

Using Objective Vehicle-Handling Metrics for Tire Performance Evaluation and Selection

Srikanth Sivaramakrishnan and Saied Taheri
Virginia Tech

ABSTRACT

This paper outlines the development of a simulation-based process for assessing the handling performance of a given set of tires on a specific vehicle. Based on force and moment data, a Pacejka tire model was developed for each of the five sets of tires used in this study. To begin with, simple handling metrics including under-steer gradient were calculated using cornering stiffness derived from the Pacejka model. This Pacejka tire model was subsequently combined with a 3DOF non-linear vehicle model to create a simulation model in MATLAB/Simulink®. Other handling metrics were calculated based on simulation results to step and sinusoidal (GM) steering inputs. Calculated performance metrics include yaw velocity overshoot, yaw velocity response time, lateral acceleration response time and steering sensitivity. In addition to this, the phase lag in lateral acceleration and yaw rate of the vehicle to a sinusoidal steering input were also calculated. Axle characteristics derived from the Pacejka models were used to plot handling diagrams for multiple sets of tires to gain greater insight into the effect of the given set of tires on the vehicle's handling performance.

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INTRODUCTION

Tires play an extremely important role in deciding the handling characteristics of a vehicle as they transmit reaction forces from the ground to the vehicle. The handling performance of any given vehicle will vary depending on the tires used. Hence, the handling characteristics of a vehicle are evaluated for multiple sets of tires and the most desirable set is selected. Various methods developed and used for vehicle handling evaluation can be broadly classified into subjective and objective. While subjective evaluation involves an expert driver who evaluates the handling performance of the tire solely based on his experience, objective testing involves instrumenting a vehicle, measuring the response due to various steering inputs (step, sinusoid, etc.) and assessing the response by processing the collected data to calculate quantifiable performance metrics.

Some of the earliest definitive studies in this area of research have been done by Norman [1] where the focus was towards defining measurable parameters that would assist in the evaluation of on-center handling performance. Following this, a new approach was presented by Mimuro [2] which involve the use of rhombus plots using four objective parameters to evaluate the overall handling performance of the vehicle and not just on-center handling performance. Following this, studies by D.A. Crolla [3],[4] and [5] were

mainly focused towards extracting more experimentally-derived objective metrics that would evaluate the vehicle. One major setback in these methods is that even through the metrics are objective in nature, there is a high level of dependence on experimental testing to obtain them as simulation models for tires and vehicles were not used to obtain them.

With the availability of high-performance computing hardware and accurate simulation models for the vehicle dynamics and tire models for predicting forces, it is possible to extract more objective parameters that would assist specifically towards understand the effect of different sets of tires on handling performance without investing valuable time and money on resources for gathering large amounts of experimental data. The biggest advantage of a simulation-based approach to objective evaluation is that it can serve as a quick and efficient way to predict the performance of a tire in a vehicle during the development phase. This method will help towards significantly reducing the number of tires sent for subjective evaluation and will eventually reduce the dependence on expensive test equipment to improve product development timeframes for both automotive OEMs and tire manufacturers.

MATHEMATICAL MODELING

The mathematical model of the vehicle used in this study has three major parts - the vehicle dynamics model, the tire model and the steering system model.

Assumptions

The following assumptions were made while constructing the vehicle model

1. The vehicle is assumed to be moving at a constant longitudinal velocity.
2. There are no longitudinal forces (F_x) acting on the vehicle, and hence there is no slip ratio (κ).
3. The slip angle (α) is assumed to be the same for both of the wheels on an axle.
4. Additional compliance effects are neglected while calculating the slip angle at the axles.
5. The vehicle roll center is assumed to be situated at half the height of the center of gravity of the vehicle from the ground.
6. The roll centers for the left and right suspensions are assumed to be at equal height.
7. The vehicle is assumed to be moving on a high-mu surface of friction coefficient 0.9.
8. All maneuvers are chosen such that the forces from the tire model can be assumed to be in steady state.

Vehicle Dynamics Model

For the purpose of analyzing the time response of the vehicle, a non-linear dynamic model with yaw rate (r), lateral velocity (v) and roll angle (ϕ) as the 3 degrees of freedom was used. These equations of motion, based on the given set of assumptions were derived using the Lagrangian method. Further explanation of the derivation of the equations of motion for the dynamics of the vehicle and their validity for simulation studies has been provided in [6].

The three equations of motion of the vehicle are given by:

$$\begin{aligned}\dot{v} &= \frac{(I_x + mh^2)(F_{y1} + F_{y2}) + mhK_\phi\phi - gh^2m^2\phi + mhC_\phi\dot{\phi}}{I_x m} + \dots \\ &\dots + \frac{mh(I_x - I_y)\phi r^2 - I_x mru}{I_x m} \\ \dot{r} &= \frac{aF_{y1} - bF_{y2} + M_{z1} + M_{z2} - 2(I_y + mh^2)\phi\dot{\phi}r - mh\phi rv}{I_z + (I_y + mh^2)\phi^2} \\ \ddot{\phi} &= \frac{-(F_{y1} + F_{y2})h - K_\phi\phi + mgh\phi - C_\phi\dot{\phi} + I_y\phi r^2}{I_x}\end{aligned}$$

Slip Angles

The slip angles at the front and rear axles are calculated as:

$$\begin{aligned}\alpha_1 &= \delta_f - \frac{v + ar}{u} \\ \alpha_2 &= -\frac{v - br}{u}\end{aligned}$$

Where δ_f is the steering angle at the front wheel

Lateral Weight Transfer

The static vertical loads at the individual axles are calculated as:

$$\begin{aligned}F_{z1} &= mg \frac{l-a}{l} \\ F_{z2} &= mg \frac{l-b}{l}\end{aligned}$$

The total lateral weight transfer at the axle is the sum of rolling and non-rolling weight transfer and is given by:

$$\begin{aligned}\Delta F_{z1} &= \frac{h'ma_y}{t_f} \left(\frac{K_{\phi1}}{K_{\phi1} + K_{\phi2}} \right) + \frac{h_1 m_f}{t_f} a_y \\ \Delta F_{z2} &= \frac{h'ma_y}{t_r} \left(\frac{K_{\phi2}}{K_{\phi1} + K_{\phi2}} \right) + \frac{h_2 m_r}{t_r} a_y\end{aligned}$$

Where the lateral acceleration is calculated as:

$$a_y = \dot{v} + ur$$

Tire Model

The type of model to be used for the simulation is decided based on the type of analysis required. Each model has its own simplifications and specific use.

Linear Model

In the linear model, the cornering force from the tires is assumed to be directly proportional to the slip angle where the cornering stiffness (C_{Fa}) is the proportional factor. This is used during linear analysis to calculate the understeer gradient. The cornering stiffness at each axle is calculated from the Force-Slip curve generated from the tires as:

$$C_{Fa} = \left. \frac{dF_y}{d\alpha} \right|_{\alpha=0}$$

Pacejka's Magic Formula

Pacejka's Magic Formula is a non-linear, semi-empirical mathematical model for calculating the lateral forces and aligning moments on the tire. This model was originally developed by H.B.Pacejka [7] based on multiple sets of experimental data. Further explanation of this tire model and its experimental validation is provided in [6]. A steady-state model for predicting the lateral forces of the tire was chosen

for this study because of the steering maneuvers involved in the simulations that vary at a slower rate and the transient response of the tire in this case would not have a noticeable effect on the overall performance metrics being extracted from the simulated response of the vehicle.

The coefficients of the magic formula are calculated based on the force and moment data obtained through experiments for 5 sets of tires. The main motivation for choosing this set is that these tires are similar to each other with slightly varying constructions and subjective handling data was available for all of them. Table 1 lists the codes for the tires used in this study. Since tire information is highly proprietary, other details were not provided by the manufacturer. In this study, we objectively evaluate the performance of each tire in the vehicle without the knowledge of specific information that would identify the tire.

Table 1. Tire information

Tire No.	Tire Code
1	P225/60R16
2	P225/55R16
3	205/55R16
4	205/55R16
5	225/45R17

The formulae used for calculating the lateral forces from the tire are given by:

$$\alpha_y = \alpha + S_{hy}$$

$$C_y = a_0$$

$$D_y = (a_1 F_z^2 + a_1 F_z) (1 - a_{15} \gamma^2)$$

$$E_y = (a_6 F_z + a_7) (1 - (a_{16} \gamma + a_{17}) \text{sign}(\alpha_y))$$

$$K_y = a_3 \sin \left(2 \arctan \left(\frac{F_z}{a_4} \right) \right) (1 - a_5 \gamma)$$

$$B_y = \frac{K_y}{C_y D_y}$$

$$S_{hy} = a_8 F_z + a_9 + a_{10} \gamma$$

$$S_{vy} = a_{11} F_z + a_{12} + (a_{13} F_z + a_{14}) F_z \gamma$$

$$F_y = D_y \sin \left(C_y \arctan \left(B_y \alpha_y - E_y \left(B_y \alpha_y - \arctan(B_y \alpha_y) \right) \right) \right) + S_{vy}$$

The generated lateral force versus slip angle curves for the given five sets of tires based on the calculated Pacejka coefficients are shown in Figure 1.

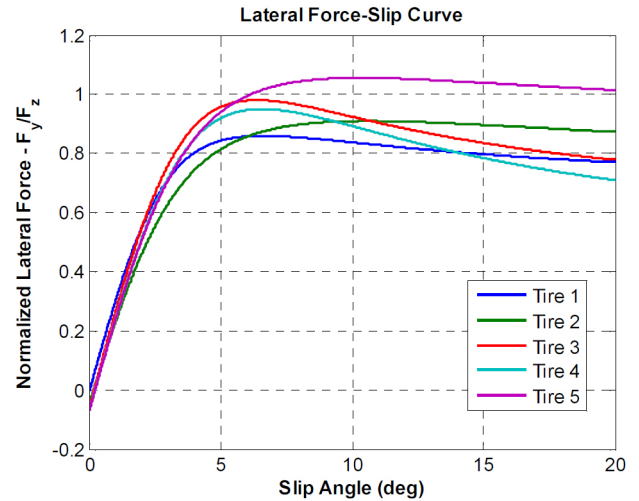


Figure 1. Lateral force characteristics of the given 5 tires

The aligning moments from the tire are calculated using the following expressions:

$$\alpha_t = \alpha + S_{ht}$$

$$C_t = c_0$$

$$D_t = (c_1 F_z^2 + c_2 F_z) (1 - c_{18} \gamma^2)$$

$$E_t = (c_7 F_z^2 + c_8 F_z + c_9) (1 - (c_{19} \gamma + c_{20}) \text{sign}(\alpha_t)) / (1 - c_{10} |\gamma|)$$

$$K_t = (c_3 F_z^2 + c_4 F_z) \exp(-c_5 F_z) (1 - c_6 |\gamma|)$$

$$B_t = \frac{K_t}{C_t D_t}$$

$$S_{ht} = c_{11} F_z + c_{12} + c_{13} \gamma$$

$$S_{vt} = c_{14} F_z + c_{15} + (c_{16} F_z + c_{17}) F_z \gamma$$

$$M_z = D_t \sin \left(C_t \arctan \left(B_t \alpha_t - E_t \left(B_t \alpha_t - \arctan(B_t \alpha_t) \right) \right) \right) + S_{vt}$$

The generated aligning moment versus slip angle curves for the given five sets of tires at the front axle based on the calculated Pacejka coefficients are shown in Figure 2.