.
TMeasy Tire Model (Hirschberg and Weinfurter, 2002)	Advantages: 1) Easy to Construct and apply; 2) efficient; 3) high accuracy at applicable region. Disadvantages: 1) Restrict to pure slip case; 2) only apply to certain types of tire; 3) difficult to predict tire behavior beyond the experimental range.	High accuracy within applicable range	1) Can be used when some data is missing; 2) only valid for pure slip steady state case	The model is constructed based on experiment tests	10 parameters are identified through experiments, and each of them has actual physical interpretations
CF-SAT System Model (Miyashita and Kabe, 2005)	Advantages: 1) Easy to construct; 2) can be applied for tire design and vehicle cornering simulations. Disadvantages: Limited to the side slip angle case.	Fit the experimental data at valid range	An analytical model for cornering force and self-aligning torque. Can be used for tire design and vehicle dynamic simulation	Based on Fiala's Model, easy to construct	The parameters are determined by least-square fit of the measured data.
Semiphysical Tire Model (Gim et al., 2005)	Advantages: 1) First includes transient steer effect; 2) wide range of application. Disadvantages: Doesn't apply at short wavelength road conditions.	Matches the experimental data well at steady state case	This model can be used at both steady state and transient state case, especially, it models the transient steer effect	Easy to construct	All the parameters are determined from experiments
Velenis's Friction Model (Velenis, 2005)	Advantages: Can be used for control design Disadvantages: 1) doesn't consider the camber, normal load distribution and belt deflection, and so on; 2) the results only fit for steady state case.	Accurate at steady state slip case	Can be used for control and on-line estimation	Based on LuGre's friction model, can be extended to longitudinal/lateral case.	Parameters are determined by the comparison between the steady state tire model and the existing tire model
Semi-Empirical Tire Model (Svendenius and Gafvert, 2006)	Advantages: 1) Easy to apply and construct; 2) wide range of application; 3) analyze the coupling between lateral and longitudinal dynamics. Disadvantages: Can't be used for short wavelength road conditions.	Accurate in steady-state situation due to semi-empirical approach.	Can be used in combination of combined slip, camber angle and velocity dependence in both steady and transient conditions	Easy to construct and apply	Only 6 parameters need to be determined
PAC2002 Tire Model (Kuiper and Oosten, 2007)	Advantages: 1) The inputs are extended with turn slip; 2) can be used for both steady state and transient state case; 3) wide range of application.	Valid up to 12 Hz	Can be used to analysis various vehicle handling behavior such as parking, low speed application, variation of friction properties and ABS braking	Belongs to Magic Formula type tire model group.	The parameters are determined from experiments.
Ph.An.Ty.M. H.A Tire model (Capone et al., 2009)	Advantages: An analytical model with low computation load. Disadvantages: The lateral and longitudinal forces are not given in this paper.	Accurate at steady state case	Used to predict the normal tire-road interaction	The model is built based on the equilibrium condition and the geometrical relations.	The parameters in this model are physical and geometrical, and can be measured directly.

Tire Models for Ride Comfort Analysis

In this section, various tire models suitable for ride comfort analysis are reviewed and the comparison is shown in [Table 2](#). Ride comfort tire models should be able to accurately capture the tire/road interactions that are the major contributing factors to human perception about vehicle ride comfort. The key point

for ride comfort analysis is to locate the idealized contact point and to properly describe the tire filtering properties ([Reinalter et al., 2007](#)). In general, driver/passenger ride comfort is dominantly associated with the vehicle pitch plane motion. Thus, 2D (In-plane) tire models are sufficient for ride comfort analysis.