Day 6

Physics of Sports

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Image https://www.disneyclips.com/imagesnewb/skating.html

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Plan for Today

- Video: https://www.youtube.com/watch?v=lNpfLyzXRdE
- A quick estimation of drag on a cycle rider
- Estimating power consumption of riders
- The magic of velodrome
- A detailed calculation of the effect of air temperature/density

Cycling and basic dynamics

- When travelling horizontally, the bike is under the influence of five forces (figure 2).
- In the vertical direction gravity and the normal reaction force (F) cancel each other out.
- In the horizontal direction there are two retarding forces, one due to the aerodynamic drag (which is commonly referred to as air resistance) and one due to the rolling friction experienced by the wheels.
- Finally a propulsive force due to the reaction of the tires of the bike pushing back on the road also acts in the horizontal direction.

Cycling and basic dynamics

- Therefore, we can assume that if the bike is moving with a steady velocity,

$$F_b = D + F_{rf}$$

- The drag *D* is given by

$$D = \frac{1}{2}\rho C_D A v^2$$

Area includes bicycle and the rider

- Rolling friction is give by

$$F_{rf} = \mu N = \mu w = \mu mg$$

Cycling and basic dynamics

- Hence we can find the power expended by the rider by multiplying the force by speed:

$$P_b = \frac{1}{2}\rho C_D A v^3 + \mu m g v$$

- It is evident that a proportion of the energy expended is used to overcome aerodynamic drag and a proportion to overcome friction.
- What comes as a surprising result to most and serves to illustrate the importance of aerodynamic design in sport, is that the greatest amount of energy generated by the athlete is spent overcoming the air resistance.

Vassilios McInnes Spathopoulos, A physics heptathlon: simple models of seven sporting events, Physics Education, Volume 45, Number 6

Cycling and basic dynamics

- Hannas and Goff have used a similar process to the one described here to successfully model the Tour de France race and from this reference one can obtain typical values for the model parameters.
- For the purposes of the analysis presented here the following values are used: $m = 77kg, C_D A = 0.3\mathrm{m}^2, \rho = 1.2\mathrm{kg\ m}^{-3}, \mu = 0.003$

$$\frac{\frac{1}{2}\rho C_D A v^3}{\frac{1}{2}\rho C_D A v^3 + \mu m g v}.100\% = 92\%$$

[A] Hannas B L and Goff J E 2004 Model of 2003 Tour de France Am. J. Phys. 72 575–9
[B] Hannas B L and Goff J E 2005 Inclined-plane model of 2004 Tour de France Eur. J. Phys. 26 251–9

The iconic cone-shaped helmet used in velodrome racing and closed-circuit time trials features smaller drag coefficients that shave precious seconds off a racer's time, but only if they are held in the optimum position.

Lisa, Michael. *The Physics of Sports*. McGraw-Hill Higher Education, 20150220. VitalBook file.

Class work

Q. In order to avoid falling over, a cyclist needs to maintain a minimum speed of about 3 mph. Consider a 180-lb rider on a 20-lb bike attempting the famous 31.5% slope of Filbert Street in San Francisco. Wind drag and rolling friction certainly aren't his main concerns! We'll ignore them.

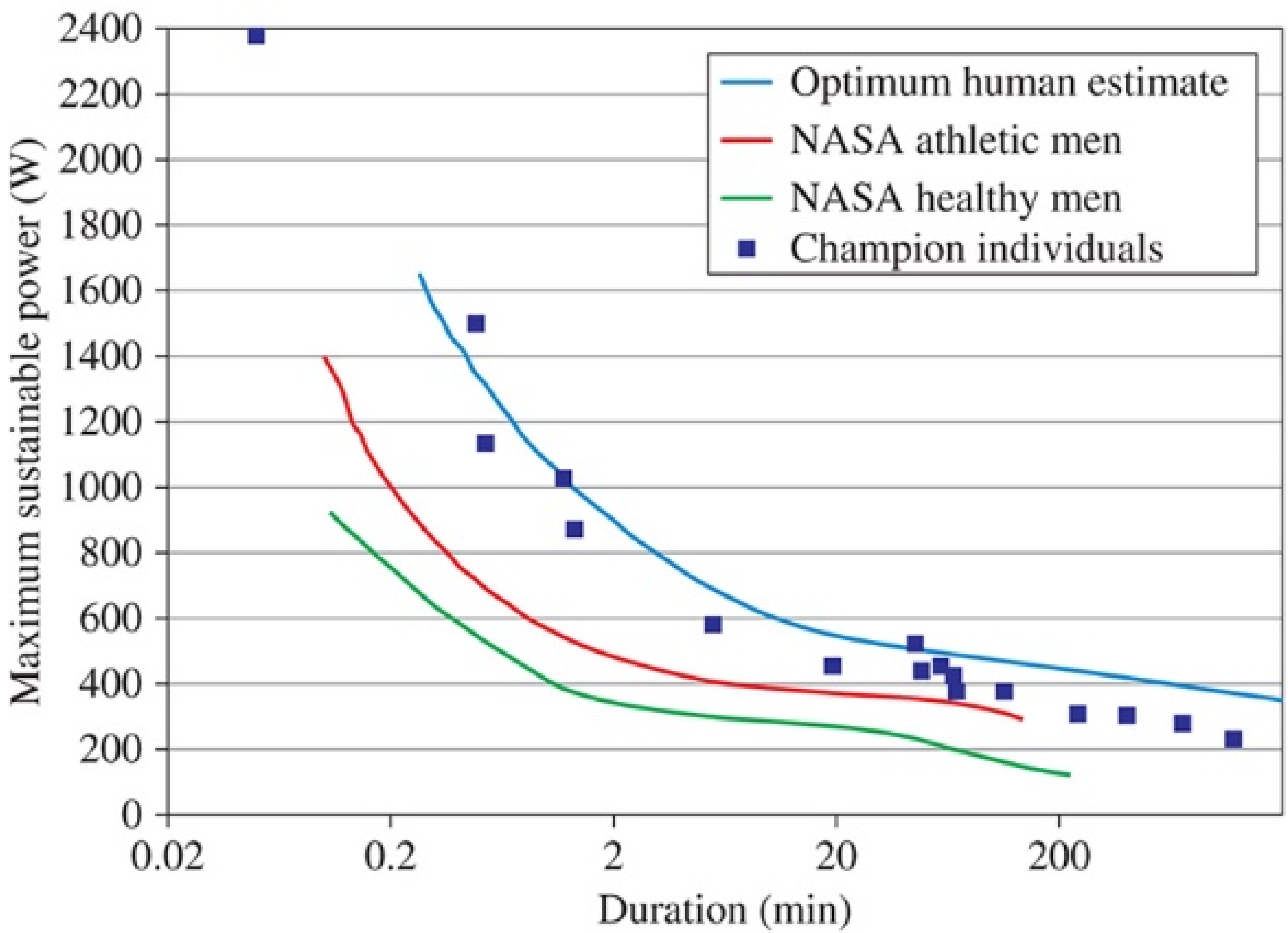
a) In lb, what is the backward force of the hill |Fhill|?

b) How much power must be put out, in order to climb the hill at a constant speed of 3 mph?

Power = Force x speed

Max sustainable power

Referring to the NASA estimate in figure, about how long could a “healthy man” continue such a climb?



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The British men's pursuit team at the 2012 London Olympics. Everything—the helmets, the visors, the tight clothing, the posture, the covered wheel spokes, and especially the group formation—is designed to fight the great enemy, air drag. Even the air is heated to reduce its density. The power measurements were done on another team in 1999 traveling at 37.5 mph. (© Christophe Ena/AP Photo).

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Let’s dig deeper: The rarefied air of the London velodrome

https://www.pinterest.com/pin/400468591840352120/?lp=true

The rarefied air of the London velodrome

- Every Olympics host city wants to be remembered, and London was no different in 2012.
- Built at a cost of £105 million (about $160 million), London VeloPark is a sleek, beautiful state-of-the-art facility.
- But the organizers wanted more than a memorable facility—they wanted records to be set at the VeloPark. It worked.
- In the first day of Olympic competition, world records were set six times in two different events.

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The rarefied air of the London velodrome

- Recall, the density of air—and therefore air drag—goes down as the temperature goes up.
- So an underflow heating system lies below the track itself, designed to keep the air temperature at a toasty 82.4 F, though the spectator level was cooled to a more comfortable temperature.
- (The famous London weather was thought to help, too, since air pressure and density drop even more when a front comes through. While participants in outdoor events might have wanted fair weather, velodrome organizers actually hoped for rain.)

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The rarefied air of the London velodrome

- In the individual pursuit, two riders start from opposite sides of the track and race 4 km, each trying to catch the other if he can.
- Ignoring the effect of the banked turns, what would be Bradley Wiggins's time in this race, for air at 70°F and at 82.4°F?
- Wiggins has a mass of 69 kg and his 1-hr PWR (Power to Weight Ratio) is reported to be an impressive 6.6 W/kg. (Notice, based on units, it should be called Power to Mass Ratio).
- The duration of the pursuit is much less than 1 hr, but for the purpose of this example, let's use this PWR, since it is more difficult to find reliable numbers for short races.
- We know that the race times that we calculate will be somewhat higher than what Wiggins actually achieves.

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The rarefied air of the London velodrome

- Using given data, Wiggins can put out a power of:

$$\overline{P}_{\text{output Wiggins}} = \text{PWR} \times \text{mass} \;= 6.6W\,/\,kg \times 69Kg = 455W$$

- Let's first estimate Wiggins time to cover 4km at room temperature (70F).
- There are no wind (v_{wind} = 0) or hills in our simple race, and at 70°F, the density of air is 1.2 kg/m^3.
- We'll use the racing bike values for C_D, A, and C_R.

The rarefied air of the London velodrome

- The rules demand that track bikes, like Tour de France bikes, have a minimum mass of 6.8 kg (15 lb), so the mass load on the wheels is 69 kg + 6.8 kg = 75.8 kg. Assume there are no hills, hence $s = \sin\theta = 0$
- Using all these numbers we can write:

$\bar{P}_{\text{output by cyclist}} =$ overcoming rolling friction

+ overcoming hills (if any)

+ overcoming wind (negative if the wind is faster and blowing in the same direction as cyclist)

+ left over for acceleration

The rarefied air of the London velodrome

$$\begin{aligned}\bar{P}_{\text{output by cyclist}} &= \text{overcoming rolling friction} + \text{overcoming wind} \\ &= C_R m g v_{\text{bike}} + \frac{1}{2}\rho C_D A v_{\text{bike}}^3 \\ &= (0.003)(75.8kg)(9.8m/s^2)v_{\text{bike}} + \frac{1}{2}(0.88)(0.36m^2)(1.2kg/m^3)v_{\text{bike}}^3\end{aligned}$$

- Since we know the left hand side (455W), we can solve this cubic equation, or just make and intelligent guess and see what we get.
- We settle for 13.1 m/s as his speed.

The rarefied air of the London velodrome

- Finally, knowing the distance travelled, we find the time taken:

$$\Delta t = \frac{\Delta x}{v_{\text{bike}}} = \frac{4000m}{13.1m/s} = 305.3s = 5\min 5.3s$$

The rarefied air of the London velodrome

- Now let's repeat for 82.4F. Without going through all the above calculations (with different values of density etc), we just report he speed found this way: 13.2m/s. Hence

$$\Delta t = \frac{\Delta x}{v_{\mathrm{bike}}} = \frac{4000m}{13.2m/s} = 303.0s = 5\min 3.0s$$

Conclusion

- The higher temperature leads to more than a 2-s difference. In a sport where times and records are set by thousandths of seconds, this is a huge effect.
- The precisely controlled environment of the velodrome is one key reason that so many track cycling records were set in London.

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Conclusion

- By the way, these times are significantly worse than Wiggins's typical times, for two reasons.
- First, as we said at the outset, we were using Wiggins's 1-hr PWR, rather than something more appropriate for a 5-min race.
- Second, we used numbers for racing road bikes, but track bikes actually have better aerodynamics and lower-resistance wheels than road bikes.
- On the other hand, we ignored the effect of turns and the fact that the rider must start from rest.
- So there were plenty of details we could treat better, but the point here was to show that the magnitude of the temperature effect—a few seconds—is quite large.

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The rarefied air of the London velodrome

- In cycling as in all sports, energy is constantly being converted from one form to another, and it's easy to get confused about what are the "input" power and "output" power being discussed.
- We saw earlier an equation relating the mechanical energy output by the athlete to the chemical energy input to his system in the form of food and oxygen:

$$\bar{P}_{\text{output by cyclist}} = \text{overcoming rolling friction}$$

$$+ \text{ overcoming hills (if any)}$$

$$+ \text{ overcoming wind (negative if the wind is faster and blowing in the same direction as cyclist)}$$

$$+ \text{ left over for acceleration}$$

Power, work and energy

Power, work and energy

- Let's first define:
- MET: is the metabolic equivalent (or metabolic equivalent task), a number measured for every type of human activity imaginable and published in tables in the scientific literature.

Power, work and energy

- Hence we can write the power from chemical-input, we write: