

Development of a Parameter Identification Method for MF-Tyre/MF-Swift Applied to Parking and Low Speed Manoeuvres

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ABSTRACT

A vehicle parking manoeuvre is characterized by low or zero speed, small turning radius and large yaw velocity of the steered wheels. To predict the forces and moments generated by a wheel under these conditions, the Pacejka Magic Formula model has been extended to incorporate the effect of spin (turn slip model) in the past years. The extensions have been further developed and incorporated in the MFTyre/MF-Swift 6.2 model. This paper describes the development of a method for the identification of the turn slip parameters. Based on the operating conditions of a typical parking manoeuvre, the dominant parameters of the turn slip model are firstly defined. At an indoor test facility, the response of a tyre under the identified operating conditions is measured. An algorithm is developed to identify the dominant turn slip parameters from the measured responses. Wherever possible, the algorithm is based on direct analytical relationships between the turn slip model parameters and the measured signals, otherwise an iterative method is applied. By means of comparing vehicle simulation results to instrumented vehicle measurements, the turn slip model, including the identified parameters, is validated. The results show the effectiveness of the developed method.

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INTRODUCTION

The development and validation of advanced driver assistance systems (ADAS) is nowadays performed based on computer aided engineering (CAE). CAE relies on computer models that predict the response of the involved systems under certain operating conditions. For the development of electric power steering systems and parking assist systems, it is important to have an accurate prediction of the forces and moments generated by the tyres when the spin, the side slip angle and the longitudinal slip change with time and the longitudinal vehicle speed is low or zero. In this context, the Pacejka Magic Formula model has been extended to incorporate the effect of spin (turn slip model) [1]. The extensions have been further developed and incorporated in the MF-Tyre/MF-Swift-6.2 model [2].

The extensions of the model can be summarized as follows:

- Adaptations of the Magic Formula (MF) equations that describe the forces and moments generated by a rolling tyre, by introduction of the spin as an input quantity [1].

- Introduction of a model that can predict the aligning moment generated by a tyre in standstill conditions [1], the Van der Jagt model [3] is used as a basis.
- Introduction of a transition model that, as function of the forward speed, can smoothly switch between the rolling tyre model and the standstill model [1].

Because of the unavailability of suitable test facilities, only a reduced set of parameters can be directly identified. The parameters related to the standstill model can be identified based on measured data; the MF spin parameters related to the rolling tyre have until now been set to the default values as suggested in [1]. To validate the turn slip model with the reduced set of identified parameters, a test vehicle, equipped with sensors to measure the forces and moments on the wheels, has been used in [4]. Both standstill and low speed manoeuvres have been conducted; the results show that the turn slip model, with a reduced set of identified parameters, can qualitatively predict the aligning moment and lateral force generated by a tyre during a typical parking manoeuvre.

In this study, a method for a complete identification of the turn slip parameters for both the standstill and rolling tyre is developed. This is accomplished with the following steps:

- definition of the operating conditions of a typical parking manoeuvre;
- determination of the dominant turn slip model parameters for the given operating conditions;
- identification of the parameters based on experimental data acquired on a Flat-Trac test rig;
- validation of the parameterized model based on experimental data acquired on a test vehicle.

After this introduction, firstly the turn slip theory is reviewed. A discussion follows over the operating conditions and dominant parameters during a typical parking manoeuvre. Next, a description of the conducted experiments and the results of the identification of the turn slip parameters is given. Subsequently, validation results of the identified parameters are shown and discussed. Finally, the conclusions of this study are summarized and recommendations for future work are given.

REVIEW OF THE TURN SLIP THEORY

The MF-Tyre/MF-Swift model is based on the well-known Magic Formula model [1] that describes the steady-state force and moment response of a tyre subjected to pure and combined slip conditions, rolling at a given speed, inclination (camber) angle and vertical load (steady-state slip model). To take into account the transient behaviour of the tyre, the flexibility and damping of the tyre carcass (carcass model) and the relaxation behaviour of the contact patch (contact patch slip model) are accounted for to determine the input quantities (slips) for the steady-state slip model.

The turn slip functionality introduced in the MF-Tyre/MF-Swift model consists of extensions of the Magic Formula model, a contact patch slip model that describes the relaxation behaviour of the turn slip in the contact patch, a standstill model that predicts the aligning moment of the tyre subjected to a large steering angle in standstill conditions and finally a speed transition model that can gradually switch between the rolling and the standstill conditions. An overview of these extensions is given in this section; for simplicity, mainly the calculation of the aligning moment is considered. For the complete description of the theory, it is referred to the original work of Pacejka [1].

Steady-State Slip Model

The tyre spin is defined as follows:

$$\varphi = -\frac{1}{v_c}(\dot{\psi} - (1 - \varepsilon_\gamma)\Omega \sin\gamma) = \varphi_t + \varphi_c \quad (1)$$

where Ω is the rotational velocity of the wheel around its spin axis, γ is the inclination angle and ε_γ is the camber reduction factor for the camber to become comparable with turn slip. The contribution of wheel yaw rate to spin ($-\frac{\dot{\psi}}{v_c}$) is described by the component φ_t (turn slip), the contribution of camber to spin is described by the component φ_c .

The general form of the Magic Formula (MF) is used to describe the aligning moment that is generated by a tyre under the effect of spin:

$$M_z = D \sin \left(C \operatorname{atan} \left(BR_0 \varphi - E \left(BR_0 \varphi - \operatorname{atan}(BR_0 \varphi) \right) \right) \right) \quad (2)$$

The product of the coefficients $BCDR_0 = \left. \frac{\partial M_z}{\partial \varphi} \right|_{\varphi=0}$ describes the aligning moment stiffness against spin; this quantity can be calculated from the aligning moment stiffness against camber:

$$C_{M\varphi} = \frac{R_0}{1 - \varepsilon_\gamma} C_{M\gamma} \quad (3)$$

where R_0 is the free tyre radius.

The same applies for the lateral force characterized by the following stiffness against spin:

$$C_{F\varphi} = \frac{R_0}{1 - \varepsilon_\gamma} C_{F\gamma} \quad (4)$$

Figure 1 depicts qualitatively the normalized aligning moment M_{zn} as calculated by Equation (2) and the normalised lateral force F_{yn} , as a function of the normalized spin. The spin is normalized by the half contact patch length a , producing the unit-less quantity $a\varphi$. The aligning moment and the lateral force are respectively normalized by their peak quantities.

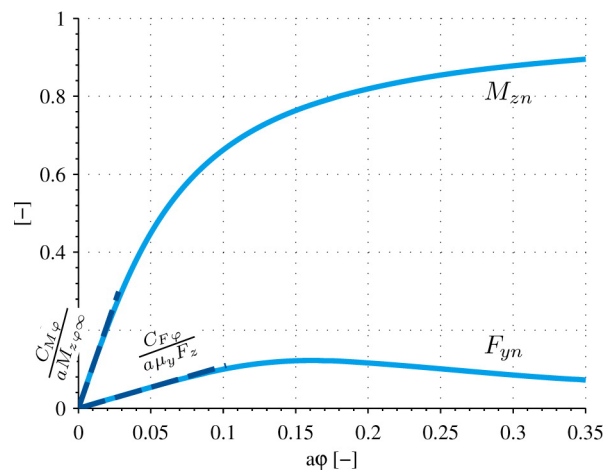


Figure 1. Normalised aligning moment and lateral force as function of the turn slip in steady-state rolling conditions

Interactions between turn slip, longitudinal slip and side slip are modelled by the weighting functions: ζ_1 , ζ_2 , ζ_3 , ζ_5 , and ζ_6 [1]. These functions are all defined in the cosine MF form:

$$\zeta_i = \cos(\text{atan}(f_i(R_0\varphi))) \quad (5)$$

where f_i is a monotonically increasing function. For example, ζ_3 is the reduction factor of the cornering stiffness when turn slip occurs:

$$\begin{cases} \zeta_3 = \cos(\text{atan}(p_{Ky\varphi_1} R_0^2 \varphi^2)) \\ C_{Fy} = C_{Fy0} \cdot \zeta_3 \end{cases} \quad (6)$$

Carcass Model

The yaw velocity of the contact patch is calculated by equilibrating the yaw moments applied to the contact patch. The yaw stiffness c_ψ , damping k_ψ and deflection angle β of the tyre carcass determine this equilibrium:

$$\dot{\beta} \cdot k_\psi + \beta \cdot c_\psi = M_z \quad (7)$$

The carcass deflection angle is the difference between the contact patch ψ_c and wheel yaw angle ψ , i.e. $\beta = \psi_c - \psi$. M_z is the aligning moment of the contact patch due to slip. Note that in Equation (7) the yaw inertia moment of the contact patch is neglected.

Contact Patch Slip Model

The relaxation behaviour of the contact patch takes into account that a certain distance (relaxation length) must be travelled before the contact patch can respond to a variation of the spin. Note that, at a given speed, the turn slip is proportional to the contact patch yaw velocity: $\varphi_{ct} = -\frac{\dot{\psi}_c}{V_c}$.

According to Pacejka [1], the relaxation behaviour of the contact patch can be decomposed into the concurrent effects of the contact patch length and of the tread width. A step response of the effect of the contact patch length is characterized by an initial slope that, after having reached a peak, asymptotically approaches zero; such behaviour can be modelled by subtracting two first-order responses ($\varphi'_1 - \varphi'_2$), each asymptotically leading to the same level but starting with different slopes. The difference ($\varphi'_1 - \varphi'_2$) is proportional to the deflection angle of the tread due to transient spin. In order to also account for the tread width in the transient response of the aligning moment due to spin, a first-order response characterized by the relaxation length σ_c is further introduced (φ'_c).

The transient slip quantity φ'_M is defined as:

$$\varphi'_M = \varepsilon_\varphi^* \varphi'_c + \varepsilon_{\varphi 12} (\varphi'_1 - \varphi'_2) \quad (8)$$

Parameter ε_φ^* accounts for the effect of the tread width, whereas $\varepsilon_{\varphi 12}$ accounts for the contact length. φ'_M is the transient spin that is used as input for the steady-state slip model to calculate the aligning moment in dynamic conditions.

The three turn slip states φ'_c , φ'_1 and φ'_2 are calculated by the following three first-order differential equations:

$$\begin{cases} \sigma_c \dot{\varphi}'_c + |V_c| \varphi'_c = -\dot{\psi}_c \\ \sigma_{\varphi 1} \dot{\varphi}'_1 + |V_c| \varphi'_1 = -\dot{\psi}_c \\ \sigma_{\varphi 2} \dot{\varphi}'_2 + |V_c| \varphi'_2 = -\dot{\psi}_c \end{cases} \quad (9)$$

Non-Rolling Tyre Model

The model described in the preceding sections can deal with both the situation of a rolling and a non-rolling tyre. In case of a non-rolling tyre, it reduces to a torsional spring with stiffness $C_{M\psi}$. This is valid as long as the contact patch is mainly in adhesion, i.e. for small yaw angles of the wheel. When a larger yaw angle is applied, sliding becomes important and the M_z response becomes nonlinear up to the moment of full sliding, i.e. friction limit. In that case, a more adequate model must be used. Experimental evidence shows that the Van der Jagt model [3] is suitable for this application. The model consists of the following equations:

$$\begin{cases} \dot{\beta} = -\left(1 - p \left| \frac{M_z}{M_{z\varphi\infty}} \right|^{c_0}\right) \dot{\psi} \\ M_z = C_{M\psi} \beta \\ \text{if } (\text{sign}(\beta) \neq -\text{sign}(\dot{\psi})) \text{ } p = 0 \text{ else } p = 1 \end{cases} \quad (10)$$

From this model, the gradient of the aligning moment when $p = 0$ or $M_z = 0$ reads:

$$\left. \frac{\partial M_z}{\partial \psi} \right|_{p=0} = -C_{M\psi} \quad (11)$$

For large values of the yaw angle, the moment equals:

$$M_z|_{\psi \rightarrow \pm\infty} = \mp M_{z\varphi\infty} \quad (12)$$

Equation (11) and Equation (12) state that, for small values of the yaw angle the response is that of a torsional spring, for large values of the yaw angle the aligning moment tends to the maximum value that can be achieved when full sliding occurs. Between these two situations, there is a transition controlled by the parameter c_0 .

Figure 2 depicts the normalized aligning moment calculated from Equation (10). The aligning moment and yaw angle are respectively normalized by their peak values.

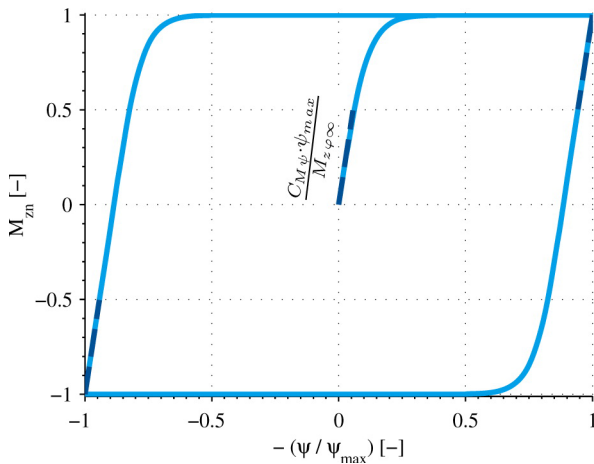


Figure 2. Normalised aligning moment as function of the yaw angle for a non-rolling tyre

Speed Transition Model

To assure a gradual transition between the rolling and non-rolling tyre models, a weighting function is applied to the moment response:

$$M_z = w_{vlow} M_{z,non-roll} + (1 - w_{vlow}) M_{z,roll} \quad (13)$$

Where $M_{z,roll}$ is the aligning moment in rolling conditions (Steady-state slip model), $M_{z,non-roll}$ is the aligning moment in non-rolling conditions (Non-rolling tyre model).

The coefficient w_{vlow} is defined as:

$$\begin{cases} w_{vlow} = \frac{1}{2} \left(1 + \cos \left(\pi \frac{V_x}{V_{low}} \right) \right) \\ \text{if } |V_x| < V_{low} \text{ else } w_{vlow} = 0 \end{cases} \quad (14)$$

OPERATING CONDITIONS OF A PARKING MANOEUVRE

Typically, a parking manoeuvre consists of braking a vehicle to a standstill, starting from a standstill and driving at a low speed (in both forward and backward directions), steering the wheels up to large steering angles when the vehicle is at a standstill as well as during driving. Because the longitudinal speed is low, the lateral acceleration is also low; in this study it is further assumed that also the longitudinal acceleration is low (a driver accelerates and brakes in a gentle manner during a parking manoeuvre).

Because the accelerations are low, the vertical load on the tyres is close to the value determined in static conditions, the longitudinal tyre slip is close to zero and the side slip angle of the tyres is close to the toe angle. The toe angle and camber angle are a function of the steering angle and depend on the suspension and steering system design. The test vehicle used for the experiments in this study shows approximately a vertical load in the range [3000, 4000] N, a camber angle in the range [-5, 5] deg and a toe angle in the range [-2.5, 2.5] deg.

The turn slip during a parking manoeuvre is a function of the vehicle motion. Because the longitudinal slip and side slip angle are small, the vehicle motion is calculated with a bicycle model based on kinematic relationships. The maximum steering angle that the inner steering wheel of the test vehicle can achieve (30 deg) is used as input signal. The model is depicted in Figure 3.

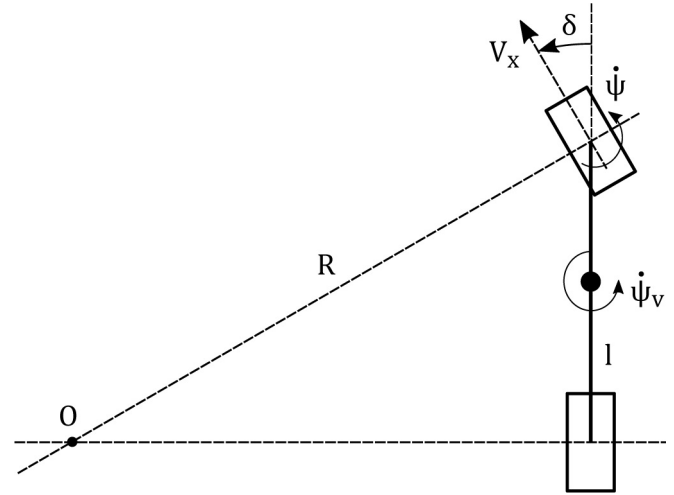


Figure 3. Bicycle model used to derive kinematic relationships for the turn slip model input quantities

The vehicle model input quantities (V_x and δ) are sufficient to define the vehicle motion. The vehicle yaw rate reads:

$$\dot{\psi}_v = \frac{V_x \sin \delta}{l} \quad (15)$$

where the value of $l = 2.5$ m is used for the wheel base; it corresponds to the value of a typical compact car. The yaw rate of the front (steered) wheel is the sum of the yaw rate of the vehicle and the steering rate:

$$\dot{\psi} = \dot{\psi}_v + \dot{\delta} = \frac{V_x \sin \delta}{l} + \dot{\delta} \quad (16)$$

Considering that the side slip angle equals zero, the tyre contact patch velocity equals the velocity V_x , i.e. $V_c = V_x$. The turn slip corresponds therefore to:

$$\varphi_t = -\frac{\dot{\psi}}{V_x} \quad (17)$$

To determine the operating conditions for the turn slip model, a reference parking manoeuvre is specified. The vehicle model input signals (V_x and δ) and the turn slip model input signals ($\dot{\psi}$ and φ_t) of the reference manoeuvre are depicted in Figure 4.

The reference manoeuvre contains typical input conditions that occur during a parking manoeuvre: stay at a standstill (time interval [0, 2] s), steer standstill (time interval [2, 4] s), drive-off during steering (time interval [4, 6] s), steer at constant speed (time interval [6, 7] s), and drive in a circular turn (time interval [7, 10] s).