Pedal Power

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*Why can't I cycle faster? **Jon Clarke** applies physics to this question.*

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I cycle a lot, both for work and pleasure. This year I was given a cycle computer which measures speed, and that has reinforced questions that have struck me recently.

- Why can't I reach 30 miles per hour (13 m/s) on a level road no matter how hard I cycle, yet elite women's races routinely hit 37 mph (17 m/s)?
- Why does a slight headwind make cycling such hard work compared to a slight tailwind?
- Why is my average speed so consistently around 14 mph (6 m/s), whether that's sprinting as hard as I can for 40 minutes to my friend's house, or riding for 7½ hours to visit the seaside?

I gradually realised that physics has a lot to say about each of these questions.

Shanaze Reade and Victoria Pendleton: two of the UK's top women team sprint cyclists, celebrating gold at the 2008 Track Championships.

Which variable?

Force: Was I limited by not being able to push the pedals hard enough? If you push down with more force than your body's weight then you accelerate upwards. Standing on one bent leg, I can easily straighten it, lifting my whole body's weight. Cyclists are not strapped down onto their seats, so pushing a lot harder is not useful, because it will simply lift you off the bike. I already seem to be capable of exerting more force than is useful, so that doesn't seem to be the limitation.

Energy: Had I emptied the chemical store of my body, so I could no longer do mechanical work? Even after cycling as hard I could for a minute or two, I can still carry on cycling. I might need to get my breath back, and let my body clear any build-up of lactic acid, but clearly I do still have energy available to me, otherwise I wouldn't be able to get home afterwards! So this isn't it.

Power: Is it that I can't do work at a high enough *rate*? Is it possible that I can't shift energy from my chemical store fast enough? The rate at which people can use oxygen during respiration to power their muscles is measured by their VO_2 max, and this is considered a critical measurement for elite athletes. The organisation which supports the British Olympic team invests heavily in measuring power and using it effectively during training. So power does look particularly relevant.

Calculating power

Imagine a cyclist providing a driving force *F* and moving with speed *v*. Both of these variables can be measured for a cyclist. Their power *P* can then be calculated from

$$P = F \times v$$

where *P* is in watts (W), *F* is in newtons (N), and v is in metres per second (m/s).

A touring bike like mine.

What force must I provide?

Lots of people have used *models* to represent the forces involved in cycling. A cyclist will need to overcome rolling resistance, air resistance, and a component of their weight if they are cycling up a hill. For simplicity, I will focus only on level roads, so we can ignore the weight. The models agree that the air resistance is far larger than the rolling resistance at my cruising speed of around 20 mph (9 m/s), so I will now consider only the air resistance.

This is modelled as having a force that increases with the *square* of the speed, that is, doubling the speed means the force due to air resistance increases by a factor of four.

Cycling in the gym – no air resistance to overcome here.

What power must I provide?

Remember that power is force times speed, so if the force increases as speed squared, then the power increases as speed *cubed*. Expressed mathematically:

$$P \propto v^3$$

So doubling the speed increases the power required by a factor of 2 × 2 × 2 = eight!

Cycling as hard as I can on a level road with no tail wind, I reach a maximum speed of 25 mph (11 m/s). One model calculates that this corresponds to a power of 330 W. For me to reach 30 mph (13 m/s, the UK speed limit in residential areas), I would need to provide:

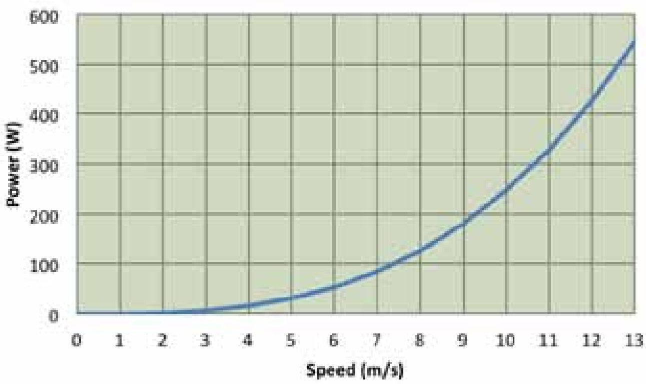
$$P = 330 \times \left(\frac{30}{25}\right)^3 = 570 \text{ W}$$

a massive 70% more power just to go 20% faster! I've already been cycling pretty intensively for two years – I'd need to train and gain the fitness of an Olympic athlete just to reach that extra 5 mph! The graph shows how the power needed to overcome air resistance increases with speed.

What if I drop my speed by 20% to 20 mph? Now we have

$$P = 330 \times \left(\frac{20}{25}\right)^3 = 170 \text{ W}$$

So dropping my speed by 20% means I can cruise along with a significant (and restful!) drop in power of 50%. No wonder my average speeds are so similar even over very different distances.



The power required to overcome air resistance increases more and more rapidly as speed increases.

Commuting by bike in San Francisco: a quick and healthy way to get around.

The same idea applies to tailwinds and headwinds. London's average wind speed is 10 mph (4.4 m/s). Cycling *with* the wind at my cruising speed of 20 mph (8.8 m/s) gives a relative speed of just 10 mph (4.4m/s) requiring a trivial,

$$P = 330 \times \left(\frac{10}{25}\right)^3 = 21 \text{ W}$$

less than I require to simply stay alive, whereas cycling against it means we're back to a relative speed of 30 mph again, needing that unachievable 570 W. No wonder I like it when the wind's behind me!

Note that the same physics applies to wind turbines. Siting them where wind speed is twice as high, for instance on a hillside compared to the centre of a city, will produce a massive eight times as much electrical power.

How do they do it?

World-class athletes like Shanaze Reade and Mark Cavendish make their achievements through years of hard training, so they are capable of higher power than me, using equipment such as specially built bikes which minimise their air resistance and, in some events, "drafting" behind other cyclists to take advantage of the air being pushed forwards by the rider in front.

So with a little disappointment, I can see that I'll never defeat the physics to cruise along at 30 mph, but I have also learnt that if I feel like taking it easy whilst riding somewhere I can do so safe in the knowledge that it won't make much difference to my speed. I've also have learnt far more respect for anyone with the fitness needed to reach that speed!

Jon Clarke cycles to work at the Institute of Physics in London.