A Direct Method of Measuring the Rolling Resistance of a Bicycle Tire

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Abstract

The rolling resistance of a bicycle tire affects cycling performance. Lower rolling resistance lowers the energy required during typical cycling which improves performance especially at low velocities. Further, there may be a correlation between rolling resistance and ride comfort on rough surfaces. Rolling resistance is usually measured either indirectly, such as with coast-down tests and power meters, or under artificial conditions, such as rolling the tire on a steel drum. These methods either fail to provide actual or accurate rolling resistance coefficients. A means of directly measuring rolling resistance in the field was developed. A bicycle wheel (of any desired size) is mounted on a trailer and towed while a horizontally mounted force transducer directly measures the rolling resistance force. Weights can be added to vary the vertical load to any desired level. Test results indicate that the device can directly measure rolling resistance in the field.

The phenomenon of rolling resistance

Rolling resistance occurs due to deformation of the tire as it rolls, and of the surface the tire is rolling on. When the tire rolls over a surface it deforms both the tire and the surface. This deformation requires energy, which is not fully recovered due to hysteresis. If surface deformation is permanent, the rolling resistance force can be much larger. Sand, for example, will deform as the tire rolls over it but will not return to its original state after the bicycle has moved on. This means that energy was lost as the tire rolled over the sand. This leads to a retarding force on the bicycle. Rolling resistance is proportional to the load on the wheel. The rolling resistance on level ground is given by:

$$\mathrm{F}_R = mgC_R \quad (0.1)$$

where F_R is the force due to rolling resistance, C_R is the coefficient of rolling resistance, m is the mass on the wheel, and g is the acceleration due to gravity. Another equation relates pressure and velocity:

$$P_R = mgC_R V \quad (0.2)$$

where V is the speed of the bike.

It is generally acknowledged that smaller diameters have higher resistance, narrow high pressure tires are faster, and supple tire casings, high thread count, and minimal tread are faster.

Importance to bicycle design

Rolling resistance can have a significant effect on the power required to ride a human powered vehicle especially when riding at moderate speeds. Figure 1 depicts the components of power required to ride a recumbent bicycle over rough asphalt at speeds up to 10 m/s. Note that for very low speeds below 2 m/s, rolling resistance is dominant. For moderate speeds from 2 to 5 m/s, rolling resistance remains a significant term. At high speeds, aerodynamic drag dominates, but rolling resistance still accounts for nearly 100 Watts of power.[1]

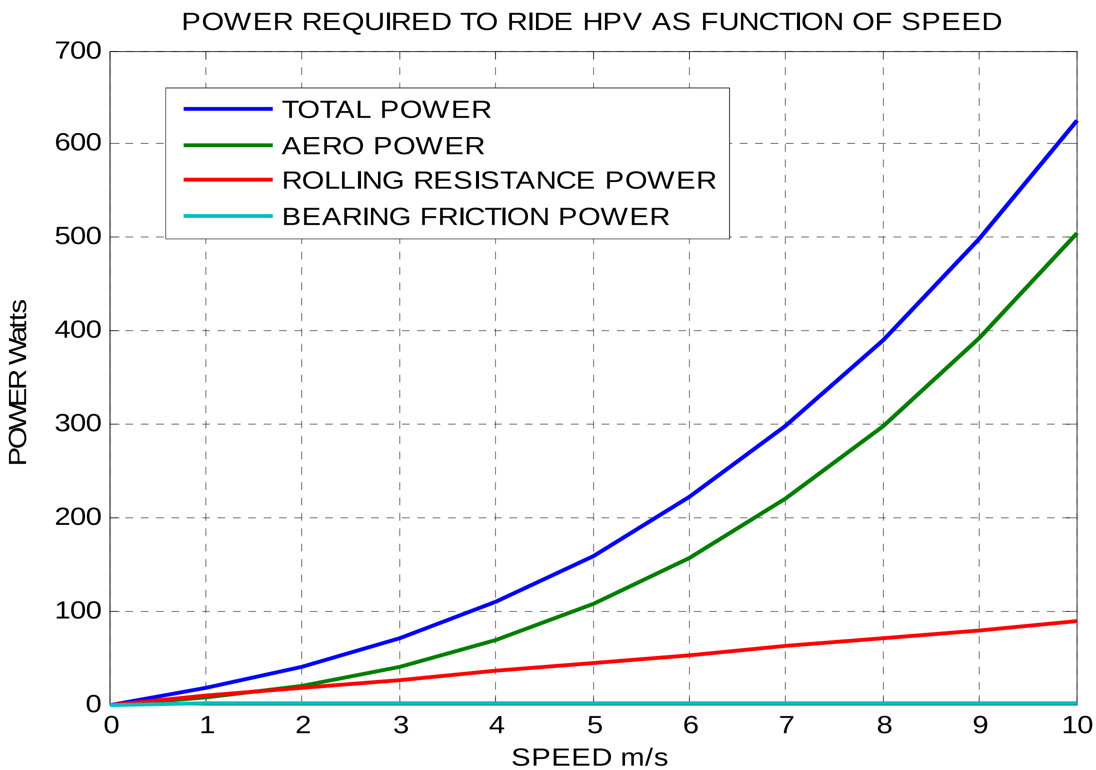

Figure 1: power required to overcome retarding forces vs speed. Source: Dr. Archibald, Design of Human Powered Vehicles

Previous studies

A study conducted by F. Grappe et al found the equations relating the coefficient of rolling resistance to both pressure and vertical load. They conducted a coastdown test where a rider peddled a bicycle for a given distance and then coasted to a stop. They found the following equation relating the coefficient of rolling resistance to inflation pressure:

$$C_R = 0.1071 P_R^{-0.477} \qquad (0.3)$$

They also found the relation between the rolling resistance coefficient C_R and the vertical force F_v to be

$$C_R = 1.92\times10^{-8} F_V^2 - 2.86\times10^{-5} F_V + 0.0142 \quad (0.4)$$

Both of these relationships had an r^2 value of 0.99. This study actually found values for the coefficient of rolling resistance, as opposed to relative values. A table of their results can be found in the article.[4]

IHPVA published an article by Charles Brown that found a relationship between the coefficient of rolling resistance and diameter. Brown used coast down tests to determine rolling resistance, and kept the speed under 1.3 m/s to minimize drag. The test was also done both directions across the floor to average out any inclines. Brown used a relative coefficient of rolling resistance and did not find an actual number that could be used in an equation to predict the force due to rolling resistance on a tire. All of the coefficients of rolling resistance were relative to 27” x 1-1/8” Japanese tires. The article does not mention the specific brand of tire used.

He found that decreasing the wheel diameter increased the coefficient of rolling resistance, lowering inflation pressure increased rolling resistance, and a higher tread weight lead to an increase in the coefficient of rolling resistance. He noted that wider tires did not have noticeably higher rolling resistance.[3]

Barry J. Hill discussed a technique for measuring rolling resistance involving an eccentrically weighted oscillating wheel. A mass hangs from the center of a wheel and the wheel is spun in contact with a surface. Data was taken for several tires on four different surface types: coarse gravel, smooth timber, medium bitumen, and wet bitumen. The device was able to resolve differences between the tires and the surfaces. Values of rolling resistance coefficient ranged from .0048 for Pirelli tires on gravel to .0027 for Soyo 45 tires on timber.[5]

Jobst Brandt has published data on analyticcycling.com showing plots of rolling resistance vs inflation pressure for different tires. Brandt used a rotating steel drum to take the data. This method spins a steel drum in contact with the tire. The torque on the drum is measured and thus the force due to rolling resistance on the steel drum is measured directly. Unfortunately, the steel surface of the drum does not accurately reflect surfaces that bicycles are typically ridden on. The cylindrical nature of the drum also means that the contact patch between the drum and the tire is smaller than it would be if tire were rolling on a flat surface. This causes the rolling resistance to be smaller than it would really be.

Brandt’s data shows that as the inflation pressure increases, rolling resistance decreases.[10] This makes sense from a theoretical standpoint as a higher inflation pressure would cause the tire to deform less and spring back to its original position more quickly.

Bicycle quarterly

Bicycle quarterly has recently published a number of interesting studies on rolling resistance of bicycle tires. They have tested rolling resistance verses tire pressure, road surface, tire width. Jan Hein, et. al. discussed a study testing the effect of tire pressure on rolling resistance. They tested the Vittoria Corsa CX Evo tubular, the Vittoria Open Corsa CX Evo clincher, and the Vittoria Rubino clincher.

They found performance differences between high and low pressures are very small on smooth road. Best performance was at moderate pressures or very high pressures. They found, that on rough surfaces, lower to moderate pressures performed better than very high pressure tires. They hypothesized that the cause was suspension losses or the vibration of human tissues which converts energy into heat, and that low pressures reduce suspension losses thus reducing power required of the rider.[7]

Jan Hein et al published another study in Bicycle Quarterly comparing the rolling resistance of three different tires, The Vittoria Open Corsa Evo CX, the Grand Bois Cypres, and the Rivendell Rolly-Poly. This test was conducted to validate the results of a previous test, where the bicycle and rider coasted down a hill, and then through a timing zone.

To validate the results of the coast down test, another test was performed where tire performance was determined by power output of the rider. The results were that the CX was fastest, Grand Bois Cypres 700 was second fastest, and Rolly-Poly was slowest.[6]

Finally, Jan Heine wrote about another study he conducted in *Bicycle Quarterly* comparing the Vittoria Open Corsa Evo CX, which has very supple casing and a thin tread, and the Schwalbe Marathon HS 368, which has a thick tread. The tested CX tires were 25 mm wide and weighed 240 g each, and the tested Marathon tires were 38 mm wide, which the testers measured as the actual width, and weighed 720 g each.

Both track tests and rumble strip tests were performed. A PowerTap rear hub was used for the track tests, and an SRM PowerMeter crank was used for the rumble strip tests. In other words, the rolling resistance of the tire was measured indirectly by recording the power output of the rider required to propel the vehicle. Pressure was not held equal between the two tires.

On smooth roads, their results were that the CX performed better. At 28.9 km/h, the rider using the Marathon tires had to expend 10.6% more power than the rider using the CX tires. They also tested both tires at 32.2 km/h, where the marathon required 12.7% more power than the CX.

To simulate rough roads, the tires were ridden on adjacent rumble strips, which the authors claim is equivalent to cobblestones. On this surface the marathon required an increase in power output of only 26% when compared to the smooth surface, whereas the CX required a power output increase of 96%. Bicycle Quarterly's results showed that, on rumble strips, the Marathon was more efficient than the CX. They conclude by theorizing that an ideal tire would have the casing and tread of the CX and the width of the Marathon, the combination of which would provide smooth performance on both smooth and rough roads.[8]

David Gordon Wilson gives some guidelines on how to conduct rolling resistance experiments. He recommends a speed of 2-3 m/s. In the current study, data was taken at low velocities in accordance with this advice.[9]

A table summarizing some interesting results of the previously mentioned studies is shown below in Table 1:

Table 1: Summary of different Cr values found in different studies

Sources	Tire Tested	Size	Crr	Type of surface	Tire pressure (psi)
Grappe et al (varying pressure)	Tubular Corsa Cx		0.01-0.0038	Tiled floor	21.76 - 174
Grappe et al (varying vertical load)	Techno Kevlar clincher		0.0035-0.0039	Tiled floor	145
Bicycle Quarterly	Vittoria Open Cx	25-622	0.0032		101.5/104.4 (front/rear)
Bicycle Quarterly	Grand Bois Cypres 700	32-622	0.0046		60.9/87 (front/rear)
Bicycle Quarterly	Rivendell Rolly-Poly	27-622	0.0063		65.3/75.4 (front/rear)
David G. Wilson	Typical values found for wide range of tires		0.002-0.01		N/A

Methods

The goal for this experiment was to devise a method of accurately and directly measure the rolling resistance of bicycle tires on actual road surfaces. Direct measurement means that the force due to rolling resistance is measured rather than the power output of the rider, or the time it takes for a bike to coast to a stop.

The testing apparatus consists of a trailer towed behind a recumbent tricycle. The trailer has a slot for the wheel, and two side slots in which to place weights. The weight on the test tire can be varied by adjusting the weights. The wheel is mounted in the center slot using a quick release. The entire unit is supported on outboard horizontal shafts by low-friction linear bearings. A force transducer (Omega LC101-25, 25 Newton capacity) provides the only horizontal link between the trailer and the towing vehicle, providing a direct measurement of the force required to tow the trailer. The support assembly, consisting of a vertical pivot, and anchor for the force transducer and guide shafts, is attached to the rear axle of the towing vehicle such that it can pivot about a lateral horizontal axis. The trailer thus has two degrees of freedom relative to the towing vehicle, allowing it to properly trail behind the towed vehicle yet keep the test tire in the vertical plane

Low friction linear bearings are bolted onto the trailer and are able to slide on case-hardened, high-precision steel rods. Thus the only significant force on the force transducer should be the force due to rolling resistance. The force transducer sends data to a Somat EDAQ-

Lite Data Acquisition unit powered by a 12 V battery. Velocity is measured with a magnetic reed switch. Since a single magnet is mounted on the wheel, speed data is only updated once per revolution of the wheel.

Initial attempts to use a bicycle as a tow vehicle were unsatisfactory. Rolling motions of the bicycle were transmitted to the trailer, making the system unstable and difficult to control. The desired low testing speeds exacerbated the problem, which was solved by using a recumbent tricycle as a tow vehicle. A drawing of the apparatus is shown below in Figure 2.

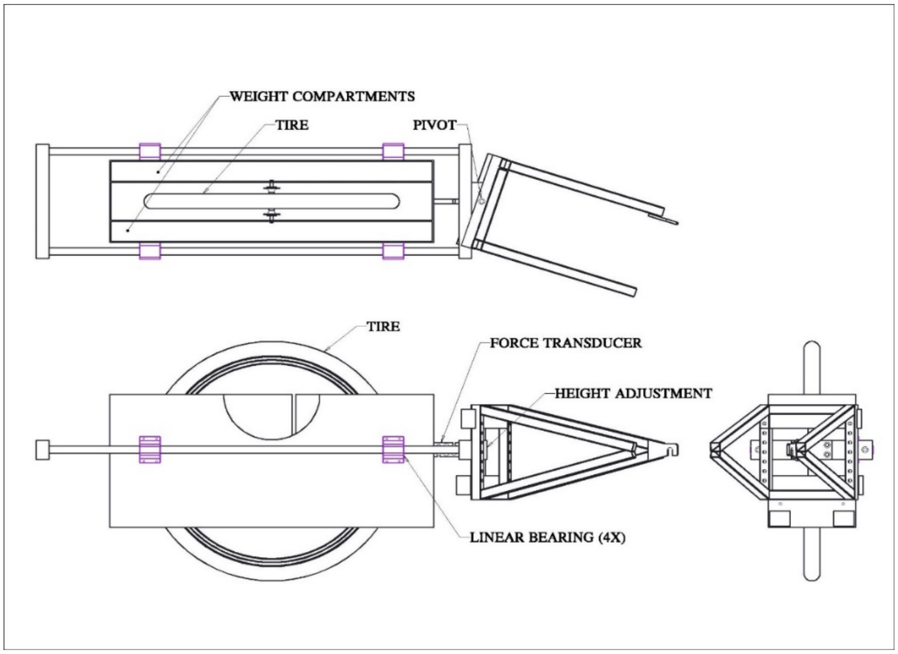

Figure 2: A diagram of test wheel setup

The vertical load on the test tire is measured with a Rubbermaid Pelouze model 4040-88 with had a resolution of 0.5 lbs. The tricycle is elevated on blocks to ensure the entire assembly is level during weighing.

Prior to each test, the force transducer is calibrated and the tire inflated and mounted. The trailer is leveled to adjust for differences in tire diameters. The trailer assembly is then towed at a low speed while measuring the towing force. Force data is sampled at 20 Hz for subsequent analysis.

The first test conducted was to determine the sensitivity of the apparatus by verifying that rolling resistance of the same tire on different road surfaces could be resolved. The first three runs were conducted on a flat sidewalk made of pavement. The pavement was dry, and cluttered. After that, five runs were conducted on asphalt. Unfortunately, the data was quite sensitive to a slight grade on the asphalt surface, resulting in bias errors. The tricycle was powered by a human rider during this test, and efforts were made to keep the cadence as consistent as possible.

Testing was then performed in the IM room in the athletic building at Grove City College to determine if different tires yielded significantly different results. The surface was of the IM room floor was smooth rubber. Testing was performed on 4 separate tires, the Durano, the Marathon, the Big Apple and the Kojak. The tires all have a rim diameter of 406mm and the same rim was used for all four tires to eliminate variability from different rims.

The testing was conducted over a period of three days. On Monday, February 2, two runs from the Durano and two runs from the marathon were taken. Each run consisted of a human rider pulling the tire in a trailer for two laps around the IM room. A test run would be started using a computer and the Data acquisition unit would collect data from the force transducer until the run was ended with the computer. An inclinometer was used before running each tire to ensure the trailer was level. The Durano tire was a 28-406 tire and was inflated to 115 psi which is the maximum recommended tire pressure. The Marathon was a 40-406 and was also inflated to its maximum recommended tire pressure of 100 psi.

On Wednesday, February 4, two runs from the marathon and three runs from the big apple were taken. The marathon runs were taken to compare between the different days. Each run on this day consisted of pulling the tire for 4-6 laps in a smaller portion of the IM room. The Marathon tire was unchanged from its runs on Monday, however the inflation pressure had likely dropped at that point. The Big Apple is a 50-406 tire and was inflated to its maximum recommended pressure of 70 psi.

On Friday, February 6, two runs were taken from each of the four tires. Each run on this day consisted of four lap sin a smaller portion of the IM room. The Durano tire was tested first to compare between the Monday test and the Friday test. This was the first time that the Kojak tire was tested. The Kojak was a 35-406 and was inflated to its maximum recommended pressure of 95 psi. In total, on all three days, four Durano runs were taken, six marathon runs were taken, four Big Apple runs were taken, and two Kojak runs were taken.

Force data is downloaded from the EDAQ and processed in MATLAB. The coefficient of rolling resistance is calculated using the equation:

$$Fr = Cr*N$$

where Fr is the mean force due to rolling resistance, N is the weight on the test wheel, and Cr is the coefficient of rolling resistance. The uncertainty of the data was also found using MATLAB.

Results

The results from Monday, February 2 show that there was no statistical difference between the two Durano runs, or between the two Marathon runs. The two Durano runs had a p value of 0.9218, and the two Marathon runs had a p value of 0.612. Both of these were at the alpha level of significance of 0.05.

There was a statistical difference between the marathon runs and the Durano runs. The first Durano run yielded a rolling resistance coefficient of 0.01693, and the second Durano run yielded a rolling resistance coefficient of 0.01691. The first marathon run yielded a rolling resistance coefficient of 0.02149 and the second marathon run yielded a rolling resistance coefficient of 0.02164.

The first marathon run on Wednesday, February 4 had to be discarded because of calibration issues with the force transducer. The second marathon run on Wednesday is significantly different from the marathon runs on Monday. The results of that run show that the coefficient of rolling resistance of the marathon on the IM room surface was 0.02841. The results of the first three Big Apple runs yielded a coefficient of rolling resistance of 0.03054, 0.03036, and .02324 respectively. There is no statistically significant difference between the first two Big Apple runs, with a p value of 0.476. The results outputted by MATLAB for both Monday and Wednesday testing are shown below in Figure 3

Figure 3: Results of testing done on Monday and Wednesday. The coefficients of rolling resistance calculated from the average force due to rolling resistance are shown here.

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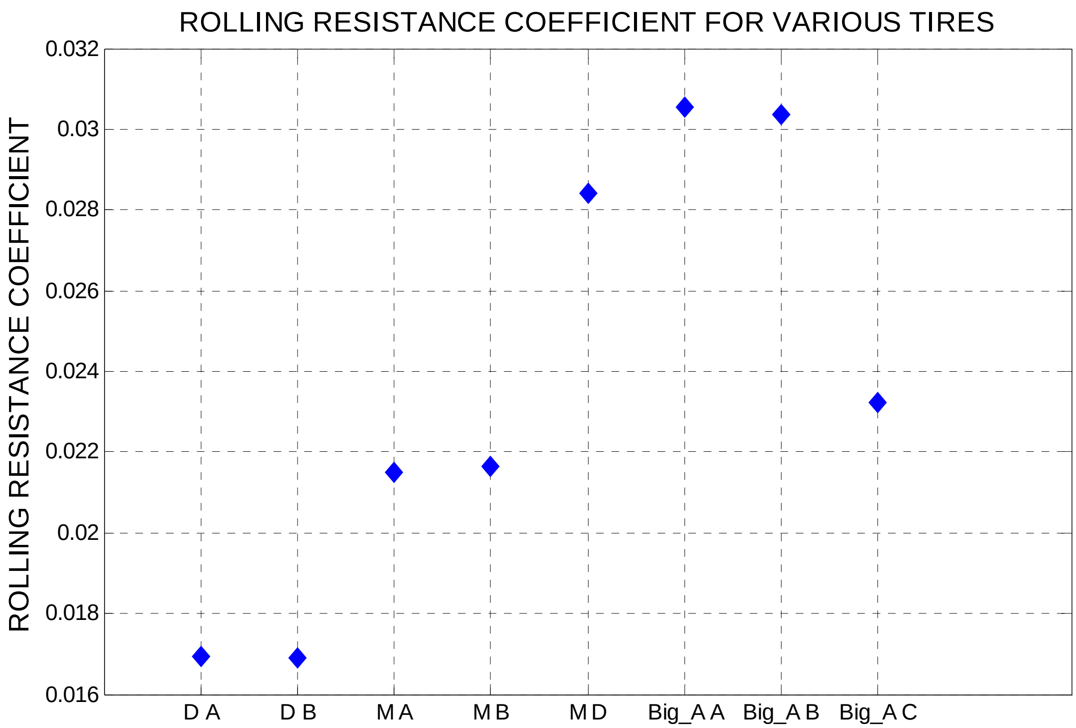

Figure 3: Results of testing done on Monday and Wednesday. The coefficients of rolling resistance calculated from the average force due to rolling resistance are shown here.

The results from Friday, February 6 show that there was no statistical difference between the two Durano runs, between the two Marathon runs, or between the two Kojak runs, but there was a statistically significant difference between the two Big Apple runs. The p values were 0.0876 for the Durano runs, 0.222 for the Marathon runs, 0.294 for the Kojak runs, and 0.0434 for the Big Apple runs. The p value for this test was very close to .05 however, so it is just on the edge of being significant.

Figure 10 shows results from Friday's testing. The results of each tire are lumped together. The Durano coefficient of rolling resistance was 0.02975. The Kojak had a rolling resistance coefficient of 0.0183, the Marathon had a coefficient of 0.01994, and the Big Apple had a coefficient of 0.03965. The results output by MATLAB can be seen below in Figure 4. A summary of the results of the testing can be seen in Table 2.

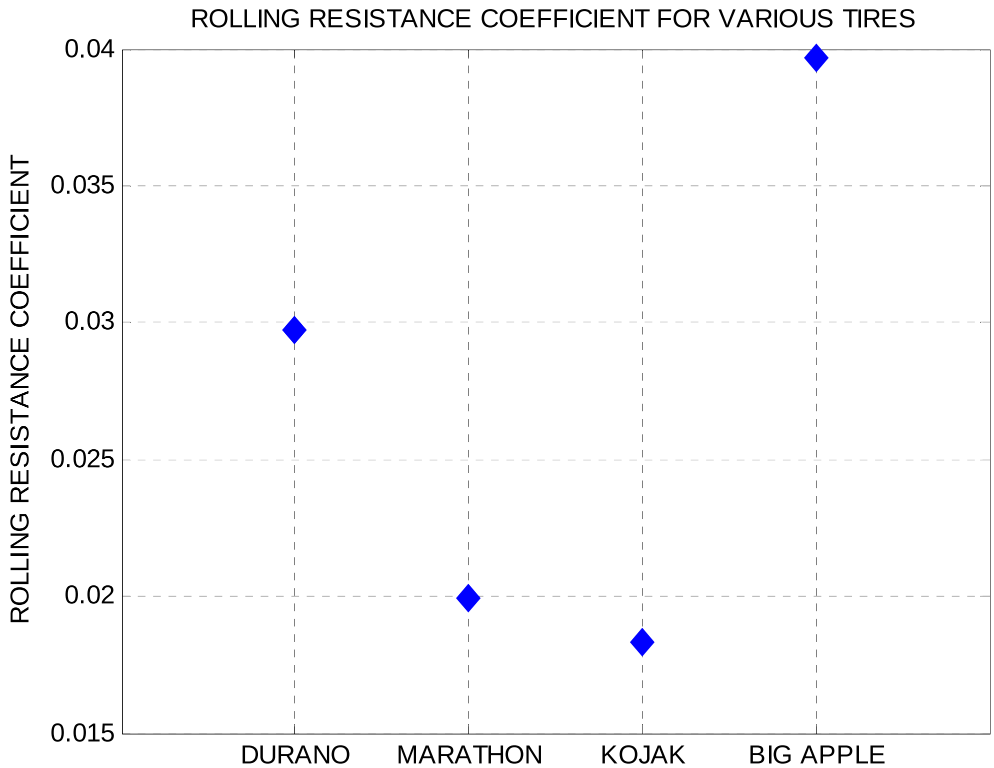

Figure 4: Lumped results for all four tires tested on Friday

Test Tire	Mean Force (N)	Standard Deviation	Number of Force Data Points	Day Taken
Durano A	4.4434	4.5968	7,549	Monday
Durano B	4.4364	4.2152	7,904	Monday
Durano C	8.0063	4.5932	6,785	Friday
Durano D	7.8711	4.5158	6,471	Friday

Marathon A	5.6402	4.3653	7,397	Monday
Marathon B	5.6785	4.7477	7,259	Monday
Marathon D	7.4548	4.3166	7,908	Wednesday
Marathon E	5.3744	4.9112	6,679	Friday
Marathon F	5.2694	5.0196	6,637	Friday
Big Apple A	8.015	4.3491	10,038	Wednesday
Big Apple B	7.9664	5.1765	9,540	Wednesday
Big Apple C	6.0992	4.9066	7,720	Wednesday
Big Apple D	10.6598	4.4295	8,020	Friday
Big Apple E	10.4539	4.5342	4,853	Friday
Kojak A	4.8472	5.5969	8600	Friday
Kojak B	4.9179	5.6118	9098	Friday

Table 2: A summary of data taken during this study

Discussion

The results from the linoleum gym floor show that differences in rolling resistance between different tires can be distinguished using the method outlined in this paper. This is shown by the statistically significant difference between the first two Durano runs and the first two marathon runs and the statistically insignificant difference between runs of the same tire.

The floor that was tested on does not accurately reflect a real world surface such as pavement or asphalt so the numbers for the coefficient of rolling resistance obtained by this test may not reflect actual road forces. However, future tests could easily be done on more conventional surfaces such as a flat asphalt parking lot or a flat sidewalk.

The values obtained for the coefficient of rolling resistance are higher than expected but this could be due to the soft linoleum floor tested on which deforms much more easily than standard surfaces such as concrete or asphalt. The tires tested were smaller than in most rolling resistance tests so that could also account for the unusually high values.

The data shows a significant difference in the rolling resistance of the Marathon runs between Monday's testing and Wednesdays testing. This is likely due at least in part to deflation of the tire, as the tire was not inflated to maximum pressure before testing on Wednesday. It was assumed that the tire would not lose a significant amount of pressure between Monday and Wednesday but that may not have been a safe assumption.

When the data was analyzed, it was discovered that the setup was much more sensitive to the angle of the trailer than was initially assumed. The tolerance of 0.5 degrees that was used for testing was too large, as a degree of 0.5 introduces significant error especially at low speeds. This explains the large difference in Crr of the Big Apple runs taken on Wednesday as shown in Figure 3.

Figure 3: Results of testing done on Monday and Wednesday. The coefficients of rolling resistance calculated from the average force due to rolling resistance are shown here.

In the first two Big Apple runs, insufficient care was taken to ensure that the trailer was level. On the third run, the mistake was realized and the trailer was leveled to within the previously mentioned 0.5 degree tolerance. This is likely the cause of the decrease in rolling resistance of the third run.

The extreme difference between the Durano runs taken on Monday and the Durano runs taken on Friday are likely due to experimental error. It is unknown what exactly caused the disparity but it is unlikely something changed that drastically between the two days. It is also unknown why the marathon tire was more efficient than the Durano on Friday's runs but not on Monday.

The Velocity data taken did not end up being useful. This is because the resolution of the data is limited by the frequency of rotations of the test tire. Since the tests were taken at low speeds, this resolution was too low to yield useful data.

There are several ways to improve the experiment. The trailer could have more precise slots for holding the weights. That would prevent the weights from sliding around during testing. Another improvement would be to add an electric motor to the tricycle. The motor would provide a more consistent speed than a human rider which would produce less noisy data. A method of measuring velocity with higher resolution would also be useful as acceleration could be determined more accurately. This would show whether spikes in the force data were due to acceleration of the tricycle or simply random noise.

A more radical alteration would be to forego the trailer and have the front tire of a bicycle slide on linear bearings and attach to a force transducer. This would mean that only the weight of the wheel and tire would affect the data on a grade rather than a trailer weighing more than a hundred pounds. This would largely eliminate the bias that grade imposes on the data. In addition, a bicycle without a trailer may reduce vibrations and rattling significantly

In the future it would be interesting to test Jan Heine's hypothesis that lower pressure tires roll more efficiently on rough surfaces because of less suspension losses. This would require a setup with a human passenger sitting above the test tire and riding over a rough surface such as rumble strips.

Conclusion

The method outlined in this paper for measuring rolling resistance is capable of distinguishing between different tires and can serve as a viable means of measuring rolling resistance of bicycle tires. There were no problems with repeatability on each individual setup.

Problems with repeatability occur between setups, particularly when ensuring that the angle of the trailer is the same for all runs, and that the tire pressure of each tire remains constant over all of its runs when the runs are taken over multiple days.

No conclusions about the relationship of various parameters such as tire pressure or vertical load can be established from the tests conducted with this method so far, however future tests can be done to more thoroughly understand rolling resistance.

The trailer method of measuring rolling resistance has some limitations due to the effect of grade but if proper care is taken during the setup of the experiment, it is advantageous over other methods because it yields the rolling resistance force directly, and does not use unrealistic conditions. The trailer can be pulled across any real world surface.

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