

MEASURING CYCLING PERFORMANCE

Possibilities with Networked Instrumentation, and a New Tool for Analysis

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Sport cyclists often use bike computers to measure time, distance, speed, and sometimes cadence, elevation, heart rate and other parameters to quantify their activities. Evidently these metrics are considered relevant enough. One metric that is more relevant than all others is propulsion power. But at present, power meters are used almost exclusively by performance-oriented cyclists and coaches, and generally perceived as special training tools for elite racing teams. This limitation is partly because they are expensive, but also because the potential utility of measuring cycling power is not well known. The subject of this paper is to explore this potential, with a premise that power meters need not be as expensive in the future when they are optimized for a larger segment of the sport cycling market.

What is cycling power and why we measure it: Elapsed time and trip distance are probably the two most commonly used metrics in cycling. From these two measurements, a conventional bicycle computer calculates speed and average speed. These metrics are sometimes used for utilitarian purposes such as navigation, etc., but in general, cycling computers are purchased and used by sport cyclists who want to measure the significance of their cycling activities. Even in non-competitive contexts, just about every cyclist considers a fast ride or long ride to be a more significant activity than a slow or short ride. A fast and long ride is even more significant. Elevation gains and wind conditions also come up in conversation. So, it is not as though we don't know what is important; the problem is that there doesn't seem to be a universally accepted metric that factors in all relevant attributes of a cycling effort, weighting each one appropriately.

But actually, there is. That metric is energy, often measured in kilojoules (kJ). Energy applies to an effort of a given duration. Power, measured in watts (W), is the instantaneous time rate at which energy is consumed. Thus, to a sport cyclist, *cycling power* is as relevant a metric as any other metric that a conventional cycling computer measures; and new technologies have lowered the cost of the equipment needed to measure it. But for the general public, watts have more in common with electricity and light bulbs than with bicycles; so, the idea of measuring a human being with the same yardstick as measuring stereo equipment, a hair drier or a portable back-up generator may be confusing and intimidating to the majority of ordinary cyclists. Still, we cyclists are intuitively familiar with the relationship between terrain features, winds, and speed. It is therefore best to think of cycling power simply as a '*grade-and-wind-adjusted speed*'. This quantity, which shall be called ***effort speed*** in this paper, is functionally equivalent to power, but has the advantage of being expressed in familiar units of mph or km/h. It is the speed that the effort would have returned in flat and windless conditions. Power can still be used when it is convenient to do so. For example: a cycling coach prescribes a training intensity in watts, and the bicycle is equipped with a power meter that displays watts. In this case, it makes sense to use watts. But training at a given power in watts is exactly the same thing as training at a given effort speed in mph. In both cases, the actual speed will vary precisely the same way according to slope and wind conditions. The reason that the fitness / training industry is standardized on power in

watts, rather than effort speed in mph or km/h, has to do with the former quantity's applicability across different athletes on different kinds of bikes and stationary trainers, and even to other activities or sports.

Input power and output power: The experience of riding a bicycle can be summed up as trying to go as fast as possible (high output) with the least amount of effort (low input) under a given set of external conditions. Of all the contributing factors that make up the external conditions, *hills* and *winds* have by far the most profound and direct effect on how much *effort (input)* it takes to reach a given *speed* (output). A power meter should measure the cyclist's *output* power. But this requirement is ambiguous because the demarcation between input and output depends on one's purpose and intent. For example, if the brakes are rubbing, or if the bearings in the bottom bracket are grinding, some tractive power will be lost and performance will be degraded. But it is not clear whether we want the power meter to register this as a loss of power. If the primary purpose of riding a bike is training, it is probably the effort that the rider wants to quantify. On the other hand, in a race, performance is everything. So, what is a power meter to do? As it happens, some power meters will register brake rub or bearing friction as loss of power, and some will not, depending on which forces they measure to calculate power. For training purposes, it is more relevant to measure the forces that the source presents to the load (e.g., pedal force). For most other purposes, it is more relevant to measure the forces that the load presents to the source (e.g., gravity, air drag and others). Expressed by fundamental laws of physics, the two sets of forces are always in balance. Locations of specific measurement points where sensors are inserted is a factor, but most bicycles' drive trains are efficient enough so that the *generic* difference between the outputs of source-measuring and load-measuring power meters is relatively small. And if a difference is found, the question isn't which meter is more accurate; the question is which metric is more *relevant*. In this paper our primary interest is output power; thus we highlight the load-measuring application.

Networked sensors and processing: Bicycle instrumentation is experiencing a paradigm shift caused by new technology. Conventional instruments must combine all necessary components and sub-systems, (sensors, processors, display, user interface etc.) into one independently operational system. In the new paradigm, the availability and standardization of digital wireless protocols allow "smart sensors" of all kinds to communicate with each other and with a number of interoperable host devices, including power meters. At present, available smart sensors do not provide a full data set from which to compute power, but as more sensors become available, it will be possible for a power meter to run on a smartphone in the cyclist's pocket (for example) and display power data on a bike computer or smart watch. Alternately the power meter could run on the computer or watch instead of the phone. Preferred configurations can be arranged by the end user. The networks are structured such that a given sensor can support multiple host devices that do different things with the data, and some of those host devices may even appear as a sensor to others. For example, a power meter broadcasts power, a speed sensor broadcasts speed, and a head unit displays both metrics. But the power meter may be calculating power using input from the speed sensor. This avoids the duplication of sensors, which is one of the advantages of the new paradigm of networked devices.

The iBike Newton power meter: Made by [Velocomp](#), this load-measuring power meter straddles the paradigm shift and uses two different kinds of sensors to calculate power: speed and cadence come

from independent and interoperable sensors in a wireless network as described above; but for other input data including wind speed and hill slope, the iBike uses dedicated built-in sensors. It also receives data from a heart rate monitor (not used for power calculation). Its hardware doesn't include a GPS receiver, but it exchanges data with a smartphone (over the iBike Cloud) to insert GPS data into the ride file it records. It functions as a head unit to other sensors, but also as a sensor to other head units by sending them power data over a standard ANT+ wireless network. However, it doesn't share the outputs of its internal sensors with other devices on the network, even though the ANT+ standard includes data fields for wind speed and wind direction. Strictly speaking, the iBike power meter does not measure the wind velocity as a vector, but instead calculates the axial component of it from stagnation pressure, barometric pressure and temperature. It records "wind speed" only as a headwind (positive) or tailwind (negative) value. Apparently this level of detail about the wind is considered to be sufficient for estimating power. However, when compared with another power meter ([Cyclops PowerTap](#)), a systematic difference between the two devices is noted under certain crosswind conditions (see Figures 7 and 8). Fortunately, in normal practice these conditions are encountered very rarely.

Power Analyzer: A load-measuring power meter that receives all of its input data from a network of wireless remote sensors would be compelling. The central processing and data logging could then be done either inside a head unit with control and display functions but no sensors, or in a remote processor (e.g., a smartphone) that sends power data to a head unit. In an alternate configuration scenario the smartphone would function as a processor and head unit, eliminating the need for a separate display and user interface. Because load-measuring power meters quantify and analyze all of the load forces, other relevant cycling metrics can be calculated as a bonus. To study the feasibility of this method of measuring power, and to test its accuracy, a 'proof-of-concept' power meter, called Power Analyzer, was developed by the author. Power Analyzer doesn't directly communicate with sensors. It is a spreadsheet program that calculates power from equations of motion, user-specific constants (user profile), and 4 input variables from a data file recorded at regular time intervals:

1. Ground speed
2. Hill slope
3. Air speed (speed of the airflow relative to the moving bike)
4. Apparent wind angle (angle of the airflow relative to the moving bicycle).

There are two important points:

- If the airspeed is input as a **mass flow rate**, it is not necessary to also know the density of air to calculate power.
- If the airspeed is input as a "**headwind component**", the dependence of power on the apparent wind angle is generally small enough in practice to be neglected under most wind conditions. But Power Analyzer is not constrained by this assumption.

How it works: Power Analyzer is indifferent to how the input data was generated or recorded. But the use scenario for the test results presented in this paper is as follows: During a bicycle ride, an iBike Newton power meter measures at 1-second intervals, the first 3 of the requisite 4 variables, and records

their values (along with the power it estimates from them) into a data file. After the ride, the recorded data file is uploaded to a PC; Power Analyzer opens this file and computes the cyclist's power for every second of the ride, using only the 3 input variables written into the file by the iBike, assuming that the 4th variable (apparent wind angle) is 0°. For most of the tens of thousands of data samples per ride, the instantaneous power computed by Power Analyzer is nearly identical to that recorded by the iBike Newton power meter, which is, in turn, nearly identical to that recorded by a PowerTap power meter installed on the same bike (see 5 mile segment in Figure 3 as a typical example). Because PowerTap calculates power from two entirely different input variables than those used by the iBike (rotation speed and torsion of the rear hub), the agreement between the three results is interpreted as a confirmation that cycling power can indeed be determined from *speed, slope and air speed only*, with sufficient accuracy under most conditions. Also knowing the apparent wind angle may increase the accuracy of the load-measuring power estimation under certain crosswind conditions, but testing this hypothesis is outside the scope of this paper.

Comparisons with other power calculators: For a given set of input variables, Power Analyzer computes the same power as the following power calculators:

http://www.analyticcycling.com/DiffEqWindCourse_Page.html

<http://www.cyclingpowerlab.com/PowerComponents.aspx>

http://www.machinehead-software.co.uk/bike/power/bicycle_power_calculator.html

The accuracy of Power Analyzer is also confirmed with calculators of limited capability (9 of them were checked), which exclude one or more of the following contributing factors: acceleration, wind angle, wind speed, and hill slope.

The main feature that distinguishes Power Analyzer from other calculators is that it operates on dynamic input data recorded during a bicycle ride, rather than only one set of input values at a time. [TCX VPower](#) and [Strava](#) also offer this feature, but they have limited accuracy because they don't account for the effect of the wind. In addition, Power Analyzer allows for a wind-yaw dependent air drag coefficient. [Analytic Cycling](#) also supports wind-yaw dependent properties, but only for the wheels.

Virtual power: Cycling power that is calculated from ride data (as with iBike and Power Analyzer) is sometimes referred to as "virtual power". This term is misleading because there is no other kind of power. Power is always calculated from measured physical quantities (e.g., voltage and current, force and velocity, etc.) and does not exist independently from them. For bicycle propulsion, unless the equations for calculating power are constrained by simplifying assumptions that are unreasonable (e.g., estimating power from heart rate), virtual power is equal to power. Distinction should instead be made according to whether the measured quantities are associated with the source or the load. Source-measuring and load-measuring power meters estimate the same power, but the latter technology offers the additional ability to itemize the estimated power in 5 distinct load categories:

1. Gravity (positive elevation gains)

2. Aero (overcoming air drag –includes the effect of wind)
3. Rolling (overcoming tire rolling resistance)
4. Inertia (power used for accelerating)
5. Drivetrain losses (power dissipated during transmission from the pedals to the rear wheel)

Since there are no other loads that can resist the movement of the pedals (the only place where the power we want to measure is applied), power must always be the sum of these 5 constituent components. Power Analyzer accounts for this actuality and provides an “energy balance sheet”, a full breakdown of instantaneous power in all 5 load categories (Figure 5). In addition, Power Analyzer extracts two other quantities from the ride data: braking energy and wind energy. Braking energy is not included in the energy balance sheet because normally a cyclist does not brake and apply pedal power at the same time.

For most road rides, even on mountainous terrain, the total energy dissipated by braking was found to be very small relative to the total propulsion energy. On the other hand, wind energy was found to be significant. Therefore, Power Analyzer calculates the impact of the wind energy, and identifies whether it was favorable (positive value) or unfavorable (negative value) for the activity in question.

Sensors: Power Analyzer is not constrained by any particular sensor technology, but some methods appear to be convenient: a Pitot tube, or a pressure gauge for measuring stagnation pressure, can be used as a wind speed sensor. Alternately, [anemometer](#), [impeller](#) or [microphone-based](#) sensors for smartphone applications may be used. Wind direction can be measured with a [wind vane](#). An accelerometer can measure the sum of forward acceleration and positive hill slope. If gravity power and acceleration power must be known independently, hill slope can be calculated from the difference between the accelerometer output and the rate of change in the output of a [wheel speed sensor](#), but this step is not required for calculating the total power.

Example screenshots: (Figures 1-6) illustrate key features of Power Analyzer and its accuracy relative to two power meters: iBike and PowerTap. Figures 7 and 8 refer to a special test ride that was conducted in the field but under relatively well-controlled wind conditions, to investigate a wind-yaw-induced difference between the outputs of the iBike and PowerTap power meters. Such difference is observed only in certain crosswind conditions, an example of which is identified with the blue circle in Figure 3a.

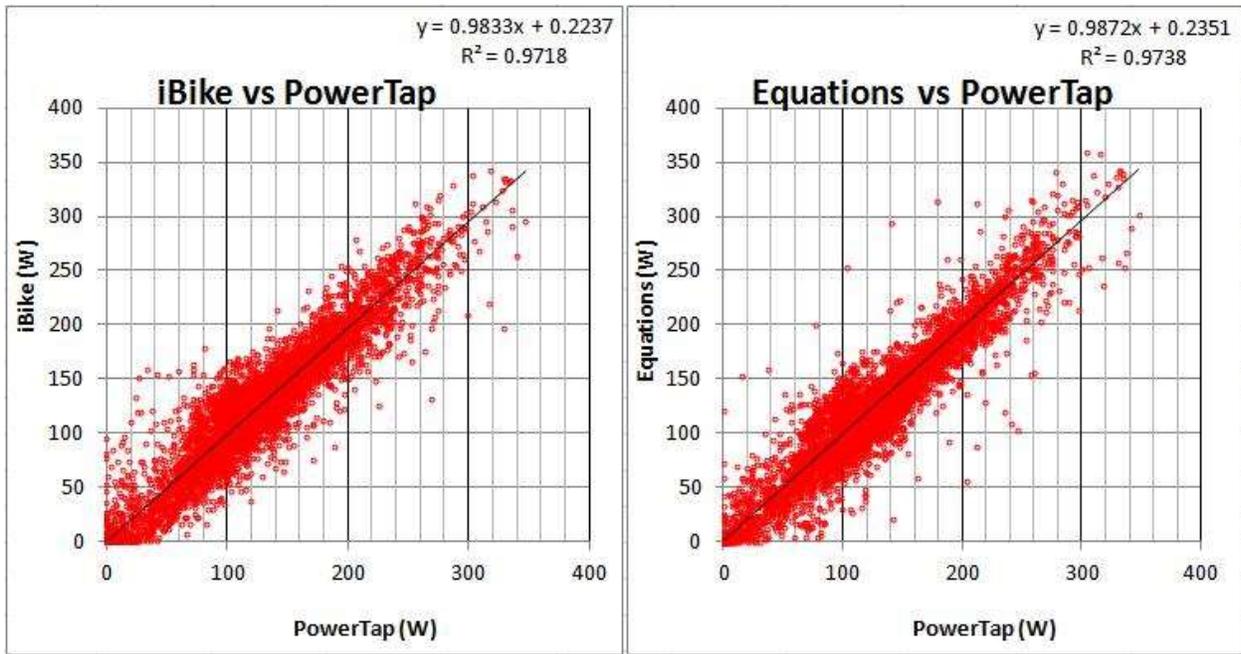


Figure 1 –Correlation between Equations (Power Analyzer), iBike Newton and Cyclops PowerTap power meters for a 27-mile ride.

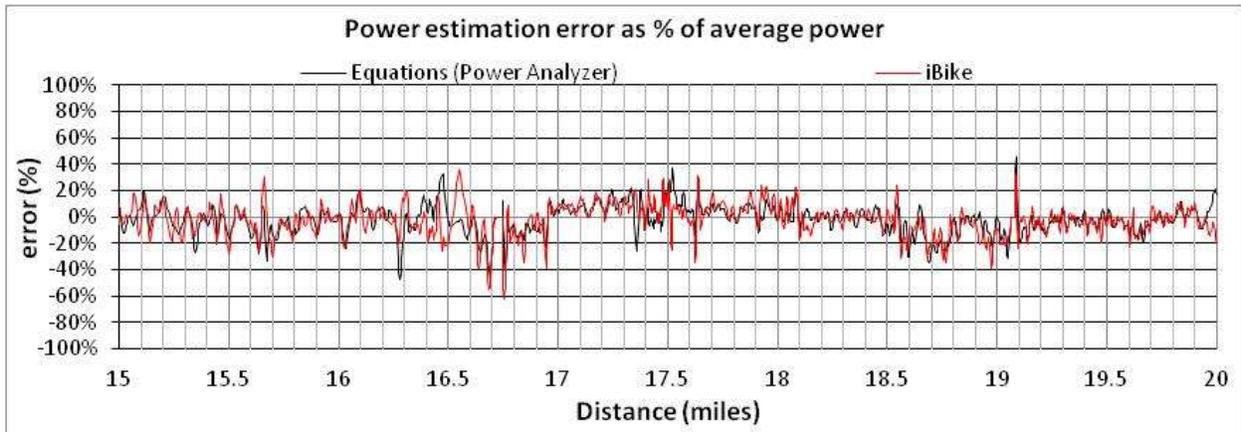


Figure 2 –Error relative to the PowerTap (considered to be the reference), shown over a typical 5 mile section of the same ride. Seemingly random fluctuations in the difference curves appear to be caused by minor timing discrepancies between devices, and diminish with data smoothing. None of the 3 data records stands out as being inherently smoother than the others.

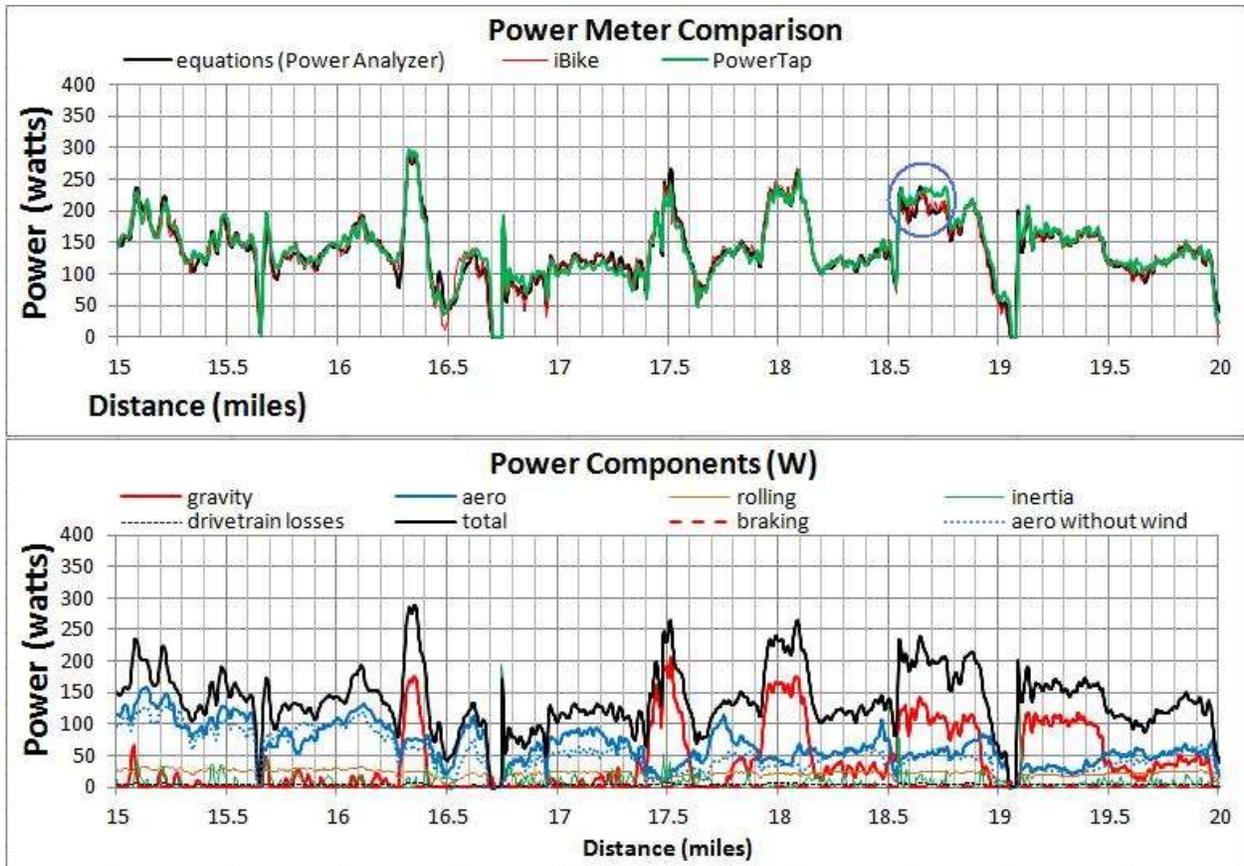


Figure 3 – (a) Typical example of Power Analyzer, iBike and PowerTap power meter outputs. Accuracy in the circled area may be improved with wind angle sensor –see Figures 7 and 8. (b) Total power is divided into 5 constituent load categories. Braking power and the effect of the wind are also shown.

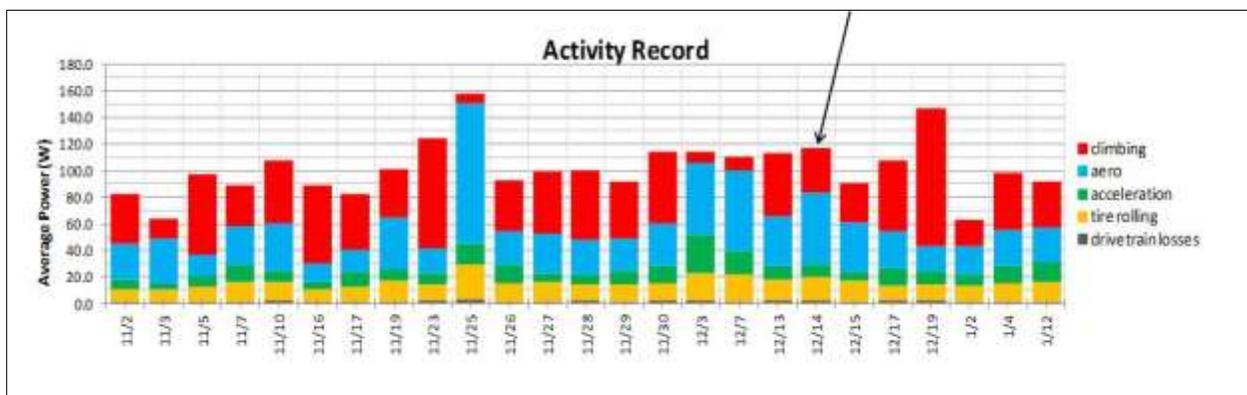


Figure 4 –Activity Chart for an example 10-week period shows each activity’s average power (energy also available) and itemizes it in 5 distinct load categories. Note the difference between workouts with similar power levels that are dominated by winds (11/25) as opposed to hills (12/19). The variability of the relative share of acceleration power across multiple activities is also noteworthy (compare, for example, 12/3 with 12/19). Arrow identifies the activity that Figures 1 - 6 refer to.

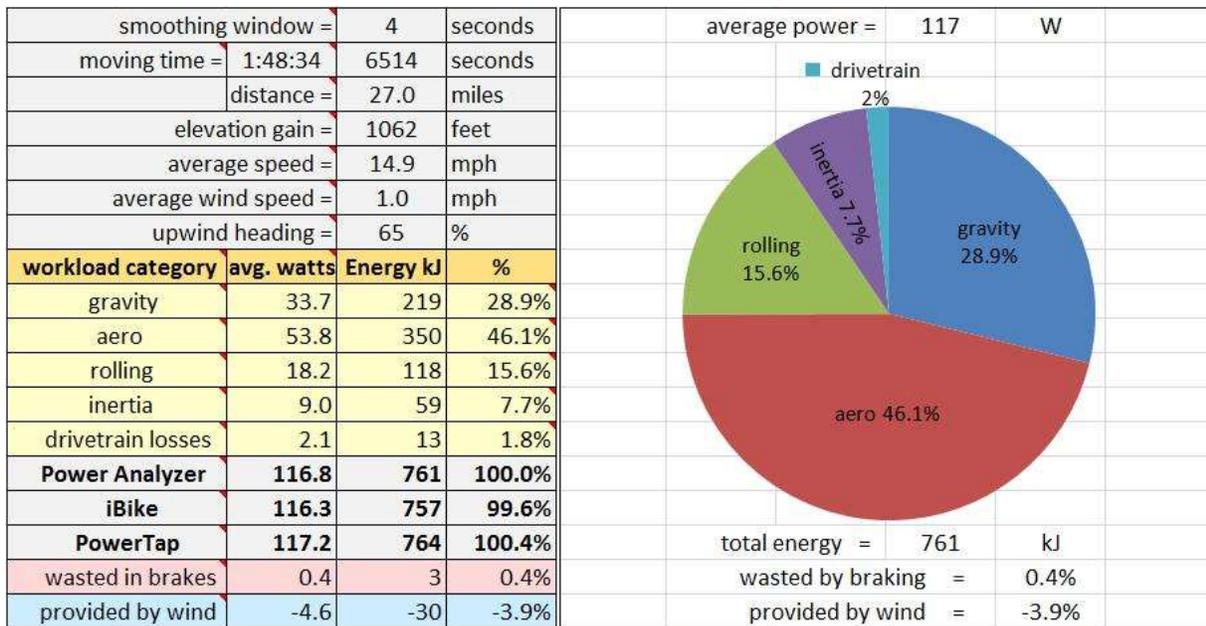


Figure 5 –Statistics for the 27 mile ride; correlation between average watts from Power Analyzer and 2 other power meters (iBike and PowerTap).

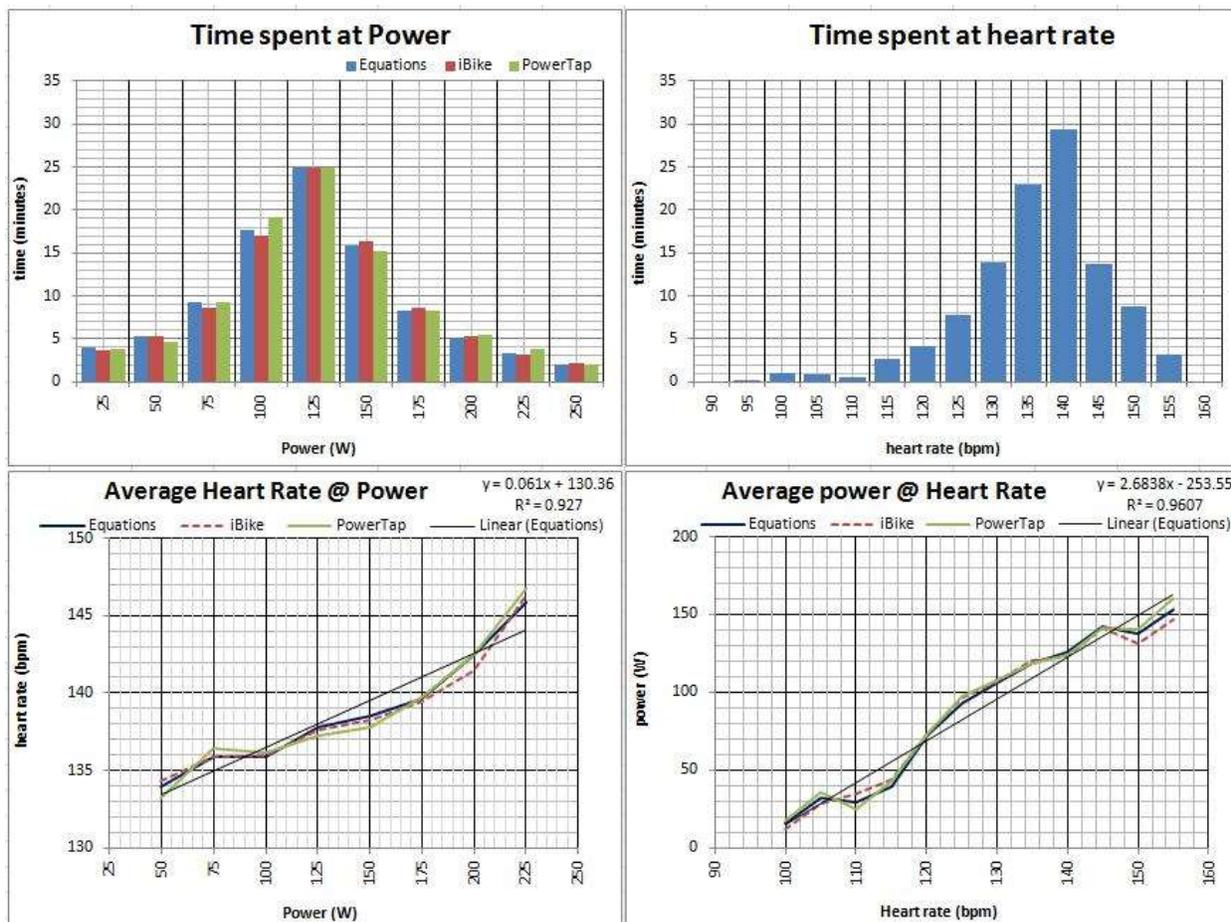


Figure 6 –Power distribution; correlation between heart rate and power.

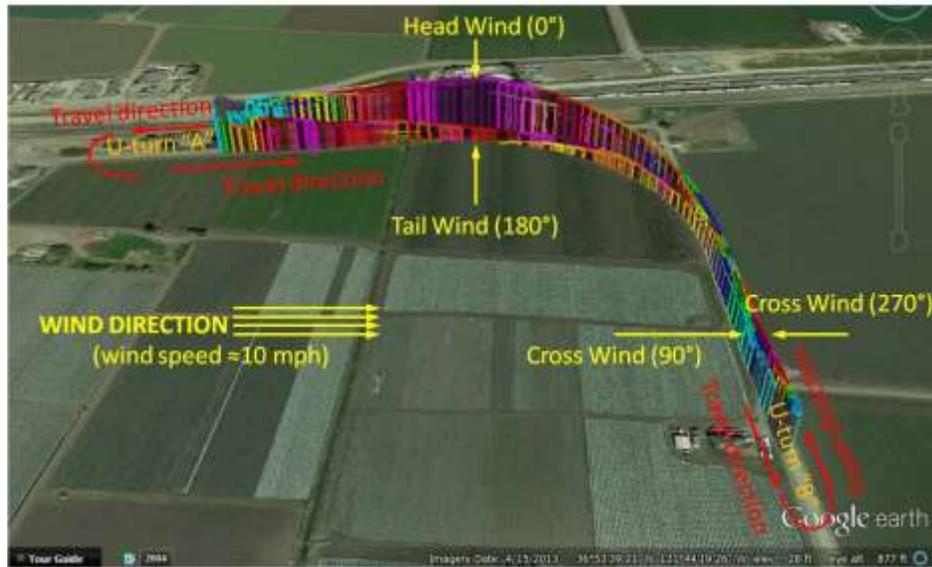


Figure 7—Wind visualization from data recorded in the iBike power meter using the Newton Tracker app for smart phones. The height of the wall represents “wind speed”, a scalar quantity derived from stagnation pressure measured by iBike’s wind sensor. The color of the wall represents bike speed.

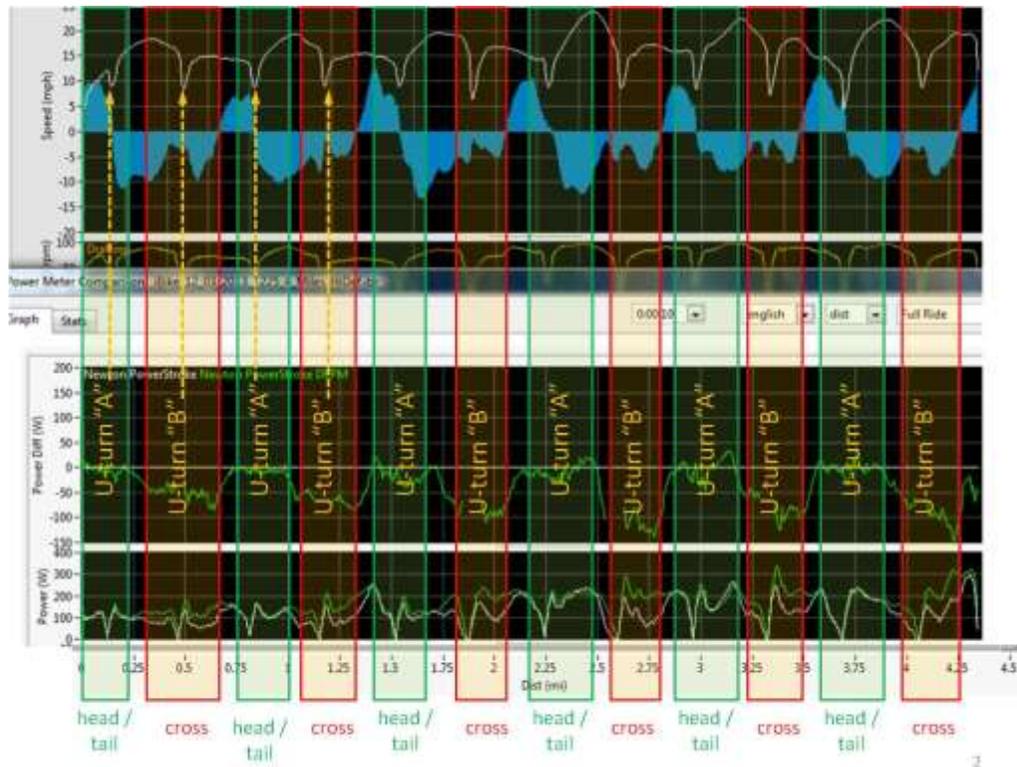


Figure 8—Data recorded during repeated laps on the course shown in Figure 5. Blue = wind speed. The “Power Diff (W)” plot is the difference between two power meters (iBike Newton and Cyclops PowerTap). In certain crosswind conditions (near U-turn B), the iBike reports approximately 50% less power than the PowerTap. Since PowerTap’s accuracy cannot be affected by wind, the discrepancy is attributed to the iBike. Measuring the wind velocity as a vector might have reduced or eliminated this error.