Experimental Determination of Bike Tire Stiffnesses

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Abstract:

A Light Alternative Vehicle's (LAV) stability and handling depends strongly on tire properties such as cornering stiffness and camber stiffness. Mathematical models are available to predict vehicle handling. However, very little data is available on properties of bicycle and tricycle tires currently on the market. Two tire parameters—cornering stiffness and camber stiffness—were measured for several different bicycle tires. Cornering stiffness is a measure of the lateral force generated when the tire heading differs from the direction of travel. Camber stiffness quantifies the lateral force generated when the tire is tilted from the vertical plane. Currently, there are no significant published values for bicycle tires for either property. The focus of this study is to experimentally determine the cornering and camber stiffness of several different types of bicycle and tricycle tires.

An apparatus was designed and constructed for measuring cornering and camber stiffness using the back-to-back method. In this method, two tires are mounted on a frame which is towed over a road surface [1]. The lateral force is measured with a force transducer mounted between the two wheels. In one configuration, the tires are pivoted about a vertical axis to produce slip angles in order to measure cornering stiffness. In the second configuration, the tires are pivoted about a horizontal axis to produce camber angles. Camber stiffness is thus measured. Both slip angle and camber angle can be adjusted over a range of angles. Weights provide vertical force.

During a test, force data is measured with a load cell and a portable data acquisition system for camber angles between zero and fifteen degrees and vertical loads between 200N and 800N. Cornering stiffness is measured with slip angles between zero and 1.5 degrees with similar load ranges. The data was analyzed by MATLAB to obtain cornering and camber stiffness over a range of vertical loads. Subsequently, the stiffness-vertical load relationship was modeled as a quadratic function. The coefficients of this function can be used in vehicle handling simulations to predict performance.

Both camber and cornering stiffness were successfully measured using this method. Camber stiffness is significantly less than cornering stiffness, as is typical of vehicle tires. For example, Ritchey Tom Slick 26X1.4 tires exhibited a cornering stiffness of 150 Newtons per degree, while the camber stiffness at the same vertical load of 550N was 4.5 Newtons per degree. Both camber and cornering stiffness can be modeled as quadratic functions of vertical load, with a peak value roughly corresponding to the tire rated load. Noticeable differences in stiffness exist between tires, providing vehicle designers a means of optimizing performance.

Introduction:

When designing a Light Alternative Vehicle (LAV), it is useful to understand the stability of the vehicle. Stability and handling are largely based on the how the tires interact with the surface the vehicle is traveling on. When any wheeled vehicle turns, the contact between the tire and the road surface must generate a turning force on the vehicle. This turning force can be achieved in two ways—by creating a slip angle or a camber angle. Slip and camber angles are orientations of a tire which cause the vehicle to turn. In relation to the axis in figure one, a slip angle, or turn of the tire, is defined as a rotation of the tire about the z-axis. A camber angle, or tilt of the tire, is defined by a rotation about the y-axis. For small slip and camber angles—$\alpha_{slip} < 2°$, $\alpha_{camber} < 18°$—the relationship between tire angle and lateral turning force is linear. The slope of this linear relationship is called cornering stiffness (for slip angles) or camber stiffness (for camber angles). Thus, cornering stiffness, C_α, is a proportionality constant and can be described by the following equations [2],

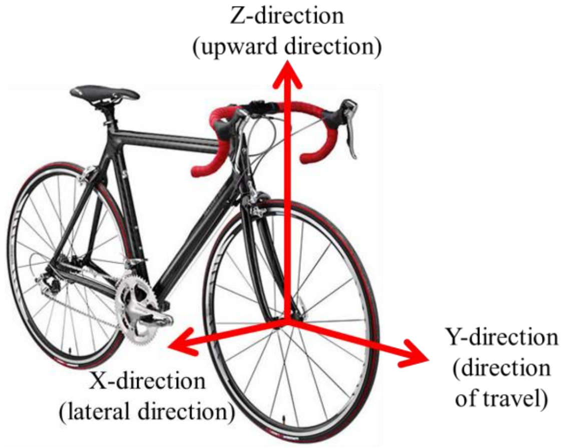

Figure 1: Definition of vehicles axes

$$F_{slip} = \alpha_{slip} * C_{cornering} \tag{1}$$

$$F_{camber} = \alpha_{camber} * C_{camber} \tag{2}$$

The units of tire stiffness are Newtons per degree or pounds per degree. Cornering and camber stiffness values change based on the type of tire, the wear and pressure of the tire, the road surface the tire is traveling on, and the vertical load on the tire. For a particular tire type on a given surface, the relationship between the vertical load (negative z-direction) and the tire stiffness can be approximated by a quadratic model. This holds for both cornering and camber data. The maximum of this quadratic equation is approximately the rated load of the tire.

The goal of this experiment was to experimentally determine the cornering and camber stiffnesses of various bike tires. Several methods exist to test tire properties. Large in-lab testing rigs which use belts or drums are commonly used to test the properties of automotive tires. For this experiment, a setup more closely approximating an actual bike tire during use was desired. A testing rig was built and towed behind a bicycle on an actual road surface. The cornering and camber stiffnesses were determined for different vertical loads using this test method.

Equipment:

Testing rig (described below), Somat E-DAQ Lite data acquisition system, LC101-50lb S-Beam load cell, 4 sets of tires, personal computer with SOMAT field analysis software and Matlab®. The four tires used were Ritchey Tom Slicks 26 x1.4, Schwalbe Durano 28-406, Tioga Comp Pool 20 x 1.75 and Schwalbe Stelvio 28-451 tires.

Experimental Setup and Procedure:

Two tires were mounted between pivoting forks which were attached to a small trailer. This trailer was towed by a bicycle. By varying the slip angle and the camber angle, the tires were made to turn against each other as the trailer was towed. This is called the back-to-back method and was used by Cole and Khoo in a 2001 tire study [1]. The version of the back-to-back device used in this study is depicted in figure two.

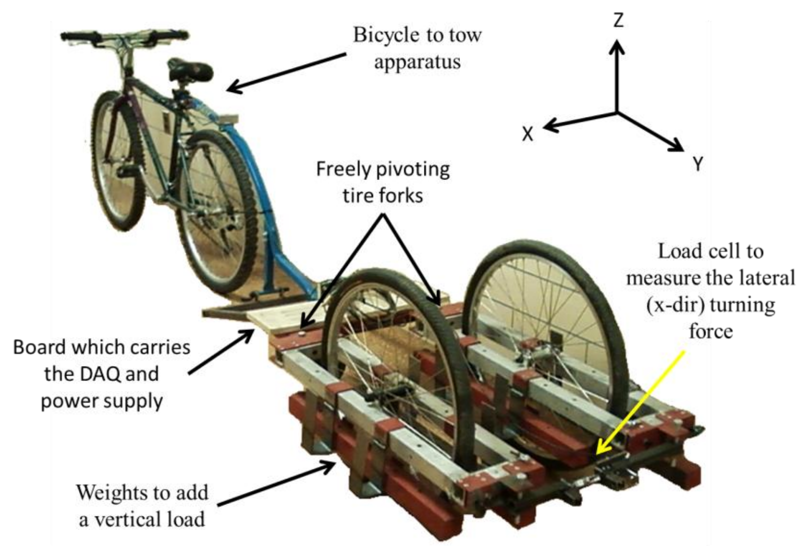

Figure 2: Experimental setup

The lateral turning force (x-direction in figure two) generated by the slip or camber angle was measured by the load cell in the rear. The load cell was attached to a DAQ unit which was secured on a board on the trailer. Varying weights were added to the device to alter the vertical load (negative z-direction in figure two). The trailer was towed at two to three miles per hour over straight, flat stretches of asphalt or concrete which were roughly 100ft long. Data was collected for four different tire types while varying the slip angle, camber angle, and the vertical load placed on the trailer. The slip angle and camber angle were not varied simultaneously—that is, when the slip angle was being varied the camber angle was zero and vice versa. The slip angle was adjusted by changing the distance between the rear ends of the wheel forks. The camber angle was adjusted by tilting the wheel on a cylindrical dropout as shown

Figure 3: Cylindrical dropout to adjust the camber angle

in figure three. For each run, the particular angle and vertical load were manually recorded to later be entered into a Matlab® script. The lateral turning force data was automatically collected by the load cell and the DAQ. Prior to data collection, the tires were inflated to their recommended pressure.

Once the data was collected on the DAQ, it was transferred to a laptop and converted into a text file using SOMAT Infield®—a data analysis software. The data was imported into Matlab® and analyzed. In order to calculate cornering stiffness, the slip angle was plotted against the lateral (x-direction) cornering force as in equation one. For camber stiffness, the camber angle was platted against the lateral (x-direction) camber force as in equation two. The slope of these linear relationships—$C_{cornering}$, and C_{camber} in eqations one and two—correspond to the cornering stiffness and camber stiffness respectively. The cornering stiffnesses were plotted against their corresponding vertical loads (negative z-direction) and fitted to a quadratic model.

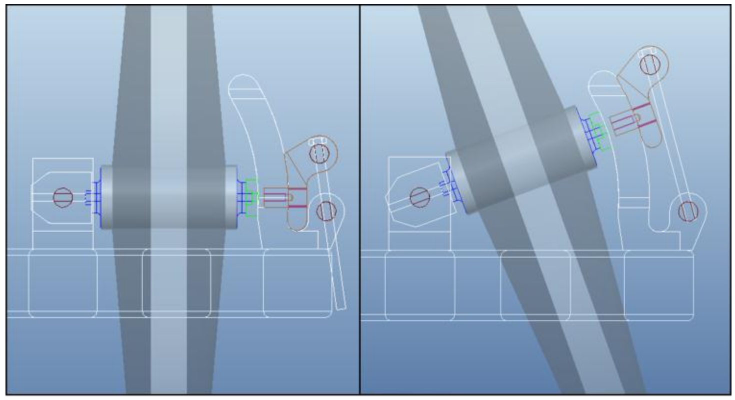

Figure 4: CAD models of the camber angle adjustment mechanism. 0° camber angle on the left and 20° camber angle on the right.

Data and Results:

The raw data collected for a single run is depicted in figure five. This is approximately the amount of data which went to determine the peak tire stiffness of one given tire. Figures six and seven are typical plots of the slip or camber angle versus lateral force. This is the linear relationship described in equations one and two. Each third of the data in figure five creates one plot such as in figures six and seven. Each of the plots in figures six and seven result in a single tire stiffness value—the red data points in figures eight through twelve.

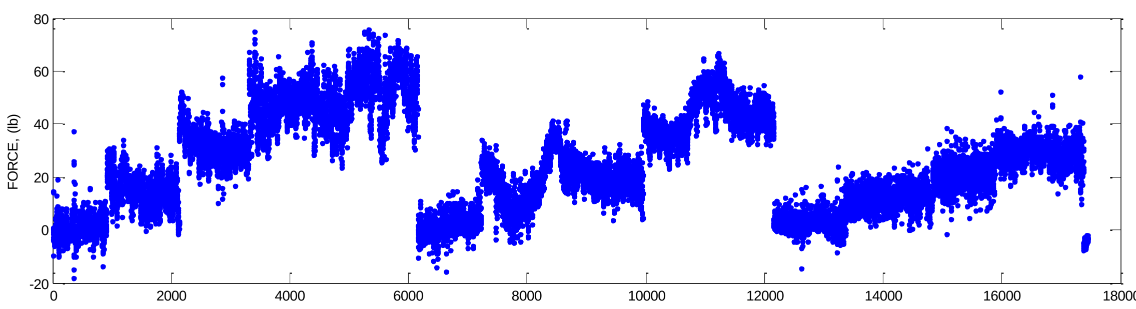

Figure 5: Example of raw data for camber force. This data represents five different camber angles for each of three vertical loads.

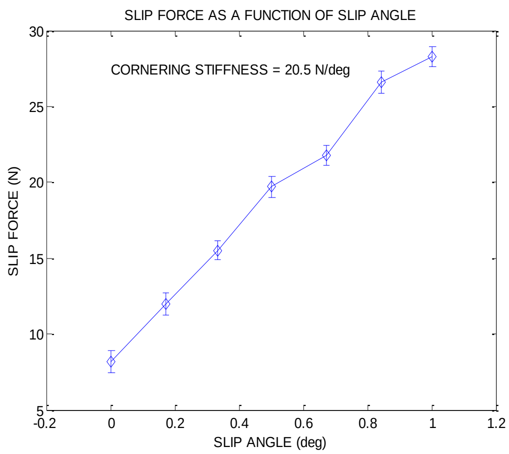

Figure 6: Slip angle versus slip force with standard error. The slop of this plot is the cornering stiffness.

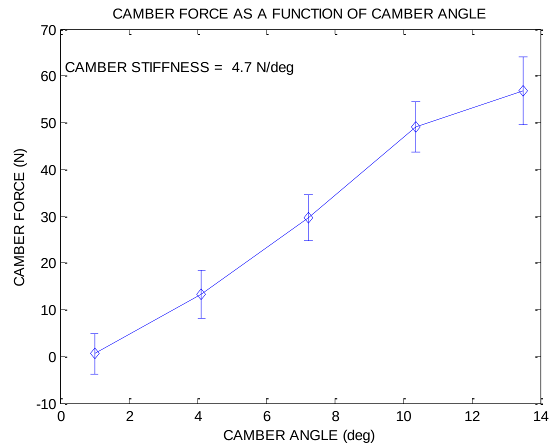

Figure 7: Camber angle versus camber with standard error. The slop of this plot is the camber stiffness.

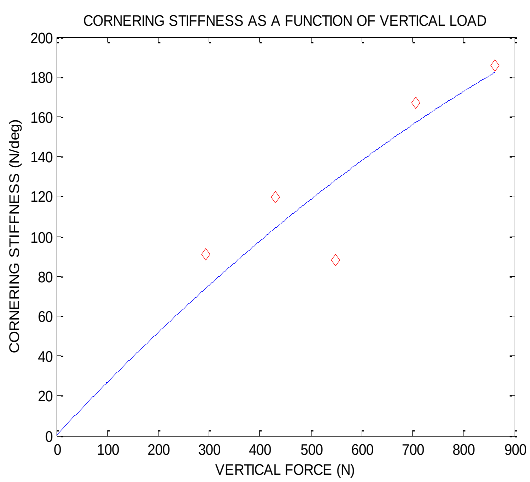

Figure 8: Durano tires cornering stiffness on dry asphalt.

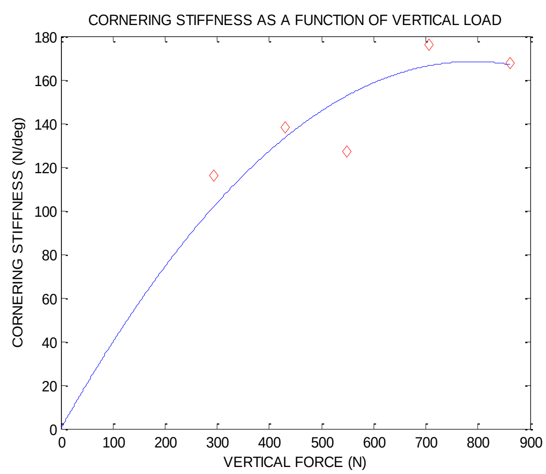

Figure 9: Tom Slicks tires cornering stiffness on dry asphalt.

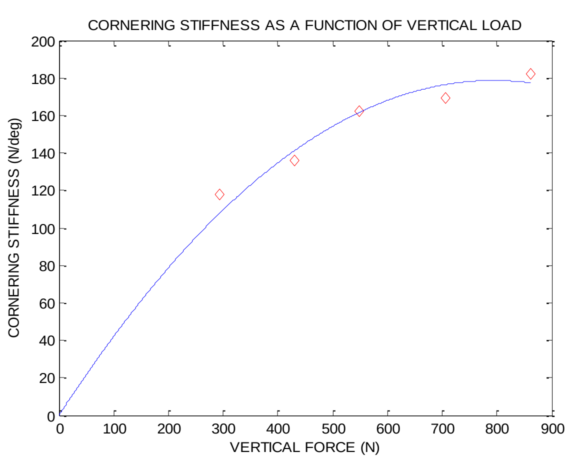

Figure 10: Tioga tires cornering stiffness on dry asphalt.

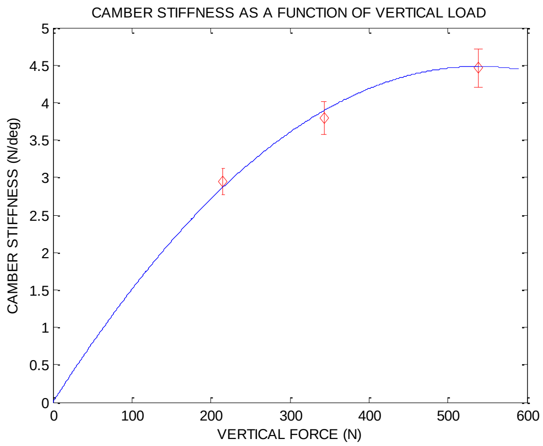

Figure 11: Tom Slicks tires camber stiffness on dry asphalt with standard error.

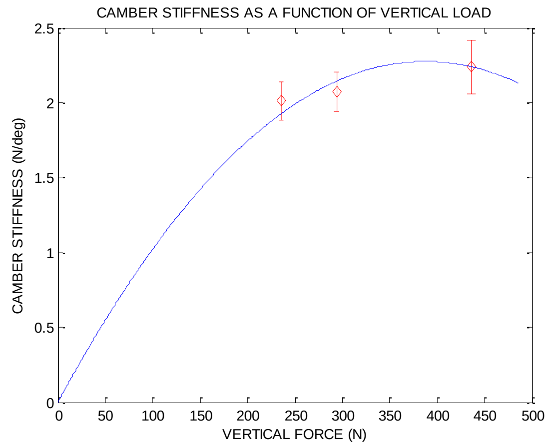

Figure 12: Stelvio tires camber stiffness on dry concrete with standard error.

Tables 1 and 2 report the A and B coefficients of each curve fit represented by the equation $y = -A*x^2 + B*x + C$ (C = 0 in all cases under the assumption that the cornering stiffness of a tire under no load is zero).

Tire	A	B
Durano	7.002×10^{-5}	0.2718
Slicks	2.715×10^{-4}	0.4215
Tioga	2.787×10^{-4}	0.4468

Table 1: Coefficients for the quadratic fit of cornering stiffness versus time.

Tire	A	B
Slicks	1.5411×10^{-5}	0.0166
Stelvio	1.5132×10^{-5}	0.0117

Table 2: Coefficients for the quadratic fit of camber stiffness versus time. The Stelvio tires were tested on concrete not asphalt.

Discussion:

The data yielded results which were consistent with prior expectations. The slip and camber angle versus lateral force plots remained in the linear region. This was predicted to be true for the small angles which were used—slip angles of less than 1.5 degrees and camber angels of less than 15 degrees. When each of these various tire stiffnesses were plotted against their corresponding vertical loads, they could indeed be fitted to quadratic models. With the exception of one unexpectedly low cornering stiffness value in each of the Durano and Tom Slicks, the quadratic model formed a good fit for the data. The two outliers were likely a result of an anomaly during the data collection. Bumps, seams, and slight sloping of the road surface were avoided as much as possible but still may have affected some data. The standard error for the camber stiffness of the Tom Slicks never exceeded 0.25 Newtons per degree and for the Stelvio tires never exceeded 0.32 Newtons per degree.

After the data was collected and analyzed several interesting observations can be made. The values of the cornering stiffness for the various tires were significantly less than the values of the camber stiffnesses. This is typical of tires of all types and was expected. For example, for the Tom Slicks the maximum cornering stiffness was 170 Newtons per degree whereas the maximum camber stiffness was only 4.5 Newtons per degree. Both of these values were taken on dry concrete in similar conditions. Even though the cornering stiffness values are much higher than the camber stiffness values, when a vehicles turns the camber angles are much larger than slip angles. While most every vehicle uses both slip and camber angle to steer, two wheeled LAVs rely more heavily on camber angle to steer than three and four wheeled LAVs do. Even so, the data collected here suggests that when vehicles tires are both slipping and cambering, the camber angle has a relatively low impact on the vehicle's lateral turning force.

The values of the maximum cornering and camber stiffnesses vary from tire to tire. Of the three tires tested for cornering stiffness the maximum values ranged from 193 Newtons per degree to 256 Newtons per degree. This indicates that when designing a LAV there is possibility for optimization. Depending on the application and needs of the vehicle a different tire with more desirable stiffness properties could be selected.

The maximum camber stiffness on concrete was 2.5 Newtons per degree versus the 4.5 Newtons per degree on concrete. It is likely that the smoother surface of the concrete contributed to the fact that the max camber stiffness on concrete was 44 percent less than that of asphalt. More data on a concrete surface with more different types of tires would allow this conjecture to be verified.

Further testing could be done to determine the limits of the linear region of cornering and camber stiffnesses. Additionally, more data could be collected and further comparisons could be made between different tire types and surfaces. Among the tires tested in this study only the Tom Slicks were tested for both cornering and camber stiffness. To get a better understanding of the relationship between cambers and cornering stiffness multiple tire types could be tested. Also, tests could be done where the slip angle and camber angle were varied simultaneously.

Conclusion:

The cornering and camber stiffnesses of several tires were successfully determined experimentally. Using the back-to-back method data was collected and then analyzed in Matlab. Maximum cornering stiffnesses were found to be around 200 to 250 Newtons per degree and maximum camber stiffnesses were found to be around 2.5 to 4.5 Newtons per degree. Camber stiffness values were significantly lower than cornering stiffness values suggesting that the majority of a LAVs turning force comes from the slip angle. The variation in tire stiffness from one tire model to another suggests a possibility for optimizing performance.

Bibliography:

[1] D.J. Cole and Y.H. Khoo, “Prediction of vehicle stability using a 'back to back' tyre test method”, 2001, Int. J. Vehicle Design

[2] Gillespie, Thomas D., *Fundamentals of Vehicle Dynamics*, SAE, 1992.