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The speed of a cyclist

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This article is of general interest, but is mainly meant to illustrate an interesting application of physics teaching. The effect of a few laws of mechanics on bicycle speed are examined, and some improvements to increase bicycle speed are considered.

The mechanics of cycling is determined only by a few simple laws of physics. When designing a 'fast bicycle', attention should be paid to these laws, to achieve more efficient use of the available energy. Although the invention of the conventional bicycle is almost a century old, only a few new ideas have subsequently been added to its design. Until very recently the scientific aspects of cycling were underestimated, even in cycle racing.

After some early experiments on so-called reclining or recumbent bicycles—the first of which were built in 1914, although in 1938 strict racing rules by the International Cycling Union put an end to their development—it was not until the mid 1970s that a breakthrough was reached. This was due to a number of cycling scientists in the US, who constructed several recumbent models with a streamlined enclosure. In 1976 the International Human Powered Vehicles Association was founded by Kyle and others, organising speed trials regularly, in order to encourage improvements in human powered transportation either on land, at sea or in the air. With these so-called human powered vehicles (HPV) the one-hour world track record for cycling was increased from some 50 km h^{-1} (conventional racing bicycle) to approximately 67 km h^{-1} for a streamlined recumbent. This record was reached under unfavourable conditions, so that a further increase may be anticipated.

In this article the effect of the laws of cycling mechanics on bicycle speed are explained. The mechanics of cycling provides an interesting application of physics for classroom teaching. It is one of the topics covered in a five-week block-course for undergraduate students at the Agricultural University of Wageningen (NL). In the second part of this article, some improvements that will increase bicycle speed are considered. When riding a HPV, an untrained touring cyclist could even double his speed at the same physical effort (from some 18 km h^{-1} to at least 40 km h^{-1}).

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Motion and energy

Moving a vehicle over a certain distance requires energy. The acceleration energy—needed to accelerate the vehicle—will not be considered in this article. However, maintaining a certain speed does require energy too, due to frictional forces acting on the vehicle. Therefore, a tractive force is needed to compensate for these forces. When all frictional forces are known, the energy per second delivered by the vehicle can be calculated, by setting up an equation of power.

Frictional forces on a rolling vehicle

As a vehicle moves at a constant speed, its motion is mainly opposed by two kinds of frictional forces: the rolling resistance (F_r) and the air drag (F_d). An additional friction in the axle bearings is usually small enough to be neglected.

As pointed out by (among others) Williams and Terry (1986), rolling resistance arises from the contact between the tyres and the road surface. In this contact tyre and road surface are temporarily deformed. Because of hysteresis (internal friction of materials) reaction forces in the 'compression stage' are higher than during the subsequent expansion. This results in a net force on the tyre, opposing the motion of the wheel. The force F_r is proportional to the weight (W) of both the vehicle and the rider, this weight being the product of the total mass (m) and the acceleration of gravity (g); this linear dependence on W can be explained in

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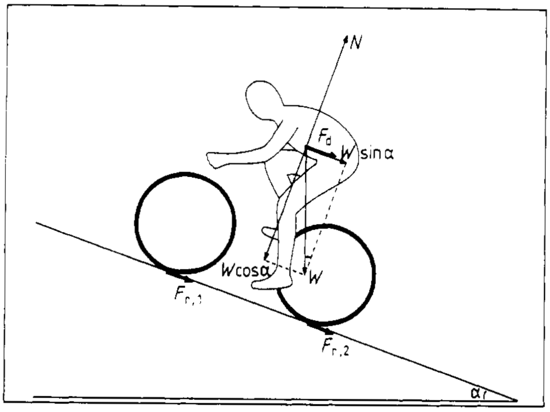


Figure 1. Rolling resistance F_r is proportional to the weight W of the vehicle due to gravity, and to the normal force N of the road on the vehicle.

terms of the normal contact force (N) of the ground on the vehicle.

On an inclined surface subtending an angle α with the horizontal there is no motion normal to the ground, hence

$$N - W\cos\alpha = 0 \qquad (1)$$

(see figure 1). The contact area of the tyre and the road, which determines the force F_r, is proportional to the normal force N. Thus, F_r is proportional to N and—because of equation (1)—also proportional to the weight W.

Neglecting a minor effect of speed on F_r (Whitt and Wilson 1982), the rolling resistance can now be written as

$$F_r = c_r N \qquad (2)$$

with c_r being the dimensionless coefficient of rolling resistance. The coefficient c_r depends on the tyre pressure, on its cross section and on the wheel diameter, as measurement of F_r shows. Rolling resistance is also higher when riding on a rough surface.

Assuming a total mass of 85 kg† and $c_r = 0.006$ for a touring bicycle, i.e. a lightweight bicycle built to racing standards, but with upright handlebars,

$$F_r = 0.006 \times 85 \times 10 = 5.1\ \text{N}$$

on a level road, where the acceleration of gravity $g \simeq 10\ \text{m s}^{-2}$ (table 1).

The air drag F_d is a force exerted on the vehicle due to its relative motion through the air, and depends on the difference in speed of the air in front of and behind the vehicle. According to Bernoulli's theory such difference leads to a pressure difference (Δp). With v_r being the relative velocity of the vehicle with respect to the air, Δp can be expressed by

$$\Delta p = \tfrac{1}{2}\rho v_r^2 \qquad (3)$$

where ρ is the density of air. The product of Δp and the so-called effective or frontal area (A) defines a force which is a measure of the air drag.

Wind tunnel experiments, however, show that the shape of the vehicle also plays an important role. This effect is accounted for by a dimensionless form factor, the so-called drag coefficient c_d in

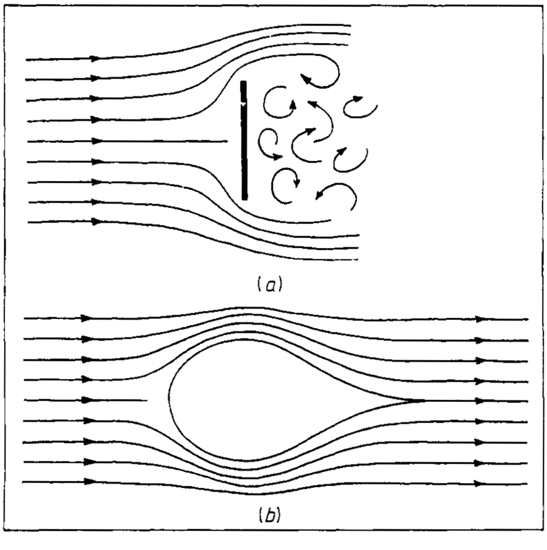
$$F_d = c_d A \tfrac{1}{2}\rho v_r^2. \qquad (4)$$

For a given bicycle (and rider position) the coefficient c_d is nearly constant over its velocity-range (Kyle 1979). In general blunt shapes lead to a larger air drag than round shapes do (see figure 2).

Table 1. Values for the Vector, touring and racing bicycles derived from Whitt and Wilson (1982) and Gross *et al* (1983). A standard weight of 850 N has been taken, except for the heavier, single-speed 'Dutch' bike and Vector vehicle.

	c_r	F_r (N)	W (N)
'Dutch bicycle'	0.008	7.2	900
Touring bicycle	0.006	5.1	850
Racing bicycle	0.003	2.5	850
Time-trial bicycle	0.0025	2.1	850
Vector HPV	0.006	5.7	950

Figure 2. Sketch of airflow patterns around an obstacle: blunt shapes such as a circular disc (*a*) lead to a larger air drag than round shapes like a falling droplet (*b*) do.



† A standard weight of 730 + 120 = 850 N is assumed for the touring and racing bicycles.

An extremely smooth surface might also help in reducing the air drag.

Neglecting friction in the bearings, the sum of F_r and F_d determines the total retarding force on a rolling vehicle. This total force can be measured directly by means of a dynamometer. The amount of power lost to the surroundings is then found by calculating the product of this total force and the speed of the vehicle.

For a touring cyclist a typical value for A is 0.50 m^2 and the form factor is 1.2 (table 2). Thus, in still air on a level road, and at a speed of 5.1 $m\,s^{-1}$ (18.5 $km\,h^{-1}$ or 11.5 mph)

$$F_d = 1.2 \times 0.50 \times ½ \times 1.2 \times 5.1^2 = 9.5\ \mathrm{N}$$

where the air density $\rho = 1.2\ \mathrm{kg\,m^{-3}}$ is chosen (at room temperature and at sea level).

Hence, the total force is $5.1 + 9.5 = 14.6$ N for the touring cycle, yielding the required power output for cycling at about 18.5 $km\,h^{-1}$

$$P_0 = 14.6 \times 5.1 = 74.5\ \mathrm{W}$$

a value easily attained by a healthy untrained person (Whitt 1971). The typical values of required power as a function of speed are shown in figure 3, for several types of bicycles (from tables 1 and 2).

As already mentioned, v_r is the relative speed of the vehicle with respect to the air. Let the wind velocity (speed of air with respect to the Earth) be v_w, then

$$v_r = v - v_w \qquad (5)$$

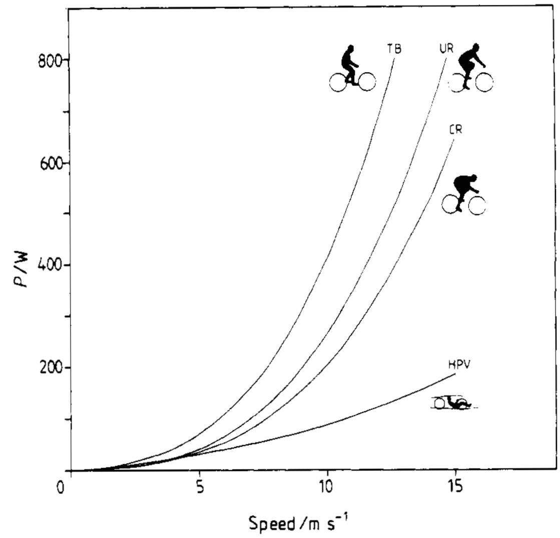


Figure 3. Power requirements for touring bicycle (TB), racing bicycle: upright (UR) and crouched position (CR), Vector vehicle (HPV).

where v is the velocity vector of the vehicle relative to that of the Earth.

In order to maintain a constant speed along an uphill road, an additional force must be delivered to overcome gravity. The component of gravity parallel to the inclined surface is $W \sin\alpha$ (figure 1) and the total force now becomes

$$F_t = W \sin\alpha + F_r + F_d. \qquad (6)$$

Table 2. Values for the Vector, touring and racing bicycles derived from Whitt and Wilson (1982) and Gross *et al* (1983). An air density of 1.2 kg m^{-3} at sea level is assumed; the drag factor K_d is defined by $K_d = ½c_dA$. For simplicity K_d factors for bikes with upright handlebars are set equal, but for the racing bike distinction has been made between an upright position (hands on brake handles) and a racing position (rider fully tucked-down over the handlebars).

		c_d	A (m^2)	K_d (kg m^{-1})
'Dutch bike/tour bike		1.2	0.50	0.36
Racing bike (upright)		1.0	0.40	0.24
Racing bike (crouched)		0.9	0.33	0.18
Time-trial bicycle		0.8	0.33	0.16
Vector HPV		0.11	0.424	0.028

Likewise, the corresponding power P_t is

$$P_t = (\sin\alpha + c_r\cos\alpha)Wv + c_d A\,½\rho(v - v_w)^2 v \quad (7)$$

on an inclined road (angle α) and at a wind velocity v_w. External factors (e.g. hilly countryside and wind conditions) strongly influence the speed of a cyclist, as a calculation shows. Using the same values for the touring bicycle as before, a 4% uphill incline has the same retarding effect as a frontal wind of 8.3 m s^{-1} (5 Beaufort). In both cases—at a standard power output of 75 W†—the speed of the cyclist will be reduced to almost walking speed (approximately 6.5 km h^{-1}).

Air density also has an appreciable effect on the speed that can be achieved. For example, at 2000 m above sea level, air pressure decreases by some 20%. An air density of 1.0 kg m^{-3} causes an increase in the (touring cycle) speed of 1 km h^{-1} (5%), to 19.5 km h^{-1} (at 75 W).

Transmission losses

Up to this point it was assumed that no frictional losses occur in the axles of the wheels, crank and pedals. For well lubricated ball bearings, the frictional losses will not exceed 1 or 2% per axle (Whitt and Wilson 1982). Postulating overall transmission losses at 8% (including chain), the power delivered to the wheels will be 68.5 W (at 75 W output). In this case the speed of the touring cycle will be reduced by some 5%, corresponding to a speed of 17 km h^{-1}.

† A healthy untrained person can deliver a physical effort at a rate of approximately 0.1 horsepower (74.6 W) during a longer period (e.g. one hour).

Reduction of frictional forces

From equations (2) and (4) it is obvious that at low velocities the rolling resistance plays the most important role, while at higher speeds the air drag—which is proportional to the speed squared—dominates. Air drag and rolling resistance are comparable at 13.5 km h^{-1} (3.8 m s^{-1}) for the touring cycle. Above this value air drag rapidly increases.

In the last few year the use of new tyre materials for bicycles has reduced the rolling resistance considerably. Typically, a 5 N to 2.5 N reduction increases the velocity by about 8% (or 1.5 km h^{-1}), to 20 km h^{-1} (at 75 W).

However, at steadily higher velocities, the largest improvement in reducing the frictional forces on a vehicle is achieved by improving its streamline profile. An only slightly streamlined cyclist will lower his air drag considerably by crouching over his handlebars, thus reducing both his frontal area A and his form factor c_d. This fact is used efficiently in the design of the racing bicycle (Schenau 1988). At 75 W the speed of a racing cyclist—fully tucked-down over his handlebars—approximates to 25 km h^{-1} (from tables 1 and 2: drag coefficient $c_d = 0.90$, frontal area $A = 0.33$ m^2, rolling resistance $F_r = 2.5$ N).

The situation is comparable to that of an open recumbent (Gross *et al* 1983) (figure 4). But, in general, the weight of a recumbent exceeds that of a conventional racing bicycle. Moreover,

Figure 4. A reclining bicycle offers more comfort than a conventional bicycle. It can reach a speed comparable with that of a racing bicycle, but only on a level road.

Figure 5. A modern time-trial bicycle—featuring streamlined tubing, closed disc wheels and a tipped-over frame—will increase the speed of the racing cyclist by a few per cent.

because its air drag is not significantly less than that of the conventional racing bike, the reclining bicycle never attained a real breakthrough. (A well designed recumbent can be faster by 3 or 4% than the racing bike, at 75 W.) Racing bicycles are often even faster, especially in hilly landscape, when the weight of the vehicle becomes important and the advantage of streamlining disappears.

Constructional improvements in the racing bike design, for example streamlined tubing, closed disc-wheels and a tipped-over frame, increase the speed only by an additional few per cent (Anderson 1984). Such a modern time-trial bicycle (figure 5) features the following values: $c_d = 0.80$, $A = 0.33\ m^2$ and $F_r = 2.1$ N (from tables 1 and 2). At 75 W its velocity will be 26 km h^{-1} (7.2 m s^{-1}).

In terms of streamlining, even a most modern racing bicycle design or a recumbent model remains inferior to other vehicles such as cars. Therefore, a streamlined casing of the (recumbent) bicycle is a more logical step. As in automobile technology, the search for the most favourable enclosure shapes was inspired by the forms encountered in nature (e.g. fish, bird, falling droplet).

The Vector—one of the fastest human powered vehicles—has a c_d value of only 0.11. A frontal area of 0.42 m^2 and a rolling resistance of 5.7 N on a level road (tables 1 and 2) enable a velocity of 33 km h^{-1} (9.2 m s^{-1}) at 75 W (for comparison the Sinclair C5 electric vehicle mentioned by Williams and Terry requires approximately 200 W at the same speed).

With these HPVs spectacular results have been reached, but so far only in track races. Unsolved problems, such as susceptibility to side winds and ventilation under the casing, so far have been an obstacle towards a commercial success.

The human factor

A well-trained person—a recreational cyclist or a racing cyclist—can reach a much higher speed. A trained non-athlete will easily deliver some 110 W (0.15 horsepower) during one hour. With his hands on the brake handles of a racing bicycle the cyclist will reach a speed of some 26 km h^{-1} (7.2 m s^{-1}) on a level road and in still air. A professional racing cyclist can deliver a power as

Figure 6. A HPV for track races. This streamlined model is a Dutch copy of the American Vector. It is unsuitable for use in traffic.

high as 400 W during one hour. The recently developed time-trial bicycle resulted in a new one-hour world track record (51 km h^{-1} by the Italian Moser, set under the guidance of a scientific team in Mexico, in 1984). With the Vector HPV an average speed of some 80 km h^{-1} should be possible in this way. Even a trained recreational cyclist could ultimately reach a speed of approximately 43 km h^{-1} in a Vector HPV (at 110 W).

Conclusions

In this article it was shown how the mechanical power output delivered by a cyclist during cycling can be used more efficiently to his benefit than is possible with present bicycle design. Since the range of technical improvements on the conventional bicycle is nearly exhausted, a further reduction of frictional forces is not likely. However, as demonstrated by tests and HPV track races, a substantial reduction of air drag is possible with enclosed recumbents. Adapting the HPV for traffic conditions would offer a fast vehicle for individuals in urban areas, which could become a reasonable alternative for commuting transport.

The topic of cycling mechanics treated in this article offers an interesting example of physics for students majoring in the field of the biomedical and environmental sciences, in transportation and in traffic engineering, as well as for all with an interest in the applications of physics into everyday life.

Practical tests on bicycles include the determination of the frictional forces acting on the bicycle and its rider. The total of these forces can be measured directly in a towing experiment in which the bicycle is towed by a car in calm air on a flat track. The towing force can be measured by means of a dynamometer at different speeds. This determines the total friction as a function of speed.

Air drag F_d can be measured separately in a wind tunnel. When the constant rolling resistance F_r is known for a given bicycle, the air drag also can be calculated from the maximum speed attained in freewheeling down a long slope of a constant inclining angle.

Another method is based on the decrease of speed as a function of time, when a cyclist is freewheeling on a flat track in calm air. Velocity measurements like these can easily be carried out by any individual requiring only a digital cycling computer attached to the bicycle.

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