

Light maketh right?

An assessment of the benefit of weight savings

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You're one of the strongest riders around when the terrain is flat, but you can't quite stay with the leaders on a steep hill more than a mile long. A pair of lightweight brake calipers, saddle, and wheels will save you 1,200 grams, but will they keep you from getting dropped on the longer climbs?

You're a recreational rider hoping to win a nearby hillclimb, but you finish two minutes back. Your bike weighs 9 kilograms, and you're contemplating the purchase of a tricked-out, sub-7.5 kg titanium dream machine. Will squandering your savings bring you glory?

The evolution of bicycle design in pursuit of speed has been inexorable, with improved aerodynamics and reduced weight being the two primary approaches taken. In the latter case, the last ten years have seen the ever-widening use of titanium alloys and carbon fiber, as well as (to a lesser extent) metal matrix composites, Kevlar[®], and aluminum alloyed with scandium. These materials are most effective on uphill terrain, where weight directly accounts for over 80% of the energy expended by a 68 kg recreational rider on grades of 4.5% or more, increasing proportionately with the slope of the road.

The benefit of weight reductions can be quantified using an equation of motion for cycling that has been validated in numerous peer-review studies by wind tunnel, tow rope/dynamometer, and coast-down tests:

$$P = s[k_a(s + v_w)^2 + mg(k_t \cos\theta + \sin\theta) + ma]$$

where P = mechanical power output of system (equipment/rider), as thrust at rear wheel, in Watts (W)

s = road speed of system in meter/second (m/s)

m = total mass of system in kilograms (kg)

g = gravitational acceleration constant in meters/second/second (m/s²) = 9.80600

k_a = aerodynamic drag constant for climbing position in kilograms/meter (kg/m) = 0.21000

k_a = aerodynamic drag constant for descending position in kilograms/meter (kg/m) = 0.20000
(barometric pressure = 763 mm Hg, temperature = 24° C)

v_w = headwind (>0) or tailwind (<0) velocity in meters/second (m/s) = 0.00000

k_t = tractional (tire) rolling resistance constant (dimensionless) = 0.00400

θ = angle of road surface from horizontal = $\tan^{-1}i$

i = road gradient (%)

a = acceleration of system in meters/second/second (m/s²) = 0.00000

Rearranging to solve for speed gives

$$s = P/[k_a(s + v_w)^2 + mg(k_t \cos\theta + \sin\theta) + ma]$$

By definition, speed is the quotient of distance traveled and the time required to do so, or $s = \Delta x/\Delta t$; rearranging this to solve for time gives $\Delta t = \Delta x/s$, so the time difference due to any change in equipment mass for a given set of conditions (grade, wind, rider mass, road surface) can be calculated as

$$\Delta t = \Delta x/s_2 - \Delta x/s_1 = \Delta x(s_2 - s_1)$$

where s_1 and s_2 represent road speed in meters per second before and after the mass change, respectively.

This expression was used to plot the three graphs below, under conditions of still air, at normal sea level barometric pressure, and a temperature of 24° C. To use them, you must know the gradient of the hill being climbed and your power output in Watts per kilogram of body mass (both assumed constant), as well as the length of the hill in kilometers (miles \times 0.6214 = km).

To use them, select the grade % of the hill on the horizontal axis and trace a straight line upward, parallel to the vertical axis, until you come to the line representing the power output that is right for you (estimate if it falls in between two lines). Then, read where this point intersects the vertical axis by moving to the left at a 90° angle to the line you've drawn. Multiply this number by the length of the hill in km and the amount of mass saved in kilograms ($\text{lbs} \times 0.4536 = \text{kg}$). The result indicates either the time you will save in seconds (Figure 1), or the distance you'll gain in meters (Figure 2), while the right ordinate scale of Figure 2 shows the ratio R of % time saved to the % mass reduction; note that the former approaches (but can never exceed) the latter as the gradient steepens and power output decreases.

Both graphs are based on a 2.5% reduction from an initial rider/equipment mass of 80 kg (176 lb), but are accurate to ± 0.14 s/kg/km (1.7 m/kg/km) where the total mass is initially 70-90 kg, the reduction is 5% or less, and power output is greater than 1.2 W/kg.

Of course, many factors determine climbing performance, and shedding a few pounds won't turn you into Charly Gaul overnight. Fitness, technique, the tempo and cadence (i.e., gear) you select, and even the condition and fit of your bicycle must all be maximized first. Retrofitting with expensive lightweight parts should never be used as a substitute for doing so, in fact, it should be given the lowest priority, and titanium jewelry isn't the only way to lighten up: a frame pump and small seat pack containing innertube and several tools can total over 700 grams, while two half-full water bottles come to about 900 grams.

Furthermore, lightness isn't the only criterion by which a component is judged; strength, durability, comfort, and overall performance must also be considered. New parts should always be thoroughly tested in training and simulated racing situations before use in actual competition.

Finally, these illustrations consider only the case of uphill cycling, but there are neither many "pure" hillclimbs, nor road races ending with a large elevation gain; most events take place on a circuit, where excess weight becomes an *aiding*, rather than resisting force on the downhill sections, so there is actually a *penalty* to weight reductions when descending. The overwhelming determinant of downhill speed, however, is the ratio of weight to aerodynamic drag, so the time loss is largely blunted as speed increases (Figure 3). In addition, bike-handling skill, confidence, and familiarity with the course all affect descending performance.

Why then are 'weight weenies' only on the endangered species list, and not yet extinct? A number of factors can be identified:

1. ease of measurement – accurate component weight can even be obtained using a postal scale, as contrasted with determining air resistance, which requires either wind-tunnel testing (costing \$700+ per hour at one of the few facilities around the country), or else field testing with a power-measuring system (a method of limited accuracy)
2. perceptual assessment – relatively small weight reductions can be sensed
3. the benefit of weight reductions is nearly cumulative (reductions aerodynamic drag are not), and can be totaled easily
4. the international ("metric") system: e.g., 100 grams is only 3.5 ounces (about the same as a Clif Bar and pack of Gu), or less than a ¼ lb, but sounds much more impressive than its Imperial equivalents
5. marketing hype fosters the impression that lightweight bicycles and components – like a lean, chiseled body – are more efficient and desirable
6. a general lack of knowledge and awareness of the dynamics of cycling

More sophisticated riders, however, know to concentrate their efforts on reducing aerodynamic drag, in all situations except the rare hillclimb with a steep gradient and significant elevation gain.

This article was developed from a similar analysis by the author that appeared in the Spring 1996 issue of Cycling Science.

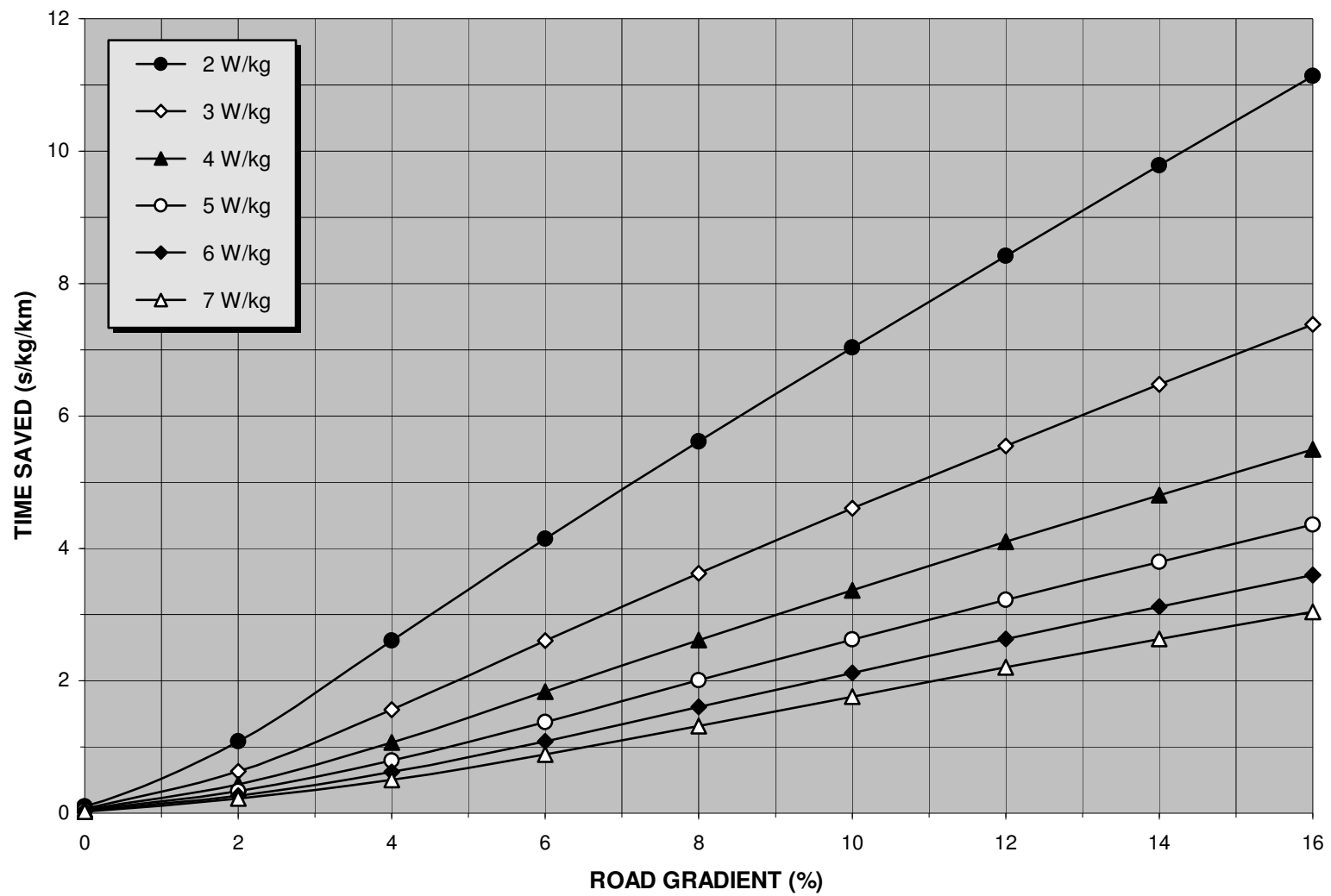


Figure 1. Time savings normalized to mass reduction and course length, as a function of uphill road gradient.

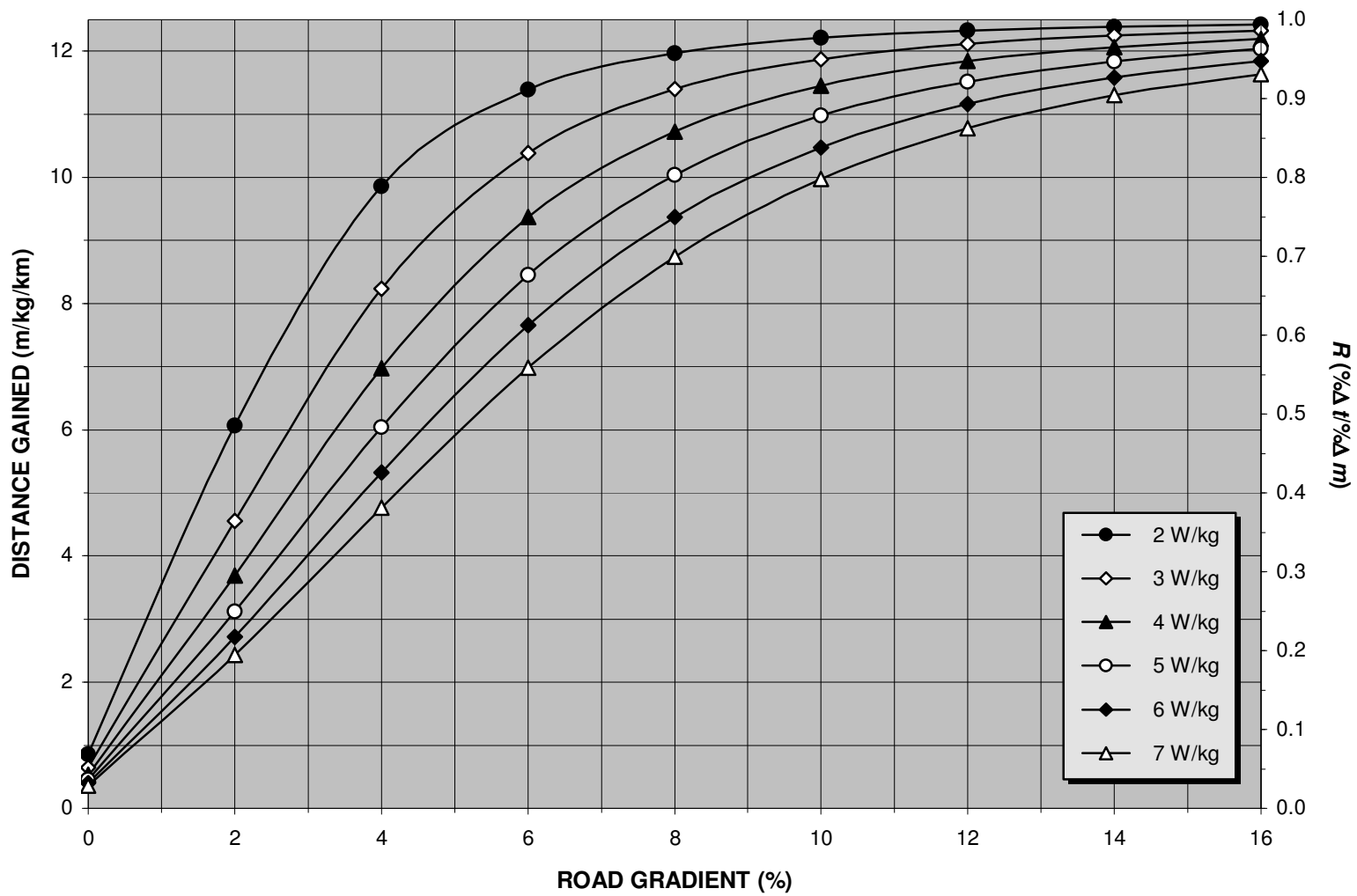


Figure 2. Relative time and distance gain from mass reduction, as a function of uphill road gradient.

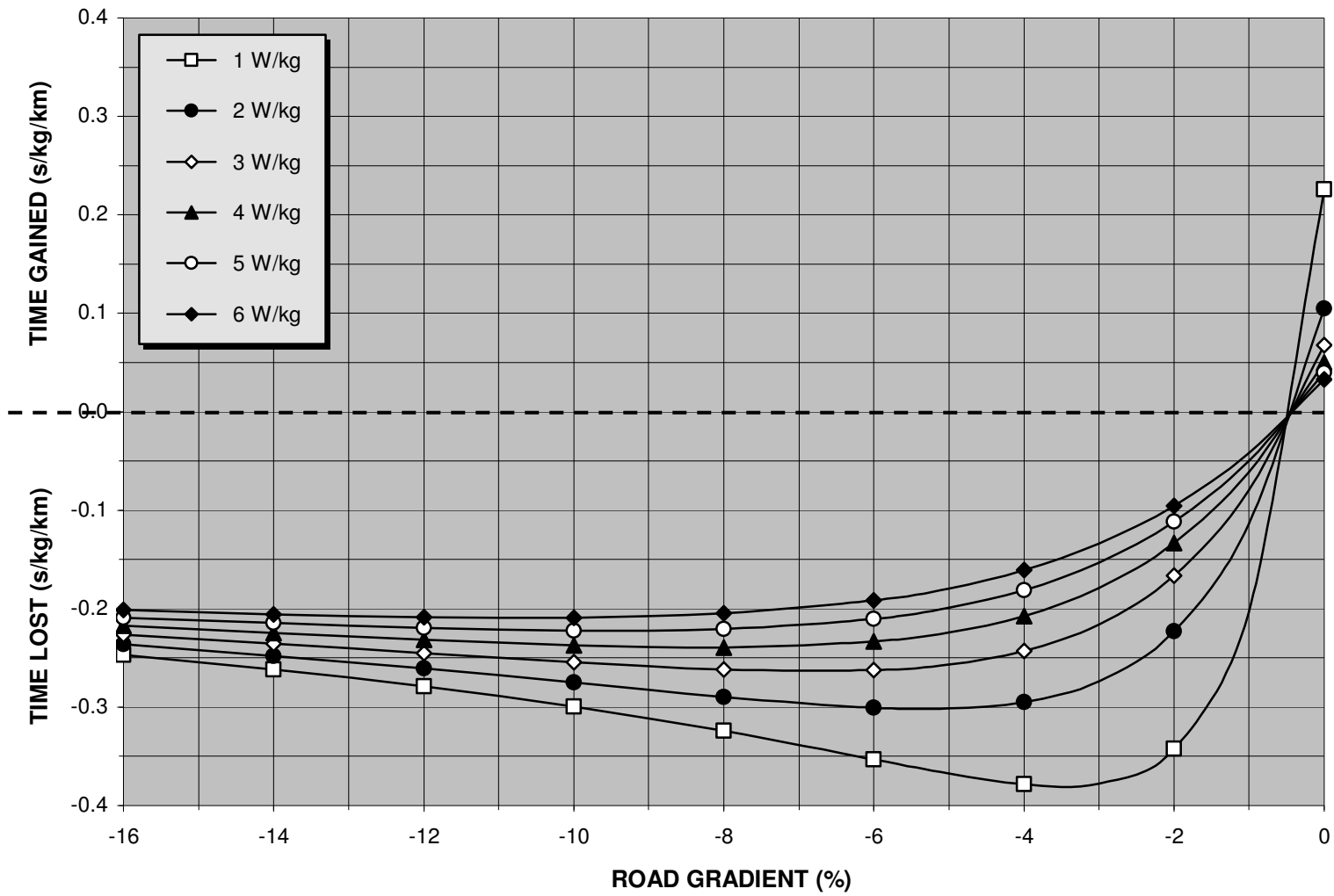


Figure 3. Time gain or loss, normalized to mass reduction and course length, as a function of downhill road gradient.

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