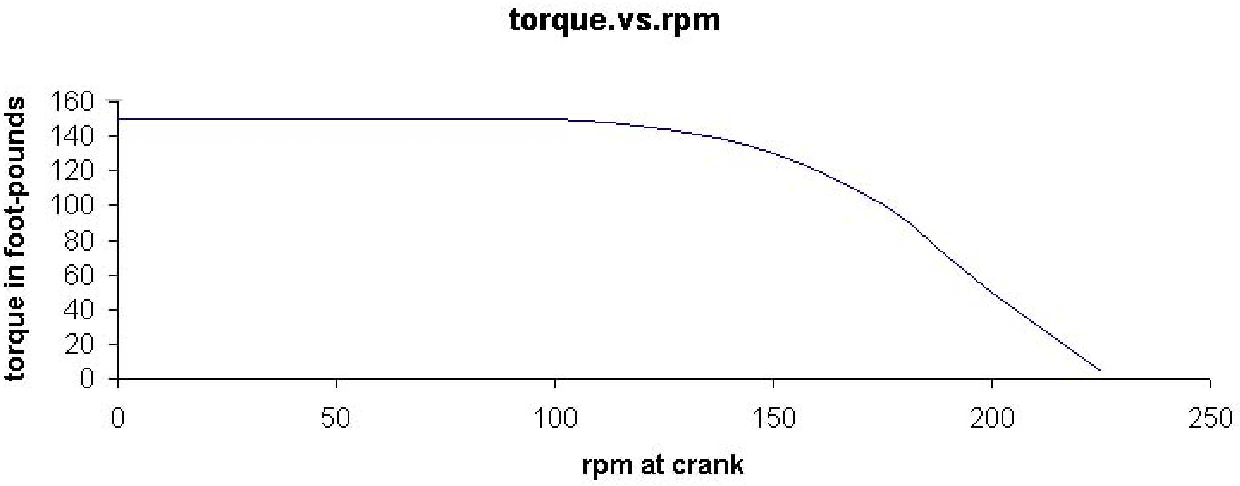
Bicycle efficiency and power -- or, why bikes have gears.

When you try to determine how fast a bike can go, what you do is you match the power available against the power required, at a given speed. This energy budget indicates whether you can go faster, or whether you can even hold your current speed.

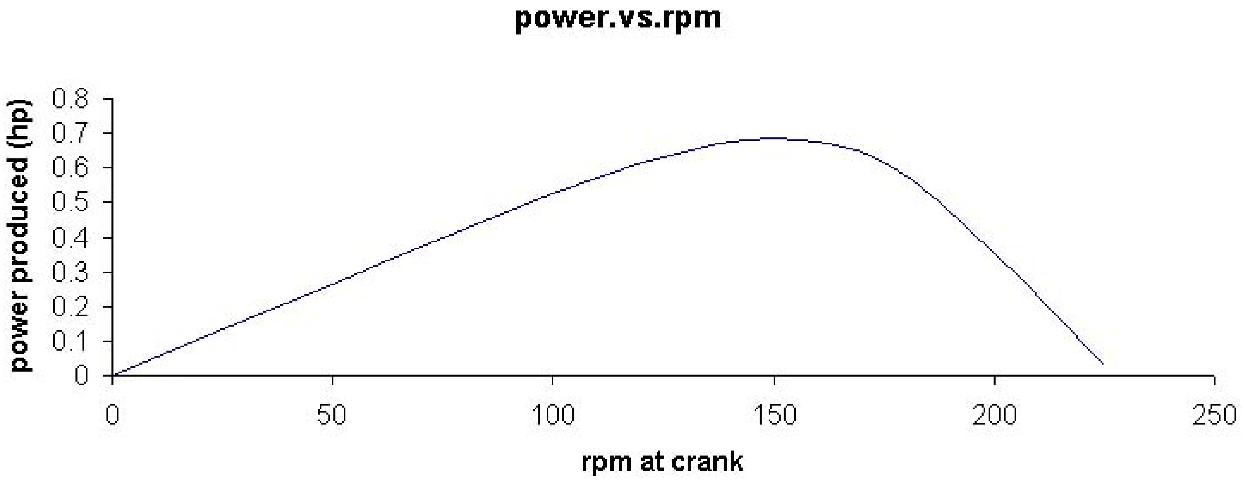
Power available:

A human engine has a torque curve similar to that of a steam engine, more or less, which is to say that it is flat until a certain critical rpm, at which point it begins to drop off, because the energy used in accelerating and decelerating massy components (legs) begins to take up all the energy produced.



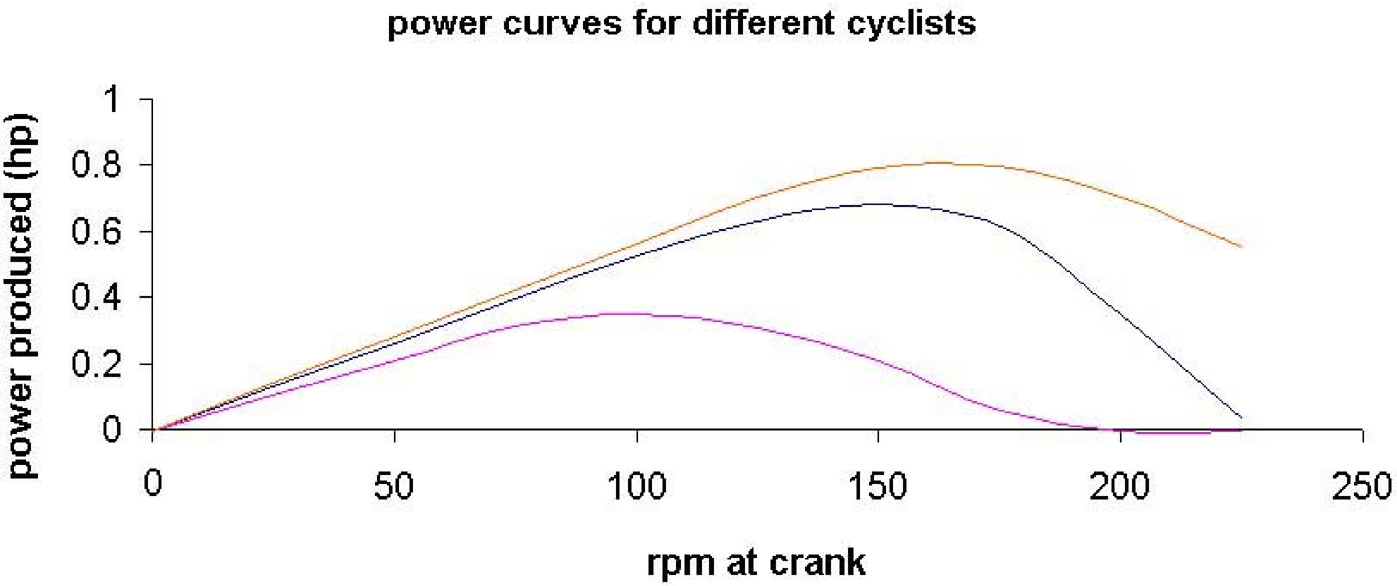
Power produced is the product of torque times rpm. (a quick digression: your torque is a product of your leg length, your crankarm length, your wheel size, your gear ratio -- what we're talking about here, though, is torque measured at the crank itself. So the only things that are of issue are leg geometry, crankarm length, the rider's weight, and, most of all -- the rider's leg strength.)

So if we revisit the previous graph to show POWER produced, it will look like this:



This is just the torque curve above, with each point multiplied by the matching rpm. One thing to notice here in comparing this to the previous graph is that your power is still rising even after you've passed the torque peak. You can actually feel this when you're pedalling really fast up a hill -- you feel like you almost can't push on the pedals because you don't have time to, but you're still going like anything.

So we can make a graph showing three different riders and their power curves, like so:



This shows three cyclists: the lowermost curve is the power curve for a beginning cyclist; the middle one for a fairly serious recreational cyclist, and the top one for a track racer. Notice that there isn't much difference in the force they can exert (I'm making some assumptions here -- a beginning cyclist can push 120 lb-feet and peaks at 90 rpm, whereas a serious track racer like Marty Northstein can generate 160 lb-feet at over 175 rpm.)

The point here is that strength is less important than smooth, fast pedalling.

Power Required:

Now, the next subject is: where does the power go?

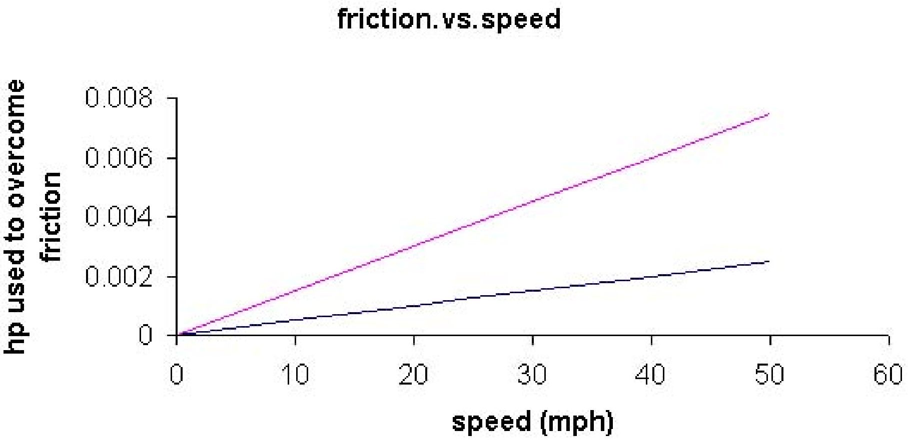
There are two places: friction and air resistance.

Friction:

Friction losses are from bearings, from the viscosity of grease, from the chain, from the tire squishing against the pavement. Knobby tires are rougher; soft tires smoosh more; heavy grease or badly-maintained and corroded bearings take more force to move.

Estimates of friction losses are between 15% of total power, for a Huffy moutainbike that has had little maintenance, to maybe 0.5% for an Olympic track bike. (The friction losses in powertrains for bicycles are the lowest of any machine, because the speeds are low and the power is low.)

The power required to overcome friction rises linearly with speed.

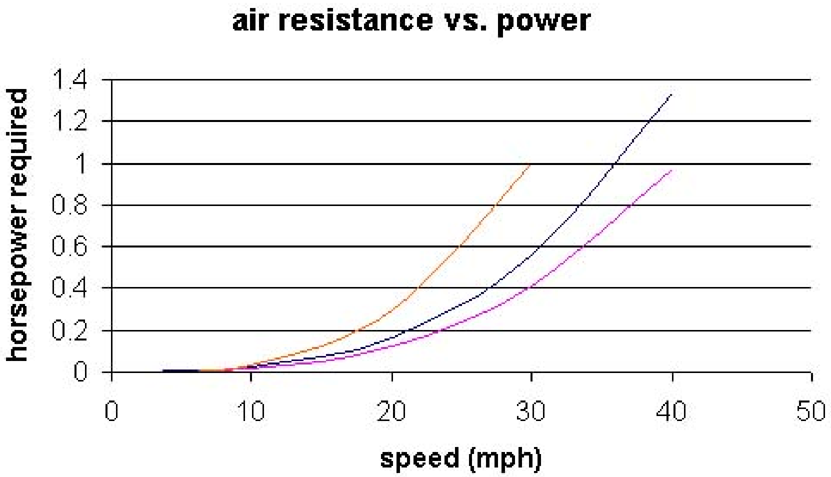


On this graph, the upper line is an old mountain bike; lower is a nice track bike.

Then there is the huge one, that serious cyclists spend most of their time fighting:

Air resistance.

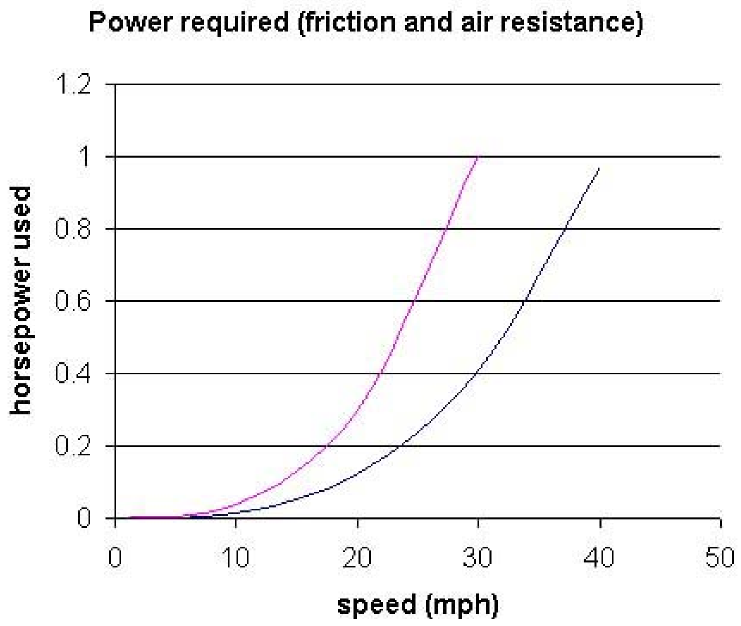
Drag from the air isn't a big problem at low speeds. However, it has one unsavory characteristic: the force required to overcome air drag rises as the square of the speed. As we saw before, power is force times speed, so the power rises as the CUBE of the speed.



The top/leftmost line is a mountain-bike with wide tires and a rider sitting upright. The middle line is a road bike with a somewhat crouched rider. The bottom/rightmost line is a time trial bike with disc wheels, the rider almost flat and wearing slick clothing to minimize clothing flutter.

The power a human can generate is highly dependent on the duration of the effort. In a four-second burst, a weightlifter might generate 3 horsepower. A world-class cyclist will generate 0.65 hp for a 1-hour time trial -- all-out effort. Most recreational cyclists generate about 0.35 hp for a sustained (2 hour) ride. Consider 1 hp to be the absolute maximum you can generate, and this chart will give you a rough idea of how fast you'll go, depending on your bike. As resistance increases by the cube of speed, the contribution to drag of different things on the bike is variable -- because not everything is going the same speed. At zero speed, the bike might contribute 15% of the total air drag of the system, more if it's a mountain bike. But, the bottom of the bike wheel is always still, right, because it is touching the ground. So the TOP of the wheel must be going twice as fast as the bike itself, and because the power required rises nonlinearly with speed, the bike takes up increasingly more of the drag as the speed rises, which is why reducing spoke count and trying to cover the wheel becomes a big issue at high speeds.

So now we can generate a sum total of power required, by adding the friction losses to the air resistance losses.



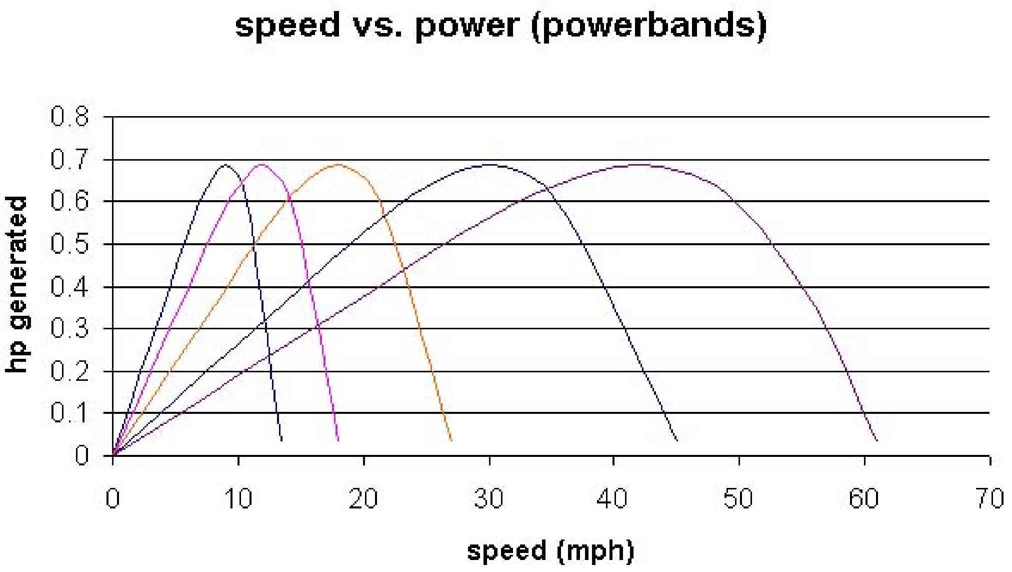
The upper line is a Department Store mountainbike -- with lots of friction and an upright riding position. The lower one is a well-maintained racing bike with lots of aerodynamic modifications to try and make it more slippery. As a general truism, on a bike you're mostly fighting rolling friction from the tires below 12 mph.

Above that speed, your power starts going primarily into fighting air resistance. If your bike is particularly friction-prone, with low-pressure tires, the crossover point will be at a higher speed.

Back to generated power!

The graphs of the amount of power generated don't tell you much about speed. That's where gears come in. What you want to do is operate at or near your power peak. If you're riding on a flat and level road with no wind, you can do this with a one-speed bike because you operate at equilibrium. This is what track bikes are: single-gear bikes that are optimized for one speed.

But if you have to deal with hills and winds, you need multiple speeds to match your power peak to the power-required curve.



This shows a five-speed bike, with the speed the rider will go in each of the five gears, barring any sort of air resistance. If you were riding on the moon, this is what you could do. Low-gear is on far left, high-gear on far right.

The speed.vs.power chart is just the power.vs.rpm chart done in several iterations; the data are the same.

Now we can combine the charts to make the actual how-fast-will-you-go chart.

There are lines for the five gears, matched against the power-required line for a fairly slippery bike.

So under this particular scenario, you would go fastest in fourth gear. What this says is that if you have high air resistance, carrying big gears is actually a waste of your time because you won't generate the power you need, in them. If you have a very fast, slippery bike, you should not be carrying tiny gears because you'll only use them for accellerating off of a complete stop. Of course, this all assumes a flat road. As soon as you start onto a climb or a descent, you effectively have a different power rating, which will shift all your gear curves upwards or downwards.

That's why we have gears and part of why mountain bikes are built with smaller gearing than road bikes have. All of this applies equally well to cars and trucks and things like that, of course...

Touring bicycles have a wide range of gears and big changes between individual gear sizes, where racing bikes have the so-called corncob or pinecone cogsets, with cogs varying by 1 or perhaps two teeth throughout the whole range of the stack. The former works very well for terrains with lots of variation, and the latter gives the highest speed for any given power setting, in one instance of terrain.

Comments or questions, email katana@frii.com and tell me what you think or where I messed up.

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