Introduction

Using wheel force transducers can be a useful way to generate tire data. Traditional laboratory tire testing characterizes the tire when running on the surface used in the laboratory – typically a sandpaper-like surface. The interaction between the tire contact patch and the road surface ultimately determines all of the force and moment response. The different road surface used in the laboratory has a potentially large effect on the tire behavior. This isn't to say that using wheel force transducers to generate tire data is the perfect solution – the condition that the tire experiences isn't tightly controlled like it is in a lab, and there is often more measurement noise on a track than in a lab – but using wheel force transducers can be another tool in the arsenal of tire and vehicle dynamics professionals.

Instrumentation

To parameterize a tire model, there are several measurements that need to be made. The wheel forces need to be measured, the slip angle at the tire needs to be measured, and the inclination angle of the tire needs to be measured.

The wheel forces can be measured using a wheel force transducer such as the Kister RoaDyn wheels (see Figure 1). The wheel force transducer makes direct measurements of the lateral and vertical forces seen by the wheel.

The slip angle measurements are a little bit more complex. The slip angle needs to be transformed from the point at which it is measured to the center of the tire. The slip angle is based on the lateral and longitudinal speed at a given point. As the vehicle turns, the lateral and longitudinal speed is different at different points on the car. If the lateral and longitudinal speed is measured at point "A" and needs to be transformed to point "B," the following relationship can be used:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix}_B = \begin{bmatrix} V_x \\ V_y \end{bmatrix}_A + \begin{bmatrix} -x \cdot r \\ y \cdot r \end{bmatrix} \qquad (1)$$

Where x and y represent the distance along the x- and y-axes from point A to B respectively. r indicates the yaw-rate of the vehicle. These quantities can be measured in two ways: with an optical sensor like the Corrsys-Datron SHR sensor (Figure 2), or with an inertial platform like the GeneSys ADMA (Figure 3). If an optical sensor is used, an additional yaw-rate sensor must be used as well (inertial platforms include a yaw-rate sensor). The slip angle at the wheel can also be measured with an optical slip angle sensor mounted to the upright assembly. In this case, the gyro needs to be mounted on the upright as well in order to measure the yaw rate of the vehicle plus the steering rate. In order to get the slip angle at the wheel when the slip angle measurement is made with reference to the body, the steered angle and toe angle must be included. The following equation can be used to find the slip angle, α. The term δ is the total steered angle and includes the toe angle.

$$\alpha = \mathrm{ARCTAN}\,(\,V_y \,/\, V_x\,) - \delta$$

The steered angle can be measured with a wheel vector system like the Corrsys-Datron RV4 (Figure 4). This sensor can also be used to measure the camber angle relative to the body. If the roll angle of the body relative to the ground is added to this, then the inclination angle of the tire can be found. The roll angle can be measured with laser ride height sensors like the Corrsys-Datron HF500 sensor (Figure 5). Alternatively, the inclination angle can be measured with a Corrsys-Datron Dynamic Camber Sensor. This sensor uses two height sensors mounted to the upright assembly to measure the inclination angle with respect to the ground.

Figure 1: A wheel force transducer

Figure 2: Corrsys-Datron SHR optical slip angle sensor

Figure 3: GeneSys ADMA inertial platform

Figure 4: Corrsys-Datron RV4 wheel vector system

Figure 5: Corrsys-Datron HF500 height sensor

Tire Models

Accurate representations of tire behavior is a very important part of any handling simulation. Tire behavior can be specified to a simulation package in a number of ways. Most commonly, it is specified as either a lookup table or as a mathematical model. Even when a lookup table is used, it is quite common to fit a mathematical model first so that the lookup table can be populated with more values that were actually tested.

There are many types of mathematical tire models (or just "tire models") such as:

- Fiala
- Harty
- Pacejka Magic Formula
  (there are many versions)
- Brush, Treadsim, other physical models

Here, we'll be discussing mainly semi-empirical tire models like the Pacejka Magic Formula models. These models are essentially sophisticated curve fitting equations. There are a large number of coefficients in these equations that can be changed to fit the collected data: in the 2002 version of the Pacejka Magic Formula, there are 118 different coefficients.

In the Pacejka Magic Formula (version 2002 will be considered), the lateral force versus slip angle characteristics are modeled as one basic relationship which is modified by a large number of factors. The basic curve is modified for vertical load and for inclination angle (camber) in the pure lateral force equations. Both vertical load and inclination angle have a quadratic relationship with vertical load. In order to parameterize the model, we need three load and three camber angles.

Test Procedure

The models that we're trying to build are steady-state tire models. Because of this, we need to perform steady-state testing of the tire. The tire needs to be swept through the full range of slip angles. This can be done with a steady-state circular test, such as ISO 4138. The constant radius version of this test can be used, as can the constant velocity version. In the constant radius version of this test, the car is driven at low speed around a given radius and the speed is slowly increased until the lateral limit of the vehicle is reached. A sample speed trace and lateral acceleration trace for this type of test is shown in Figure 6. This figure shows that the test starts at about 10m/s velocity and ramps up to 23m/s. The corresponding lateral acceleration starts at 0m/s^2 and the test ends when the lateral acceleration is $-1.12m/s^2$. This test was run on a 50m radius skidpad.

During a steady-state circular test, the tire slip angle increases with the lateral acceleration. At the same time, the vertical load on the tires changes due to the weight transfer. This is shown in Figure 7. This figure shows that the slip angle for both front tires begins near 0° and increases to a peak of about 4.5°. The vertical load on the both tires starts at about 3500N. The inside tire decreases in vertical load to 1500N and the outside tire increases in load to 5500N.

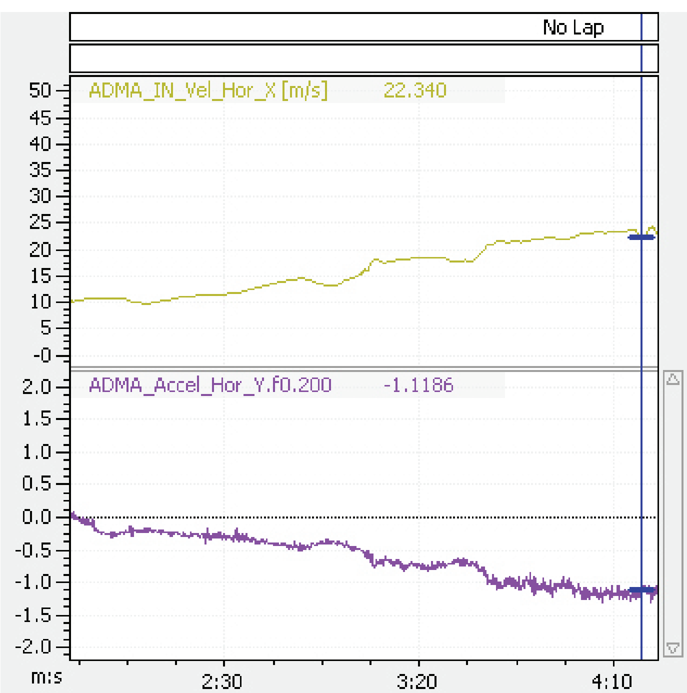

Figure 6: Speed [m/s] (top) and lateral acceleration [G] (bottom) for a constant-radius steady-state test

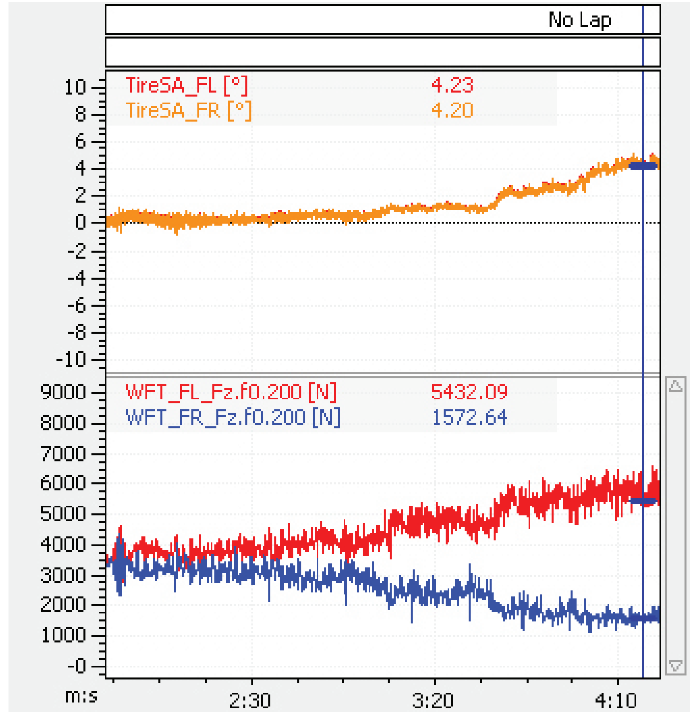

Figure 7: Slip angle (top) and vertical load (bottom) for the front tires during a steady-state circular test

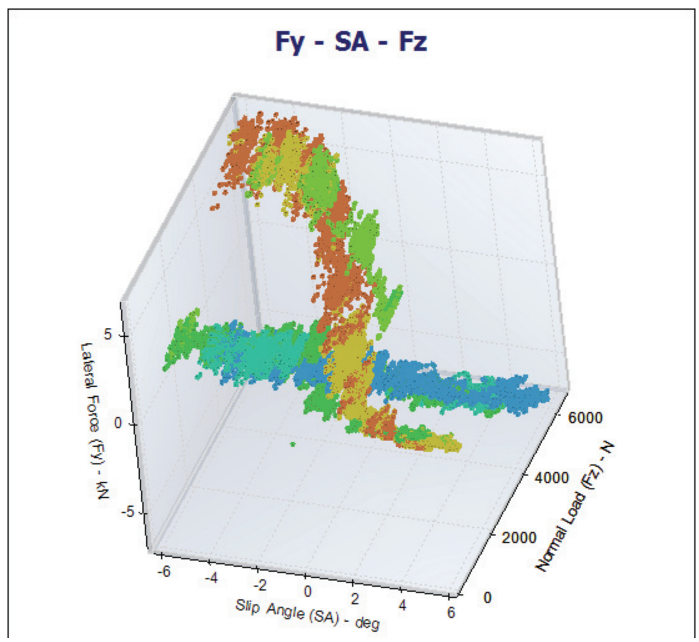

Figure 8: The relationship between the slip angle, normal (vertical) load and lateral force for a steady-state circular test. The data is colored by the inclination angle.

The lateral force generated by the tire is a function of the slip angle and the vertical load (in addition to other factors, like the inclination angle, which will be covered later). Figure 8 shows a 3d plot of slip angle vs. vertical load and lateral force. This data was collected for both turn directions. The second turn direction is required to obtain both signs of the slip angle.

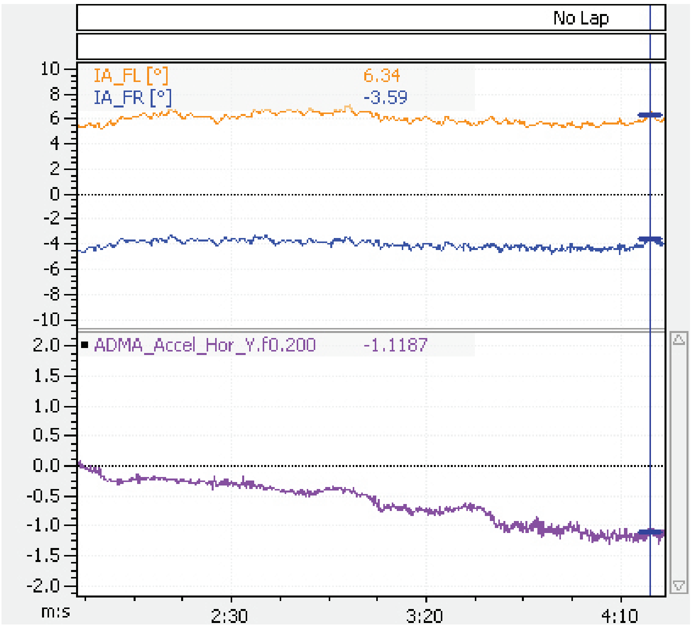

Figure 9: Inclination angle (top) and lateral acceleration (bottom) for a steady-state circular test

As noted earlier, the camber response is modeled with quadratic terms, so measurements at three camber angles is required. The inclination angle will change throughout a steady-state circular test because of body roll and suspension kinematics. Figure 9 shows how the inclination angle changes throughout the test. By running the test at three different static camber angles, three different inclination angle traces are generated. This allows for construction of a quadratic camber response.

Fitting a Tire Model

OptimumG's tire modeling tool, OptimumT, can be used to fit a tire model to wheel force transducer data. After importing the data using OptimumT's import wizard, OptimumT's fitting tool can be used to fit a steady-state tire model. The model (shown as a surface) fit using OptimumT is shown in Figure 10.

The fitting process in OptimumT has several different stages. These are:

- Choose a data file
- Choose the model to be fit
- Enter the user parameters
- Choose the coefficient boundaries
- Choose the error evaluation method
- Fit the model

The data file used is a composite of several different tests. The steadystate circular testing described in Chapter 2 was used. Three static camber angles were tested and tests were run in both turn directions. The actual test runs were identified in MoTeC i2 and the data from just these segments was exported as a CSV file and imported into OptimumT. Before exporting, the data was filtered using a moving-average filter with a window length of 0.2*s* and downsampled to 20*Hz*. A long filter was chosen because the data is nearly steady-state and hence has little actual high-frequency content. All high- and medium-frequency signal content is noise. The imported files were merged into a single data item in OptimumT.

For this project, a Pacejka 2002 model was chosen. With the data available, a pure Fy model was fit. Before the fitting process could begin, a reference vertical load needed to be chosen. This reference load, termed F_{z0} in the Pacejka model, is used to non-dimensionalize the forces. A value approximately equal to the static load was chosen.

Due to the limited data available, some of the coefficients must be set to zero. First of all, the *pEy* coefficients are set to zero to force symmetry. The *pHy2* is also set to zero. This coefficient controls how the horizontal shift is affected by the vertical load. Since zero slip angle data is only available at one load, the shift with load cannot be estimated with the wheel force transducer data. For the same reason, the *pV y2* coefficient is also set to zero as this coefficient controls how the vertical shift is affected by vertical load.

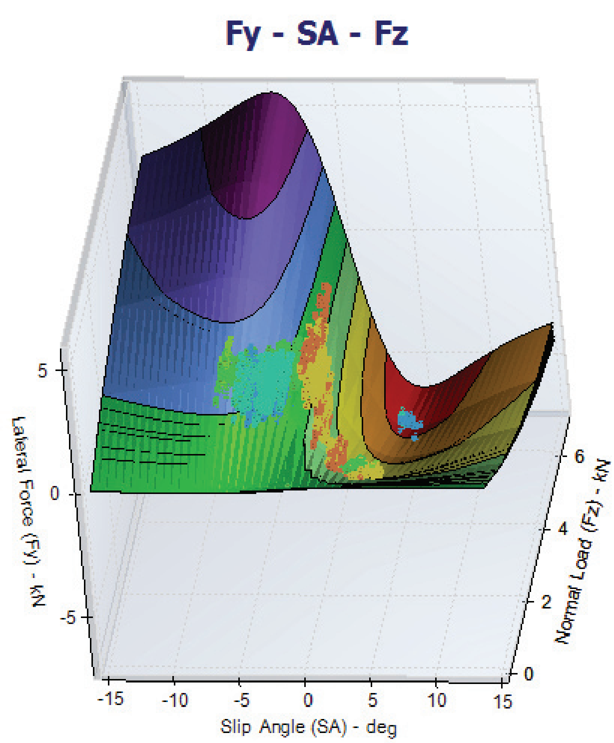

Figure 10: Data and the Pacejka 2002 model fit to the data. The model is shown as a surface and the data is shown as points. The data is colored by inclination angle.

OptimumT allows for four different error evaluation methods. The default error evaluation, the least squares method, is the preferred method for most situations. It was found that this method works best for wheel force transducer data.

Because of the large number of data points (about 22000 data points), the fitting process takes 2-3 minutes.

Tire Model Analysis

Once the tire model has been fit, some analysis of the tire behavior can be made. Simple graphs of lateral force versus slip angle (Figure 11) show much of the tire characteristics. From this graph, the peak lateral forces and their location can be read (these can also be found other ways). This graph shows the lateral force response at two different inclination angles as well. This tells us about the way in which the lateral force is influence by camber.

To gain a better understanding of how the tire operates, it is useful to look at some of the "advanced quantities" available in OptimumT. One example of this is the Instantaneous Cornering Stiffness, which is a measure of the sensitivity of the lateral force to changes in slip angle. Instantaneous Cornering Stiffness is defined as $(\delta F_y/\delta\alpha)$. At zero slip angle, it is identical to the Cornering Stiffness. The instantaneous cornering stiffness for the model fit to the wheel force transducer data is shown in Figure 12. This graph indicates that the tire rapidly looses its slip angle response as the slip angle moves away from zero degrees. Around 5°, the slip angle response is zero, indicating the lateral force peak.

Another "Advanced Quantity" that can be investigated is the Instantaneous Camber Stiffness. Similar to the instantaneous cornering stiffness, the instantaneous camber stiffness is defined as $(\delta F_y/\delta\alpha)$. Figure 13 shows this quantity plotted against the slip angle for three vertical loads. This graph indicates that the camber response is greater at higher loads (not surprisingly!) and that the camber response is highest at low slip angles. As the slip angle moves away from zero degrees, the camber response rapidly drops off. This means that the camber will have a large effect when the car is moving in a nearly straight line, but during hard cornering, changes in camber angle will have much less effect on the lateral force.

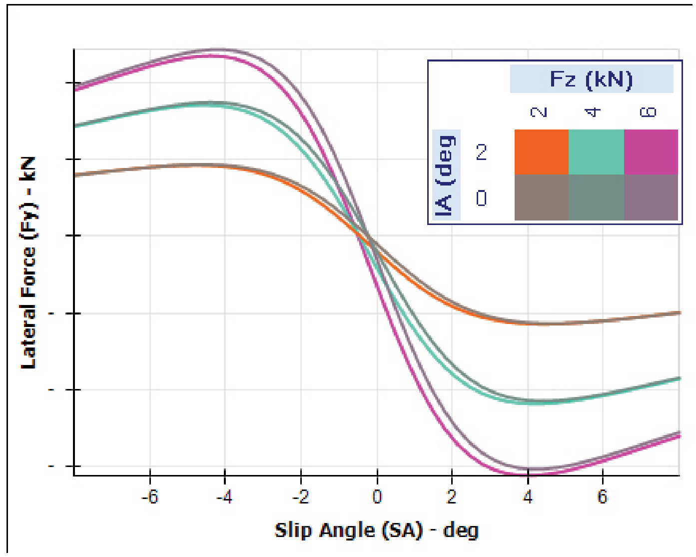

Figure 11: Lateral force characteristics of the tire model fit to wheel force transducer data

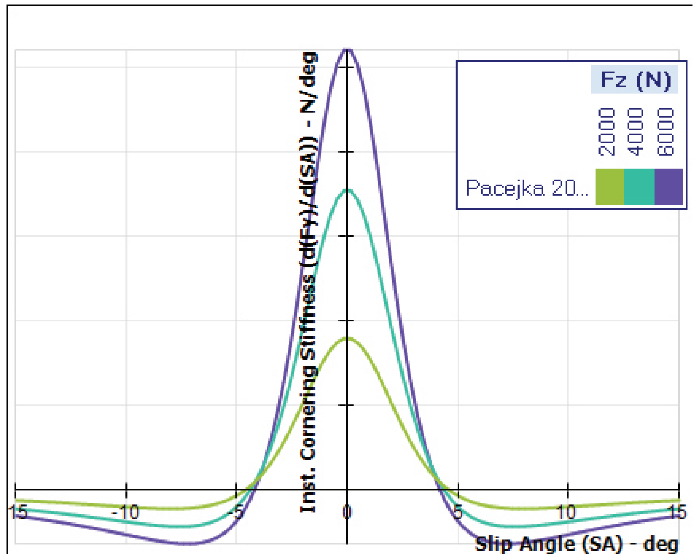

Figure 12: Instantaneous cornering stiffness $(\delta F_y/\delta\alpha)$

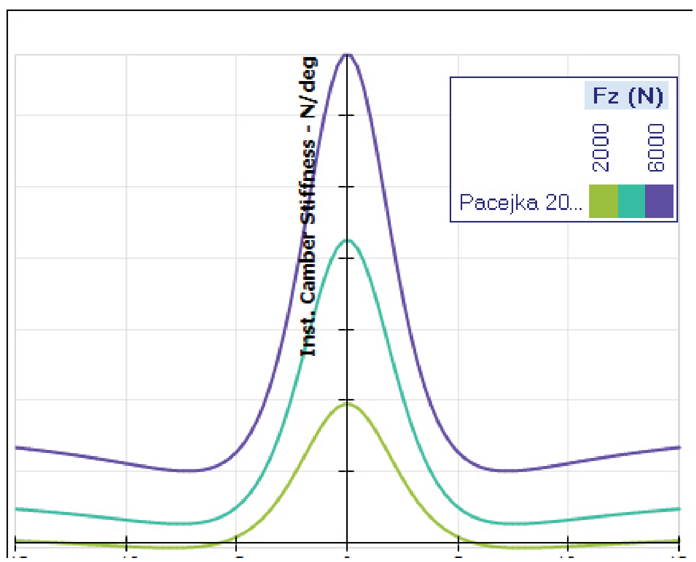

Figure 13: Instantaneous cornering stiffness $(\delta F_y/\delta\alpha)$ shown in the Adapted ISO coordinate system for clarity

Conclusion

Wheel force transducers and slip angle measurements can be used to generate lateral force tire models. This approach has some advantages over tradition laboratory tire testing because the interaction between the tire and an actual road surface is measured. More noise is typically present in on-vehicle measurements, but building tire models from wheel force transducer data can still be a useful strategy for vehicle dynamics professionals. The process of building lateral force models from wheel force transducer data is a relatively simple task with OptimumT.