Proceedings, Bicycle and Motorcycle Dynamics 2010
Symposium on the Dynamics and Control of Single Track Vehicles,
20 - 22 October 2010, Delft, The Netherlands

# Measuring Dynamic Properties of Bicycle Tires

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## ABSTRACT

Dynamic tire properties, specifically the forces and moments generated under different circumstances, have been found to be important to motorcycle dynamics. A similar situation may be expected to exist for bicycles, but limited bicycle tire data and a lack of the tools necessary to measure it may contribute to its  absence in bicycle dynamics analyses. This paper describes tools developed to measure these bicycle tire properties and presents some of the findings.

Cornering stiffness, also known as sideslip and lateral slip stiffness, of either the front or rear tires, has been found to influence both the weave and wobble modes of motorcycles. Measuring this property requires holding the tire at a fixed orientation, camber and steer angles, with respect to the pavement and its direction of travel, and then measuring the lateral force generated as the tire rolls forward. Large, sophisticated, and expensive devices exist for measuring this characteristic of automobile tires. One device is known to exist for motorcycle tires, and it has been used at least once on bicycle tires, but the minimum load it can apply is approximately 200 pounds, nearly double the actual load carried by most bicycle tires.

This paper presents a device assembled for less than US$1000 that measures bicycle tire cornering stiffness. It consists of a small cart designed to take advantage of any sufficiently long, level, rigid, and smooth stretch of floor adjacent to a plumb, straight, rigid, and smooth wall to provide the test track. Several purpose-built tracks, however, are also described. A flat and straight track avoids issues created by either vertical or horizontal curvature. The apparatus uses an instrumentation system from Pasco intended for classroom experiments: two force sensors to measure lateral force, and one force sensor to measure torque, and a rotary motion sensor to measure distance traveled.

**Keywords:** Bicycle, dynamic, tire, property, measurement.

## 1 INTRODUCTION

Dynamic tire properties, specifically the forces and moments generated under different circumstances, have been found to be important to motorcycle dynamics. [1][2] A similar situation may be expected to exist for bicycles, but limited bicycle tire data and a lack of the tools necessary to measure them may contribute to their absence from bicycle dynamics analyses. [3][4] This paper describes tools developed to measure these bicycle tire properties and presents some of the findings.

## 2 MOTIVATIONS

Kooijman et al. found tire properties to be not significant on bicycles at speeds below 6 m/s by physical experimentation. [7] On the other hand, cornering stiffness, also known as sideslip and lateral slip stiffness, of either the front or rear tires, has been found to influence both the weave and wobble modes of motorcycles. [1] We wondered if bicycle tire properties matter at higher speeds, and we started by looking for the influence of tires on the wobble mode for bicycles in numerical simulations.

To perform the simulations, we first entered the geometry and mass distribution described by Meijaard et al. in their benchmark paper [5] into the FastBike numerical simulation described by Cossalter et al. [6] We set the suspension to be fixed and the tire properties to be as close as possible without causing numerical difficulties to rigid, knife-edge wheels that roll without slip. We calculated stability eigenvalues in FastBike and exported them in the maximum precision available, two decimal places. Ignoring additional values caused by the additional degrees of freedom, we found the remaining eigenvalues to agree with the published results, validated by Kooijman et al. [7], to within the available precision.

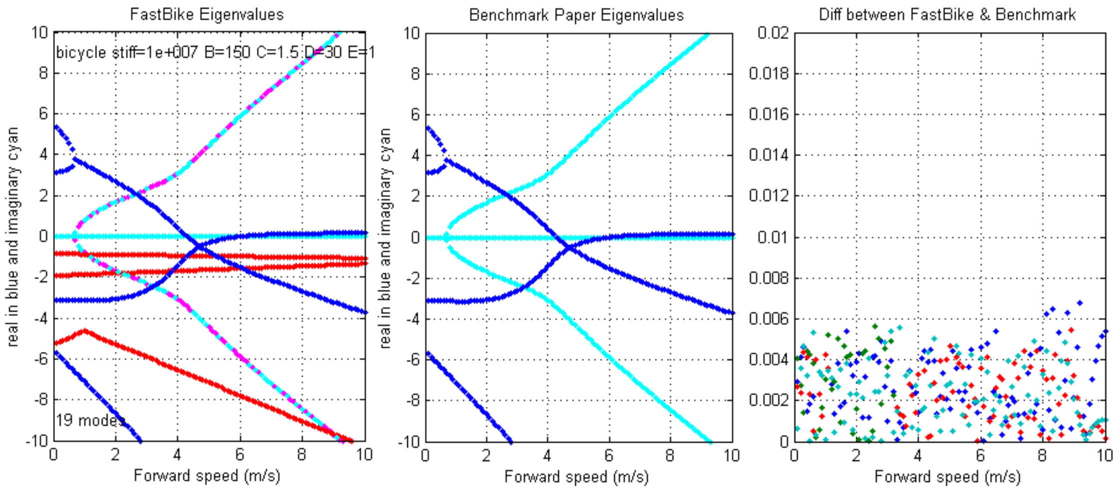


**Figure 1**. Stability eigenvalues from FastBike, the benchmark paper, and their differences.

We then used this validated bicycle model in FastBike to gauge its sensitivity to dynamic tire properties. To specify bicycle tires, we started with the stock motorcycle tire properties provided with FastBike and modified them to incorporate the dimensions described by Kooijman, 28 × 1 3/8 inches. [7] We then used the limited bicycle tire dynamic properties described by Cossalter [1] to generate new Magic Formula coefficients, [2] as required by FastBike.

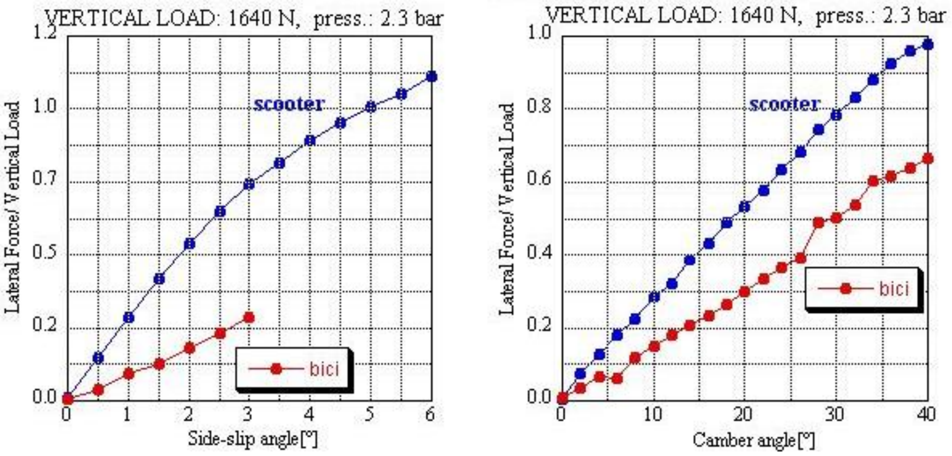


**Figure 2.** Bicycle tire and scooter tire dynamic properties data provided by Cossalter.

We also incorporated bicycle front fork flexibility data by Rinard [8] and bicycle wheel flexibility data by Trovati [9] that we found online into the model to increase fidelity.

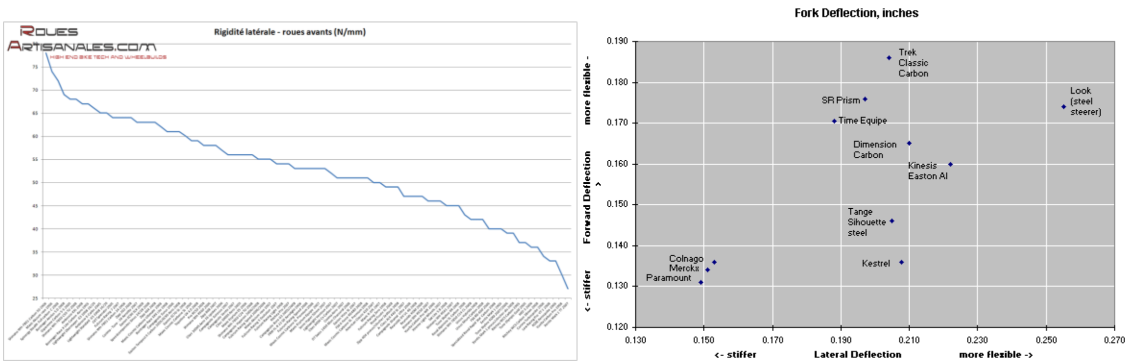


**Figure 3**. Bicycle fork and wheel flexibility data found online.

Through brief trial and error, we selected a combination of fork and wheel stiffnesses that, along with the combined tire properties, produced a barely stable wobble mode. Then we altered the tire lateral stiffness by ±10% to find that it would indeed cause the wobble mode to become unstable. We took this to mean that physically measuring the dynamic properties of bicycle tires might prove worthwhile.

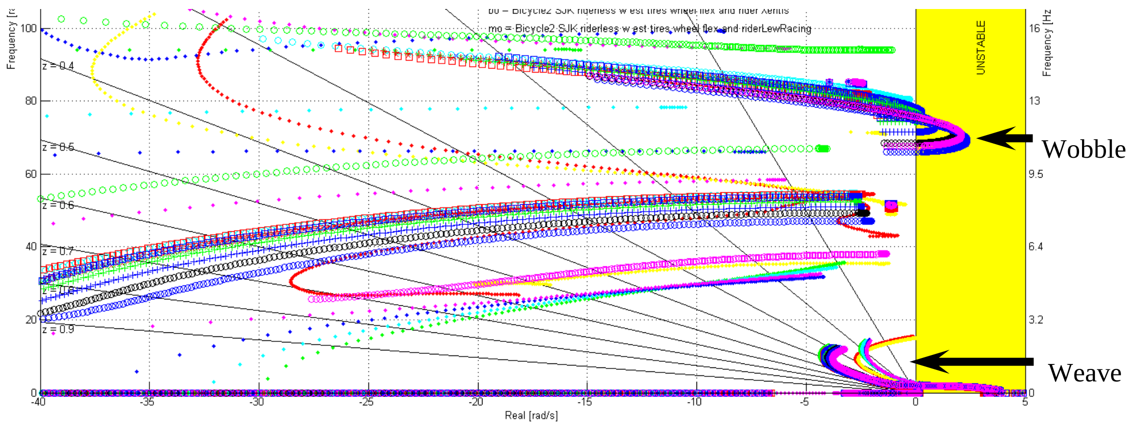


**Figure 4**. Root-locus plot from FastBike showing wobble mode becoming unstable.

## 3 METHODOLOGIES

Measuring these dynamic tire properties requires holding a tire at a fixed orientation, camber and steer angles, with respect to the pavement and its direction of travel, and then measuring the lateral force generated as the tire rolls forward. Our general design to accomplish this consists of a small cart that holds a bicycle wheel in the desired orientation, allows it to roll forward on the ground, applies a vertical load, and measures the lateral force that builds up between the tire contact patch and a fixed vertical surface.

### 3.1 The Cart

The cart is assembled predominantly from common dimensional lumber, mostly 2x4s, joined with various bolts and screws. This affords us very quick and cheap construction and easy modification. Door hinges provide the steer and camber axes, and their orientations are held fixed by large, rigid turnbuckles originally intended to be used as the top link in small 3-point hitches used to attach implements to farm tractors. It was understood that the frame would have some finite flexibility, but it was thought that a final lateral force value could be read after any slack was taken up. In hindsight, this flexibility makes establishing a measurable tire orientation problematic.

**Figure 5.** The test device showing the wheel held in place with a bicycle fork and the turnbuckles used to alter its orientation. Two for camber angle, and one for steer angle.

Although steer and camber angles must be measured separately, they can be set precisely and finely with the turnbuckles in any combination. Two swivel casters along the back edge of the cart enforce the desired camber angle. The orientation of the tire is also enforced and wheel flex minimized by two sets of guide wheels that run on the braking surface of the bicycle rim. One is at the bottom of the wheel, near the contact patch, to prevent flexing due to the lateral force generated at the contract patch. The second is at the front of the wheel to prevent rotation about the steering axis due to torques generated at the contact patch.

The cart went through several iterations before reaching its final form. At first, it held the wheel between two horizontal boards and modified camber angle by pivoting near the wheel axle. Unfortunately, this meant that the track on which the tire rolled had to be 6 inches or more wide. The second iteration moved the pivot axis to very near the contact patch. This way, changes in camber angle barely alter the tire track. The third iteration moved the wheel mount from the horizontal boards to an actual bicycle fork bent to remove all offset and mounted in a headset cut out of a bicycle frame. This allowed much better measurement of the torques generated normal to the contact patch. The fork was initially prevented from rotating by a force sensor attached to the end of the stem to measure torque generated in the contact patch. This proved to be too flexible and allowed the steering angle to change during a test run as torque built up. The fourth, and so far, final design moved the force sensor to a pair of bearings mounted near the front edge of the wheel. This minimized changes in the steering angle caused by flexing of the force sensor or the wheel.

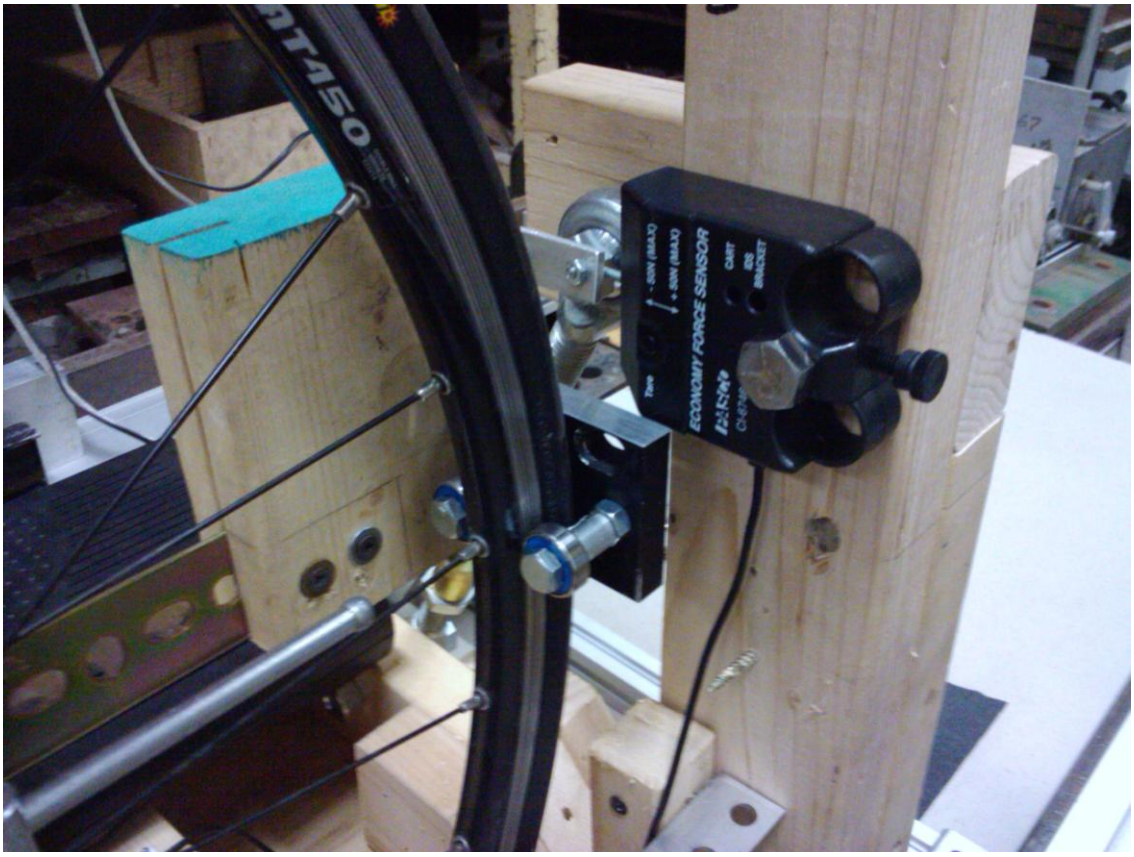


**Figure 6.** Final torque measuring and wheel orientation-enforcing setup.

The desired vertical load on the tire is generated by appropriately-sized steel blocks simply clamped to the frame near the contact patch. Loads of 50 and 100 lbs were used.

### 3.1.1 Data collection

Nearly any sufficiently accurate force measuring system may be used to detect the generated lateral force, and this implementation uses a system from Pasco intended for classroom experiments. [10] The Pasco sensors themselves are rated for only ±50 Newtons, far less than the maximum expected lateral force from the tire, and so a simple lever mechanism, similar to the one Pasco uses on their stress-strain apparatus, is employed to scale down by five-to-one the expected lateral force generated by the tire, well below the 50-Newton maximum. In total, three force sensors are used: two to measure lateral force while also maintaining cart and wheel steer angle, and one to measure torque.

We calibrated the values from the two lateral force sensors against the actual force generated in the tire contact patch by suspending the cart from a vertical cable just enough for the bottom of the tire to clear the ground, and then pushing against it with a third force sensor. The ratio between the sum of the first two with the third is used to convert recorded data into lateral force values.

A fourth sensor, which measures rotary motion, measures the horizontal distance moved. The Pasco system enables us to record all these values along with the time at which they are collected.

### 3.1.2 Orientation measurement

There are no gauges or indicators on the cart to show the actual tire orientation. Instead we calculate it from four measurements between the vertical track and the braking surface of the rim: at the top, bottom, front edge, and rear edge. Once we found the wall to be unsuitable for the vertical track and selected an extruded aluminum track instead, we no longer had a vertical surface to measure against. Instead we constructed a jig out of extruded aluminum bars that provided 4 properly located points to which we could measure the distance from four points on the wheel. We placed the jig on the track to measure the orientation whenever we changed it, and removed the jig in order to roll the cart forward to measure the tire dynamic properties.

## 3.2 The Track

We chose a flat and straight track, instead of a drum or disk to avoid issues created by either vertical or horizontal curvature, such as those described by Cossalter. [1] Although we initially thought that we could take advantage of any sufficiently long, level, rigid, and smooth stretch of floor adjacent to a plumb, straight, rigid, and smooth wall to provide the test track, we were unable to find such a suitable combination. The recorded lateral force data were very noisy and it was difficult to pick a single value from them. Instead, we built several special tracks on which we could test.

The first purpose-built track is actually a 10 foot section of counter-top purchased at a local home supply outlet. The surface is nice and smooth, but not nearly as flat nor as rigid as we expected or hoped. We spent considerable time trying to support it properly with shims so that it would provide the level and flat surface we needed, but we were never able to accurately predict how it, the shims under it, and the bench under the shims would shift and bend under the approximately 100 lb load on the contact patch. We could see the shape of the horizontal track in the recorded data as the cart either cambered towards or away from the vertical track. We were confident in the straightness of our vertical track because it was a 6 inch deep piece of extruded aluminum.

In an effort to eliminate issues of measuring flatness and levelness, we turned to self-leveling compound, a highly plasticized quick-curing concrete. The third track we constructed was of a thin layer, about 3/8 of an inch thick, poured onto the lab floor. We could not modify the lab floor, so we poured the concrete into a form lined with a sheet of plastic. Unfortunately, because it could not bond to a rigid surface, the concrete curled up and cracked as it cured.

The fourth and final track we tested consisted of a 10 foot long, 3 foot tall, and 1 foot wide steel I-beam laid on its side. The steel web was not sufficiently flat or smooth, so we poured the self-leveling compound onto it. To ensure a quality bond, we treated the steel with a bonding agent and attached a thin steel mesh about 1/8 inch off the surface with epoxy. The compound bonded well and cured nicely, but was far from level. It is too viscous and cures too quickly to flow from high spots where it is poured. We thought that it might flow better without the steel mesh, so we again applied the bonding agent to the top of the first layer and made a second pour. This did come out better, but still not as good as we liked. For the third and final pour, we added a retardant to the compound to give it time to flow and we added a mechanical shaker to the I-beam web to induce flowing. This came out much better.

In all cases, the necessary coefficient of friction between the track and the tire is provided by anti-skid tape: approximately 80-grit sandpaper.

**Figure 7.** The test device on its final track: the self-leveling compound poured on the web of a large steel I-beam. The black strip of anti-skid tape can be seen along the right edge.

### 3.2.1 Vertical Load Measurement

Because of the geometry of the cart and how it changes to accommodate changes in steer or camber angle, the vertical load must be measured after any change in steer or camber angle and before any data collection. This is accomplished with an antique but perfectly functioning balance scale mounted at the end of the track. The cart is simply rolled so that only the bicycle tire rests on the scale and its weight is recorded.

### 3.2.2 Cart Towing

We wanted to tow the cart forward at a consistent speed to produce the best results. At first we merely pulled by hand on a cord attached to the front of the cart. We quickly replaced that with a crankset cut out of a bicycle frame and a chain attached to the front of the cart. Finally, we stumbled upon a scrap piece of soil testing equipment that had a working electric motor, three speed gear box, and an external half-inch pitch chain drive. It fits at the end of the track perfectly and provides a wonderfully consistent towing force.

The lateral force generated by the tire is transitory and dissipates quickly once the tire stops rolling: by about 0.05 Newtons per second per sensor. This indicates that the tire needs to be rolled forward at sufficient speed, but forward speed also adds noise to the recorded data as the cart jostles due to imperfections in contacting surfaces. To minimize both force dissipation and noise, we increased forward speed until we found no change in the lateral force, and then used the slowest speed that produced that force.

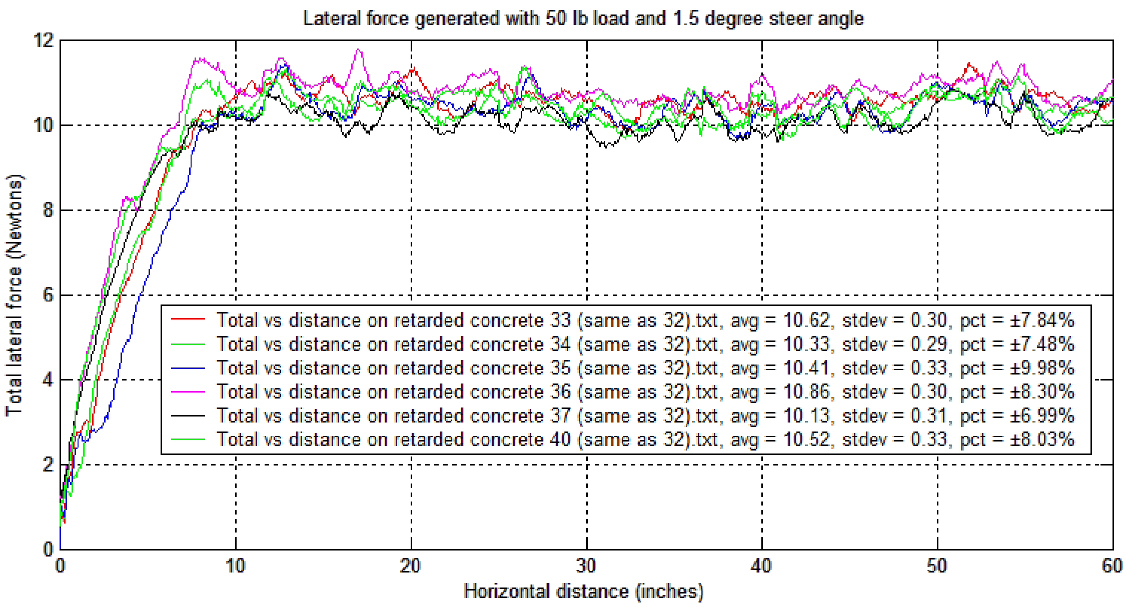


**Figure 8.** Raw test data from 6 consecutive runs.

## 3.3 Testing Protocol

Recording quality data with this apparatus requires a strict protocol.

1. Tire pressure. Inflate to target value and record.

2. Orientation. Set the measuring jig on the track around the cart. Make sure it is firmly up against the vertical track and the two end uprights are vertical with a spirit level. Measure the perpendicular distance from the inside edge of it to the wheel rim at the top, bot-

tom, and left and right extremes. Enter these values into a spreadsheet to calculate the wheel orientation in degrees. Adjust turnbuckles as necessary to produce the desired camber and/or steer angle. Remove the jig and tow the cart forward under simulated test conditions. Stop half way down the track. Replace jig and measure orientation under near-target lateral force and steer torque.

3. Vertical load. Put the scale and a wooden ramp at the end of the track, and roll the test cart onto the scale. Record the vertical load.

4. Move the cart back onto the track; make sure it is just barely up against the vertical track to enforce the desired steer angle.

5. Momentarily hold the contact points away from the force sensors and zero them.

6. Attach the tow chain, start recording data, and turn on the electric tow motor.

7. At the end of the track, the advancing cart automatically turns off the electric motor, and data recording stops automatically at 60 inches.

8. Disengage the tow chain from its sprocket and roll the cart back to the start, reorient the cart, re-zero the sensors, and return to step 6. Repeat for several runs.

9. Export data from the Pasco software. Import it into MATLAB. Check for repeatability of average lateral force value: standard deviation of the averages < 0.20 and standard deviation of each run <0.5. If good, record average value and return to step 2. If not, return to step 6.

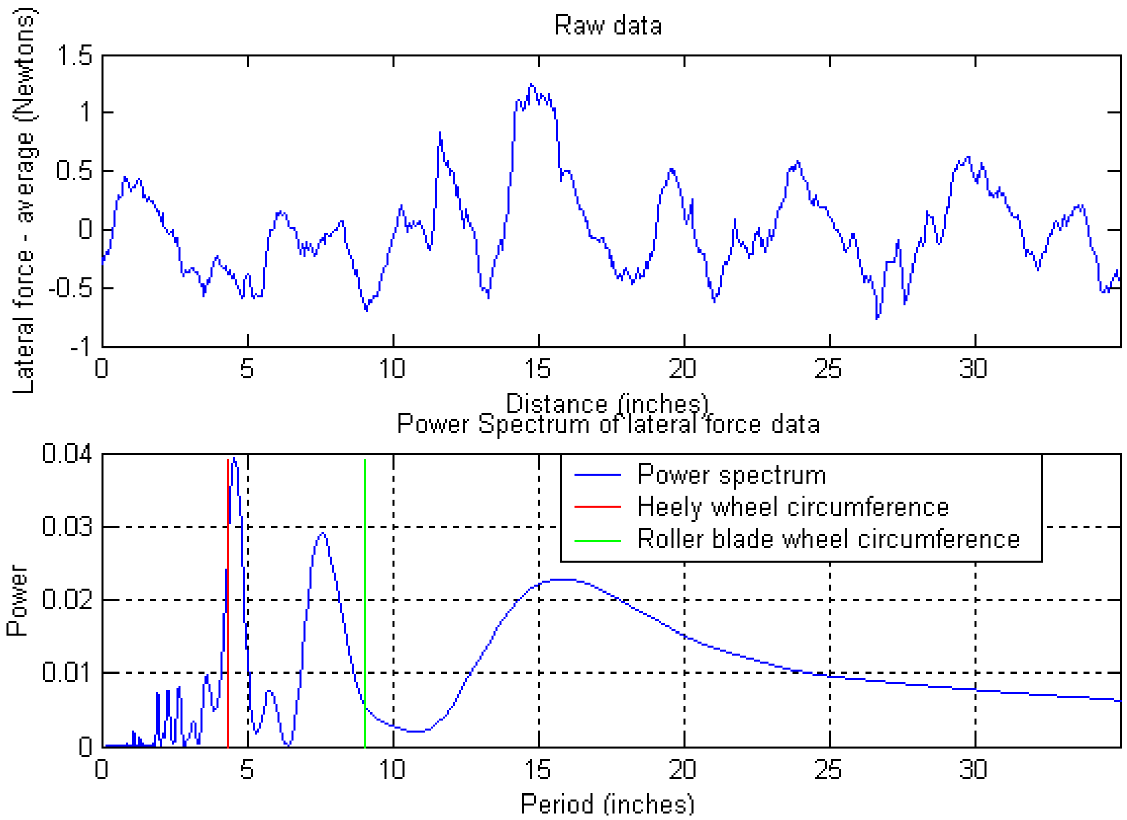


**Figure 9.** Fourier analysis of raw lateral force data showing signal from irregularity in the Heely wheels and the Roller Blade wheel.

### 3.4 Data Processing

Several runs are performed at each orientation until a desired level or repeatability is reached. Outliers are rejected, and the final recorded value for that camber and steer angle is the average of the closest cluster of values.

### 3.5 Sources of Noise

Besides issues with the horizontal and vertical tracks, we identified several other sources of noise in the data. A fast Fourier transform of the data reveals periodic signals with periods that closely match the circumferences of the wheels that run against the vertical track and the wheel that runs against the braking surface of the rim. We replaced the original inexpensive casters with neoprene wheels on ball bearings: off-the-shelf in-line skate and Healy wheels and bearings.

## 4 RESULTS

In general, the bicycle tires tested generate a larger lateral force for a given slip angle and a slightly smaller lateral force for a given camber angle than the bicycle tire tested by Cossalter. [1]

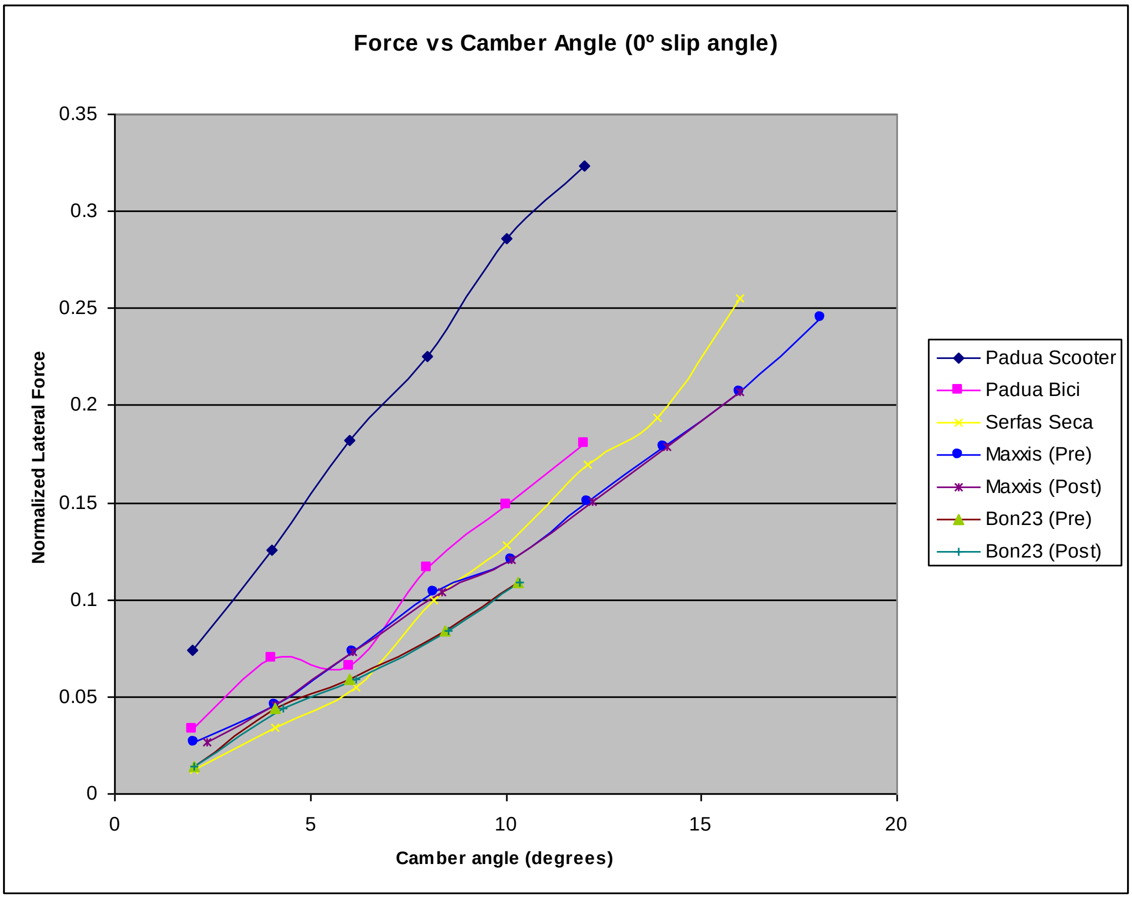


**Figure 10.** Force vs camber (lean) angle plotted along with data reported by Cossalter for a scooter tire and a bicycle tire.

The lateral force generated in our tests by different tires under the same camber and steer angles are easily found to vary by 10% or more: the threshold we used in the numerical simulation to determine the influence of tire properties on the wobble mode. Thus we predict, subject to confirmation by physical testing with real tires on real bicycles, that with the right combination of fork and wheel flexibility, changing the tires on a bicycle may make a stable wobble unstable or vice versa.

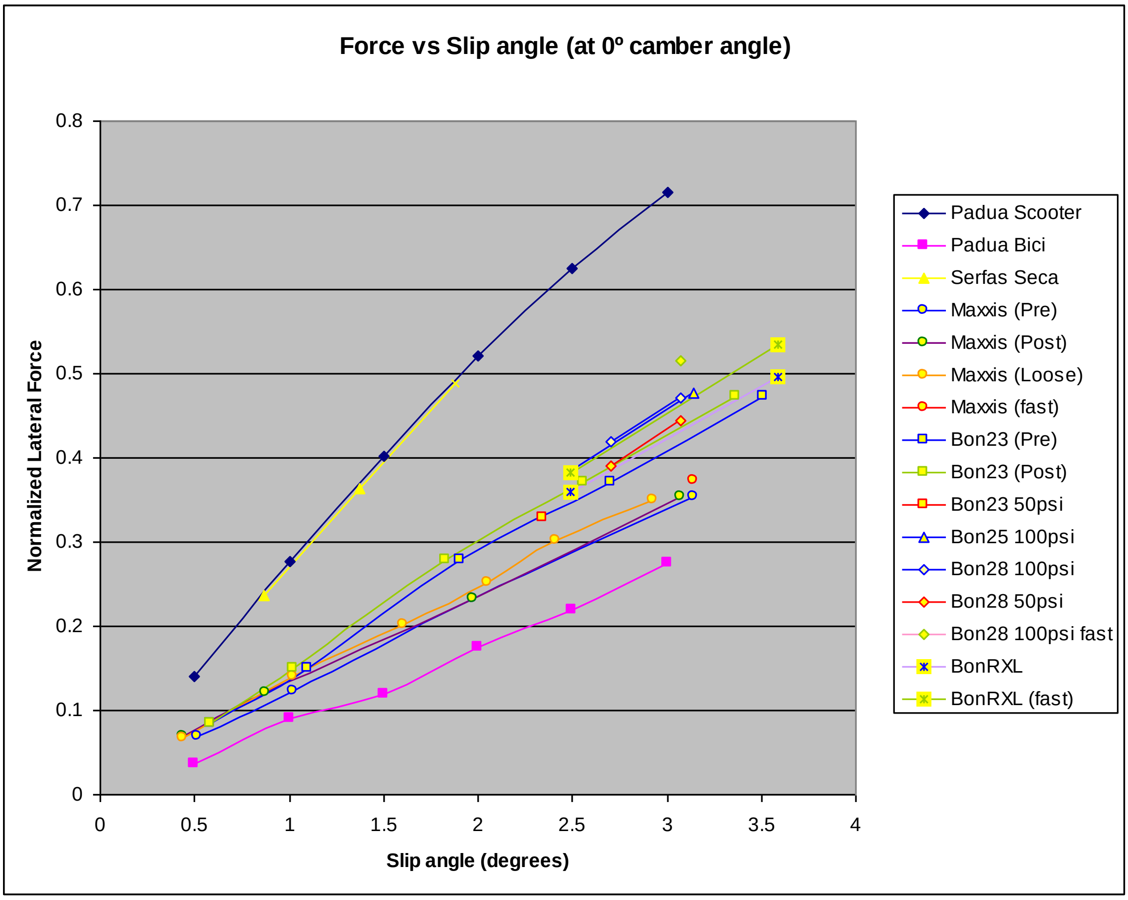


**Figure 11.** Force vs slip (steer) angle plotted along with data reported by Cossalter for a scooter tire and a bicycle tire.

### 4.1 Radial vs. Bias ply

We found the largest predictor of lateral force to be the orientation of the ply in the casing. The radial tire produced consistently more force for a given camber angle and less force for a given slip angle than the bias ply tires.

### 4.2 Inflation pressure

We found inflation pressure to have some effect on lateral force with higher pressure producing slightly higher force.

### 4.3 Tire Size

We found tire size, 23, 25, or 28 mm width, for the otherwise same tire, model and brand, not to have a significant effect on lateral force.

### 4.4 Other Details

In several cases, we measured the wheel orientation before measuring the lateral force and then again afterwards in an attempt to detect significant changes due to flexing of the cart frame. In all cases the difference was found to be very minor.

The Serfas Seca tire was measured on an early prototype, and so its numbers are suspect. They are included here merely for completeness.

We discontinued testing of non-zero camber angle after we discovered that the lateral force generated by bias ply tires was not sufficient to keep the rim pressed up against the Roller blade wheel.

## 5 COSTS

Our target was to assemble the device for less than US$1000 because the project has no outside funding. In reality, achieving that goal depended on borrowing expensive items, such as 10-foot long, 3-foot tall steel I-beams, that can commonly be found in a large Civil Engineering Structures Laboratory or finding discarded items, such as various pieces of aluminum stock, in a large Engineering School machine shop.

**Table 1.** Out-of-pocket expenses:

| Item | Quantity | Each | Extension |
|---|---|---|---|
| Self Leveling Compound | 4 | 29.99 | 119.96 |
| Epoxy | 2 | 8.49 | 16.98 |
| Drop Cloth | 1 | 2.99 | 2.99 |
| Bonding Agent | 1 | 6.47 | 6.47 |
| Counter top, 10' long | 1 | 52.00 | 52.00 |
| Anti-skid tape | 3 | 13.99 | 41.97 |
| Top Link | 3 | 15.99 | 47.97 |
| U-bolts | 2 | 1.99 | 3.98 |
| Healy Wheels (2 pack) | 1 | 14.99 | 14.99 |
| Roller Blade wheels | 2 | 2.99 | 5.98 |
| Rigid Casters | 2 | 1.59 | 3.18 |
| Swivel Casters | 2 | 4.99 | 9.98 |
| Bearings (6 pack) | 1 | 9.99 | 9.99 |
| Hinges | 2 | 3.99 | 7.98 |
| Hinge | 1 | 2.19 | 2.19 |
| Screws (box) | 1 | 13.99 | 13.99 |
| Screws (box) | 1 | 6.49 | 6.49 |
| Bolts | 1 | 4.66 | 4.66 |
| Fasteners | 1 | 4.69 | 4.69 |
| Sub total | | | 376.44 |
| Tax | 5.10% | | 19.20 |
| Total (US Dollars) | | | 395.64 |

**Table 2.** Donated or found items

| Item | Estd. value |
|---|---|
| I-beam: 10 feet long, 3 feet tall, 1 foot wide | 1000.00 |
| Electric drive with gear box and sprocket | 500.00 |
| Dimensional lumber: various 2-by-4s | 10.00 |
| Scrap Aluminum Stock | 100.00 |

| | |
|---|---|
| Pasco Sensors: 3 force sensors, 1 rotary motion sensor | 500.00 |
| Balance scale | 300.00 |
| PC with MATLAB and MS Office | 600.00 |
| Various bicycle parts: wheel, chain, crankset, headset | 100.00 |
| Lab space with utilities | |
| Machine shop and wood shop tools | |
| Total (US Dollars) | 3110.00 |

## 6 CONCLUSIONS

Though sufficient for proof-of-concept, the test device proved too awkward to use to test the range of tires we would like in a timely fashion. Our next design will focus on easily and reliably setting camber and steer angles so that more time may be devoted to actual testing and less to setting up for each test.

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