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AERODYNAMICS

Who Will Win the DuPont Prize?

Drag vs. Power at 65 Mi/hr

Douglas J. Malewicki

Editor's note: In January, 1984, the E. I. DuPont de Nemours Company established a substantial $15,000 cash prize for the first vehicle powered by a single human rider to reach 65 mi/hr average speed through a 200-meter-long timing trap. At DuPont's request, the International Human Powered Vehicle Association (IHPVA) has drawn up rules to govern competition for the prize.[1] If the 65 mi/hr limit is not attained in four years' time, the prize money will go to whoever has reached the highest speed in an official record attempt.*

Shortly after the prize was announced, we started to receive a steady stream of questions from readers. How was the 65 mi/hr limit chosen? Is the computer simulation that was supposedly used to set the limit actually valid? Do the laws of physics even allow the possibility of reaching 65 mi/hr with human power? Some articles we saw said "No," but, then again, skeptics questioned the human-powered flight objectives of the Kremer Prize, at least until the winning flight of Dr. Paul MacCready's Gossamer Albatross *in 1979.*

To clear up the questions about the DuPont Prize, Bike Tech *commissioned Doug Malewicki to do the engineering study printed here. No stranger to human-powered speed, Doug is the systems engineer for John Howard's 150 mi/hr Motor-Paced Bicycle Speed Record attempt slated for July, 1985. His work in aerodynamics is recognized by a listing in the*

**Footnote numbers refer to references listed at the end of this article.*

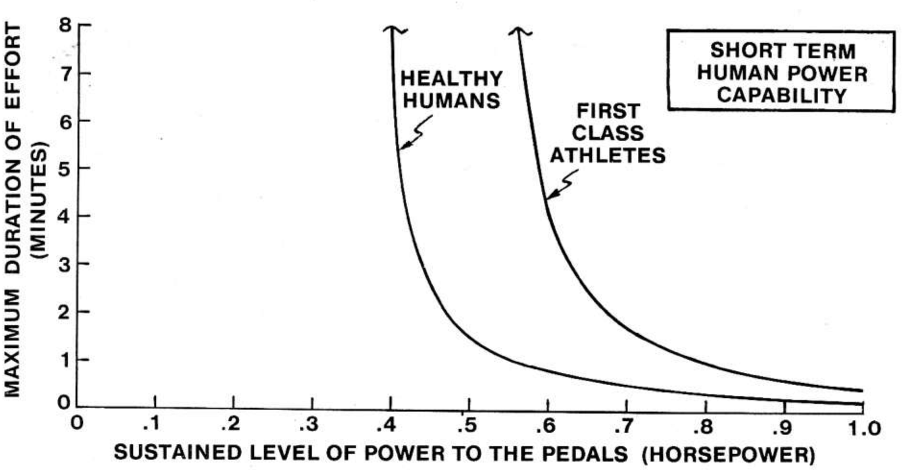

Figure 1. Short-Term Human Power Capability varies widely among individuals. A "first-class athlete" can produce 1.0 horsepower for some 30 seconds, while "healthy humans" can sustain this power level for a mere 12 seconds. Usually a constant power output from the rider of 1.0 hp is assumed for making predictions of the top speed of streamlined HPV's. Agreement between these speed predictions and actual measured speeds at the IHPVA Annual Speed Championships has been quite good. (Adapted from Ref. 3; see also Ref. 4, Chapter 2.)

IN THIS ISSUE

BIKE TECH NOTE—"There will be no December 1984 issue of BIKE TECH. The next issue will be February 1985, Volume 4, Number 1."

Guinness Book of World Records *for gasoline- and diesel-engine-powered fuel economy records set at freeway speeds. In the cycling world, he's an event coordinator for the IHPVA, and a co-author of the* Scientific American *article on HPV aerodynamics.*[2] *Doug holds the M.S. degree in Aeronautical and Astronautical Engineering from Stanford University.*

I was talking recently with my friend Chester R. Kyle, Ph.D., (a co-founder of the IHPVA, the primary instigator of the first HPV competitions ten years ago, and the acknowledged expert in HPV research,) about what it will take to win the $15,000 DuPont Prize. Chet quoted me some interesting results, which appear later in this article, from his own research at California State University, and also made these predictions for this *Bike Tech* article:

- the 65 mi/hr limit won't be broken within the four year period;
- the DuPont money will finally be awarded for a speed of only 60 mi/hr.

As of this writing, some nine months after the prize was established, only three official attempts have been made on the DuPont Prize, and all were unsuccessful. I assume many entrants in the Tenth Annual International Human Power Speed Championships (September 27-29, 1984, at the Indianapolis Motor Speedway) were motivated by the Prize. But the current single-rider record (set in 1980) remains intact, and the 65 mi/hr prize seems all the more untouchable.

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Is 65 Mi/hr Possible?

The current speed record of 58.89 mi/hr over 200 meters is held by the Vector Single streamlined tricycle, a creation of Versatron Research Corporation of Geyserville, California (headed by Al Voight, John Speicher, and Doug Unkrey). This record was set in 1980 at Ontario (California) Motor Speedway by rider Dave Grylls, a top track cyclist who rode for the U.S. silver medal-winning 4000-meter pursuit team in the 1984 Olympics.

Achieving 65 mi/hr requires a whopping 10% improvement in speed over this current record. This fact disturbs knowledgeable engineers, because the horsepower required to overcome air drag (the major retarding force) increases with the cube of the speed increase. Therefore, a 10% speed increase actually represents a 33% increase (approximately) in required power with today's best HPVs. This is why some informed observers have said the 65 mi/hr speed is "impossible."

In the research for this article, I have gone back to the basic physical laws that relate speed, drag, and power of a human powered vehicle, to see what is really possible within the constraints of the DuPont Prize competition. (See accompanying sidebar for mathematical derivations.) We all know intuitively that top speed of any vehicle will be much higher going down a grade with a tail wind, compared to traveling on level ground in still air. That is why the IHPVA has established rules regarding maximum slopes and winds for DuPont Prize attempts. Without such rules, for example, the Vector Single would reach a steady 90.1 mi/hr by merely coasting down a long 5% grade, by my calculation.[3]

Even within the confines of the DuPont rules, many factors can be varied to improve the odds of winning. For instance, all of the following options are allowed:

— tires with super-low rolling resistance;
— streamlined fairings with super-low air drag;
— riders of world-class sprint caliber;
— scientific training of the rider in the specific vehicle and for the specific task;
— selection of high-altitude sites with favorably low air density.

Which of these factors are most important? Where should the designer concentrate his efforts? These are precisely the questions that I've tried to answer in the "speed performance" graphs accompanying this article (Figures 5-9). These graphs will certainly be useful to anyone pursuing the DuPont Prize. Even if you're not in competition, they'll help your understanding of these variables in ordinary cycling.

The bottom line, folks, is good news! There are engineering loopholes! The existing 58.89 mi/hr Vector Single, and many of its look-alikes, can go 65 mi/hr and still be totally "legal." In fact, under ideal conditions, the Vector should be able to reach almost 74 mi/hr. I predict that the 65 mi/hr limit can be reached, but it will take a lot of hard work by a team that understands how to use all the tradeoffs between drag, power, physiology, and hardware design. And I predict that it will happen before the four-year deadline. If I'm wrong . . . I'll have to buy Chet Kyle a couple of beers at the establishment of his choice.

The Human Engine

The first factor to consider is that the human engine can produce a high level of power output for only a very short period of time (see Figure 1). For example, a "first-class athlete" can produce 1.0 horsepower (hp) for only about 30 seconds until exhausted. However, he could alternatively produce 50% of that value for a whole 30 minutes, or 40% all day long!

During a record HPV attempt, the rider's high power output capability is conserved until the very end of the run. Typically, the athlete starts with a low power level just to warm up his leg muscles. An easy 1/4-hp would get an HPV such as the Vector Single up to 35 mi/hr. Next, the rider commences to produce about 1/2 hp, a level that a first-class athlete can generate for about half an hour. This effort would bring a Vector Single up to about 48 mi/hr. The rider then kicks in his maximum hp, to bring the vehicle up to peak speed through the timing traps. Note, however, that the first-class athlete probably won't be able to produce a full 1.0 hp for the full 30 seconds shown on the graph, because of those previous exertions.

All of the calculations in this article are based on a simple "steady-state terminal velocity" equation that assumes *constant* power input from the rider (see sidebar). But this assumption is not totally realistic at high power levels because of limitations of the human engine: the rider simply cannot sustain his highest level of power output long enough for the vehicle to reach its final steady-state velocity. Nevertheless, the simple steady-state velocity equation, and the speed performance graphs in this article that are based on it, will indicate the same tradeoffs (between drag reduction, rolling resistance, weight, etc.) that a more complex calculation (which included limitations on the rider's power output duration) would find. I'll return to this point later in this article.

Training

The athlete who is used to riding a standard bicycle can produce only about 95% of his full power level in the recumbent or prone position without retraining.[5] He must become accustomed to riding in a new position, and David Gordon Wilson estimates that one to three months of training will recoup most of the loss.[6]

Record attempts at high altitudes (without oxygen apparatus) will also require a short acclimatization period of generally hard exercise. Most of the 5% power capacity that is lost coming from sea level to Denver (6000 feet elevation) can be recouped in a week, according to Kyle.

Perhaps even more important is a scientific training program such as that outlined by Dr. Joseph Mastropaolo.[7] In four studies with already well-trained elite athletes, he found the average gain was 11.2% over a period of 7.6 weeks of training without signs of a plateau. The sequence of power input requirements for an HPV record run is different from anything a racing cyclist has previously trained for. Thus, a few weeks of scientific training would certainly help any athlete in the DuPont prize attempt.

A word about using the arms for extra power in addition to the legs: Kyle's research shows about 20% more power is available for a short time. Steve Ball's successful Dragonfly vehicle, for example, is partially arm-powered. The mechanisms are complicated, and steering while arms are pedaling becomes interesting, to say the least! Personally, I'd prefer to have a recumbent or prone rider using an arms-overhead position with no arms pedaling. The arms-overhead posture reduces a human's maximum width across the shoulders by 20%. An HPV with 20% less frontal area requires roughly 20% less power input. The final result is the same as adding 20% power with pedaling arms — with much less mechanical gimmickry.

Air Drag

The single most important factor to consider when designing a high-speed HPV is aerodynamic drag and how to reduce it. The importance of streamlining is shown in Figure 2. For instance, a cyclist riding a traditional racing bike and exerting 1.0 hp can barely reach 35 mi/hr. But the same rider in a highly streamlined Vector-type recumbent can travel at 60 mi/hr, maybe even faster, with the same level of exertion. I plotted the curves of Figure 2 using the basic equation (see sidebar) that gives the bicycle's terminal (maximum) speed as a function of power input from the rider and the mechanical properties of the cycle. I've also used this equation to generate the four "speed performance graphs" (Figures 5 through 8), which focus on conditions at the magical 65 mi/hr. The numerical quantity which best expresses the vehicle's streamline properties is the "effective frontal area" (abbreviated C_DA. See Figures 3 and 4). In Figures 5 through 8, effective frontal area appears on the horizontal axis, and the heavy black curves represent the following baseline conditions:

— 220 pounds total weight (vehicle plus rider);
— 1.0 hp input to the pedals;
— 0.0045 rolling resistance coefficient;
— level road;
— no winds;
— standard atmosphere (59°F, sea level).

For reference, the effective frontal area of the existing record-holding Vector Single (C_DA = 0.5 ft^2 according to Versatron[8]) is shown on these graphs as a vertical dashed line. Also, the 65 mi/hr goal is indicated by a horizontal dashed line.

Starting with Figure 5, and looking at the heavy line that represents "baseline" conditions, we can see that the existing Vector will reach 61.4 mi/hr *if* the rider could produce 1.0 hp continuously. But if the vehicle's effective frontal area were reduced by 20% to 0.4 ft^2, the top speed would be 66 mi/hr. A 40% reduction in effective frontal area, to C_DA = 0.3 ft^2, would increase top speed to almost 72 mi/hr (still assuming a continuous 1.0 hp input)! These are the sorts of speed improvements that HPV builders get excited about.

There are basically two ways to reduce a vehicle's effective frontal area:

• Make it more streamlined, which means reducing the aerodynamic drag coefficient (C_D) by improving the external shape of the

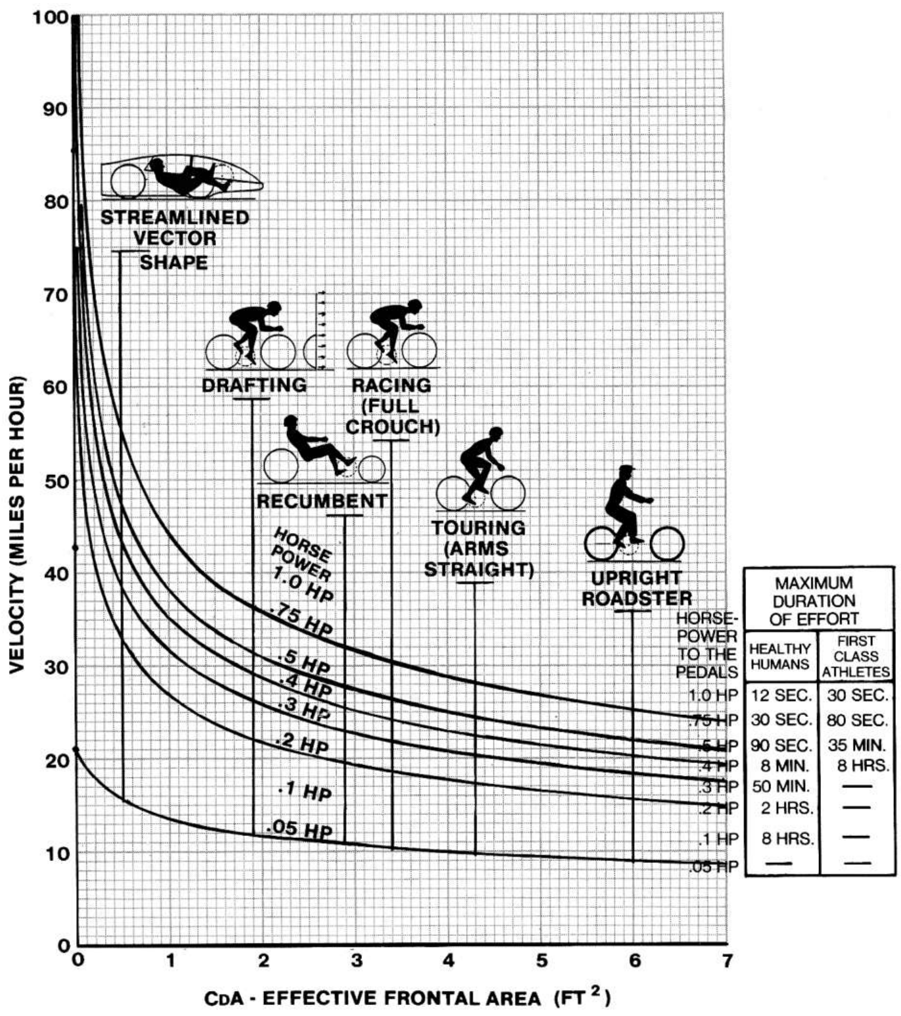

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Figure 2. Streamlining improves the performance of human-powered vehicles at all power levels. Effective Frontal Area (C_DA) expresses the aerodynamic qualities of the various vehicles. Effective Frontal Area is the product of the aerodynamic drag coefficient C_D, a measure of the streamlining efficiency of the shape, and the projected frontal area of the vehicle A, which measures its size. An upright roadster cyclist has about the same effective frontal area (6.0 ft^2) as the 1984 Corvette automobile (6.5 ft^2). Note from the curves that a vehicle with highly streamlined fairings, such as the Vector, can travel about twice as fast as a touring cyclist riding a conventional bike. (Adapted from Ref. 3)

vehicle while paying attention to internal flows and interference factors. Glen Brown has outlined some important points in this direction.[9] Designers of the Vector Single[8] claim that its C_D is 0.11. A much better (lower) value is theoretically possible (C_D = 0.07), based on data[10] for ideal airfoil shapes with length-to-width ratio of 3.5. But in practice, it's impossible to achieve this low theoretical value due to complications such as wheels protruding from the fairing, wheels churning up air, imperfect seams and joints, and the need for airflow over the rider (for respiration and cooling). Clever technical tricks also enter the picture. For example, to reduce drag from internal flows without suffocating the rider, Steve Ball's Dragonfly, the fastest single-rider machine at the 1983 Championships, has a ventilation flap that is closed by the rider during the last few hundred meters before the timing traps.

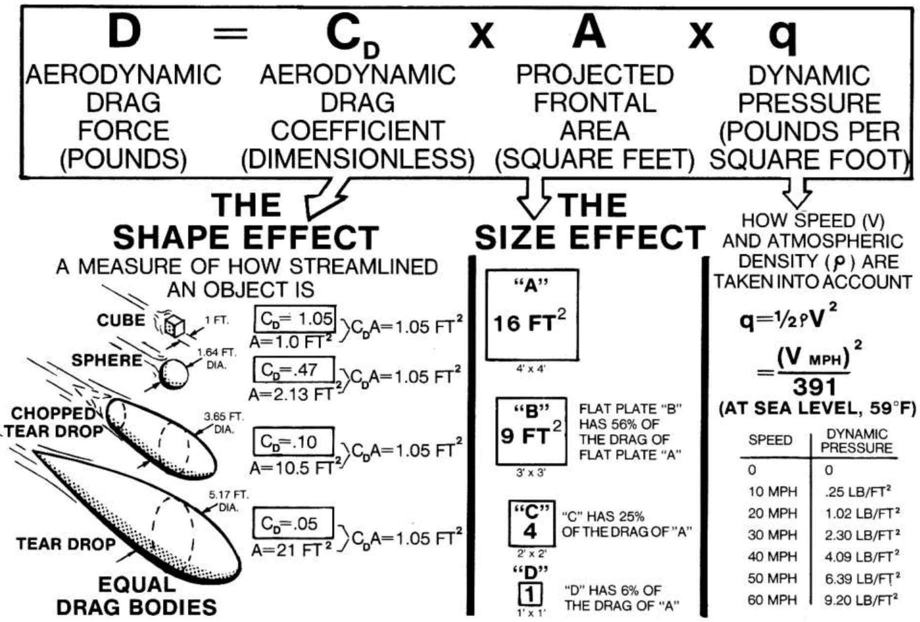

Figure 3. Components of Aerodynamic Drag (Ref. 3)

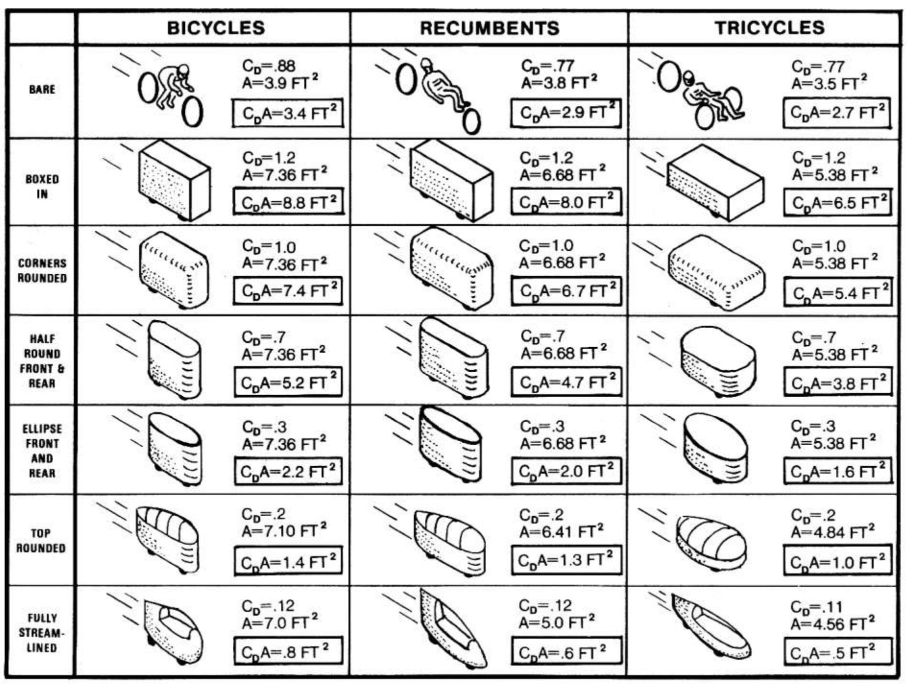

Figure 4. Tradeoffs Between Size and Shape in HPV Fairing Design (Ref. 3). The product C_DA is called the Effective Frontal Area.

For some new ideas on streamlining, look at the motor-powered Bonneville Salt Flat Land Speed Record racers: they make the smallest possible frontal area package for the man/machine, and then gently round the corners and nose. I can't recall a single laminar airfoil machine in the Bonneville 200 mi/hr club. Of course, these motorized racers are working well into the turbulent flow regime. But it's easy enough to calculate that a ten-foot long HPV traveling at 65 mi/hr will have a Reynolds number on the order of $6 \cdot 10^6$ (see Ref. 12, Chapter 11 for formulas), which puts it smack in the turbulent regime, well past transition. The whole subject of HPV aerodynamics at 65 mi/hr becomes quite complex at this point, and would require a separate article to cover it properly.

- The second way to reduce the effective frontal area is simply to make the vehicle smaller, which means reducing both its actual frontal area (A), and its "wetted" surface area that contributes to skin-friction drag. There's no reason for the vehicle to be any larger than the spatial envelope occupied by the rider moving through the normal range of pedaling motions. But who says the rider must pedal with his whole leg? A much more compact capsule would result if the rider kept his legs straight, and simply "ankled" his feet back and forth, as in pressing a clutch, to provide power.[11] This is far-fetched, of course, but before you laugh, look at the numbers: a supine human with arms overhead and legs straight can be enclosed in a capsule of slightly less than 1.0 ft² actual frontal area. By contrast, the Vector's actual frontal area is about 4 ft². If the bullet-shaped "capsule" vehicle had the same drag coefficient as the Vector (C_D = 0.11), its effective frontal area would be so small (C_D A = 0.1 ft²) that it would take only 0.26 hp to sustain 65 mi/hr. The big question is: can the ankles do it? We'd love to see some ergometer data for the power duration capability of the recumbent first-class athlete, just ankling back and forth with no knee motion.

Power Variations

Figure 5 shows how small variations in rider horsepower affect maximum speeds. If the rider could exert 1.10 hp (a 10% increase over nominal), the Vector Single's theoretical top speed would increase from 61.4 to 63.7 mi/hr, a meager 3.2% increase in speed. Similarly, a 10% reduction in power (to 0.9 hp) would reduce the theoretical (top) speed from 61.4 to 58.9 mi/hr. This, by coincidence, is essentially right at the 58.89 mi/hr actual Vector Single record.

Remember that recumbent and prone riding positions initially incur about a 5% penalty in power output. Regaining full power requires a muscle retraining program of one to three months.[6] Never in IHPVA history

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has a top-caliber bicyclist been available for even one month of serious training in the specific competition vehicle of interest. The speed records seem to be held by top cyclists who get their first rides in the machines the day before the event, and merely pump as best they can on race day.

Rolling Resistance

In Figure 6, the horsepower is now fixed at 1.0 hp (746 watts), and only rolling resistance is allowed to vary. Kyle's tests of high-pressure sew-ups on polished concrete show that a rolling resistance coefficient (C_R) of 0.002 is the obtainable state-of-the art for 27-inch-diameter tires. The Vector Single has smaller tires, and real track surfaces are not nearly as perfect. Versatron's published data[8] show a C_R of 0.006. Kyle believes a somewhat lower C_R of 0.0045 is realistic for the Ontario Motor Speedway surface where the record was actually set.

But these rolling resistance improvements mean a speed increase of only about 2 mi/hr! Running on a straight and polished smooth surface with $C_R = 0.002$ would bring the top speed up to only 63.5 mi/hr, compared to 61.4 mi/hr with $C_R = 0.0045$. This is only a 3% increase in speed for a 55% decrease in rolling resistance!

There is nothing in the rules that prevents using tires that are different from standard bicycle tires. The C_R for polished hard steel wheels on a polished steel track is about .0002 to .0004.[12] What would be the benefit of using such a railroad-type wheel and track system? To carry this idea to the extreme, even if rolling resistance were reduced to zero, the top speed would increase to 65.3 mi/hr. This will win the prize, but who can afford to lay out three to five miles of rail track for such a performance? The message should be clear: trying to reduce rolling resistance below that of conventional high-quality bike tires, does not yield an adequate return for the amount of effort expended.

Choice of Road

The prize rules state that the slope must be flat to within 2/3 of 1%. This means *you are allowed* to find a road that has up to 2 feet of drop in every football field of length (300 feet). This might not sound like much, but its effect on performance is significant (see Figure 7). For example, the theoretical top velocity of the existing Vector Single, with a continuous 1 hp input, increases from 61.4 mi/hr to 67.3 mi/hr on the maximum allowable downhill slope — almost 10% faster. One would have to reduce the effective frontal area of the Vector Single by a phenomenal 22% to obtain the same maximum speed on a level surface!

Or, to look at it another way, riding on the maximum legal downslope provides the same boost in speed as adding a 1/4 hp engine to aid the rider (which is quite illegal!) on a level run. This is calculated by use of the formula:

power = force · velocity, where
force = 0.00667 slope · 220 lbs weight
velocity = 65 mi/hr

and the result is divided by the numerical constant 375 lb·mi/hr/hp for conversion of units.

In other words, forget about trying to win the DuPont Prize at the near-level Indianapolis Speedway during the IHPVA Annual Speed Championships. Instead, learn about surveying and topographic maps, and find yourself a properly sloped, smooth paved road.

One slight complication found in the rules: the total drop from one end of the course to the other cannot exceed 30 meters (98.425 feet). This means that only 2.8 miles can have the maximum amount of downslope. This makes finding an acceptable long course more difficult. But since the initial acceleration phase is the rider's warm-up period, it will be quite acceptable to perform this warm-up on a level section of road prior to entering a couple of miles of downslope.

Don't run out to search your state maps until you read the rest of this article about the effect of air density. You may be in the wrong state!

Winds

The graph of Figure 8 shows the effect of

Derivation of Terminal Velocity Equation for an HPV

Terminal velocity, also called steady-state velocity, for any vehicle is defined as that speed at which the propulsive power input (usually from the human rider) is exactly in balance with the power consumed by retarding forces such as air drag, rolling resistance, uphill slope, etc. The net sum of all these quantities will be zero, which means that the vehicle will not accelerate, but will simply maintain a steady speed. We'll now assume, for the moment, that the road is level, there are no winds and we're at sea level at 59°F. The equation that expresses the "balance of power" just described will be:

(1) Propulsive power to the wheels	=	Power consumed by rolling resistance	+	Power consumed by aerodynamic drag

A more detailed expression can be written for each of these quantities, as follows:

(2) Propulsive power to the wheels	=	Power input to the pedals by the rider (horsepower)	×	Mechanical efficiency of the drivetrain (typically 95%)		
	=	P	×	η		
(3) Power consumed by rolling resistance	=	Rolling resistance force (lb)	×	Speed (mi/hr)	/	Conversion factor to hp
	=	$(C_R \times W)$	×	V	/	375
(4) Power consumed by aerodynamic drag	=	Aerodynamic drag force (lb)	×	Speed (mi/hr)	/	Conversion factor to hp
	=	$(C_D \times A \times V^2 / 391)$	×	V	/	375

It's now a simple matter to substitute equations (2), (3), and (4) into our "balance of power" equation (1), and then divide both sides by the quantity η, to solve for the rider's power input P:

(5) $P = [C_R \cdot W + C_D \cdot A \cdot V^2 / 391] \cdot V / (375 \cdot \eta)$

This equation gives power input P as an explicit function of vehicle velocity V and all the other quantities on the right-hand side. This can be solved for P on a pocket calculator; no computer is needed. It's also possible to go the other way, to solve for velocity V given power input P, without a computer, by using the known formula for the roots of a cubic equation (Ref. 12, Chapter 2).

For the more realistic case of non-level roads, windy conditions, and sites at various altitudes and temperatures, the equation for the rider's power input P becomes slightly more complicated:

(6) $P = [(C_R + a) \cdot W + d \cdot C_D \cdot A \cdot (V+U)^2 / 391] \cdot V / (375 \cdot \eta)$

where a = slope of road from horizontal, positive (+) for uphill
W = total weight (lb) of vehicle plus rider
d = air density correction factor (percentage), from Figure 9
(air density at stated conditions / air density at standard conditions)
U = windspeed (mi/hr), positive (+) for head wind

I used equation (6) to generate all the curves plotted in Figures 5 through 8, and I found it convenient to write a short computer program to automate the calculations. (See Ref. 4, Chapter 7, for more information concerning power vs. speed equations.)

the maximum legal wind speeds of 1.67 meters/second (3.73 mi/hr). Note that this limit applies to tail, head, or crosswinds. Why restrict head winds? Because some HPVs are wing cross sections and might obtain a slight forward component of thrust, like a sailboat, in the right head/crosswind condition. (Witness wheeled land-sailers.) Personally, I'll take the legal tail wind and a low C_D A-designed HPV instead of a sail any day.

On level ground with 1.0 hp input, the 3.73 mi/hr tail wind would raise the Vector Single's ultimate speed from 61.4 to 63.7 mi/hr, a 3.7% increase. This result agrees well with Kyle's rule-of-thumb, given more than ten years ago[13], that "a bicycle is affected by about half the wind speed." Thus, a 4 mi/hr tail wind produces about a 2 mi/hr speed increase. This result also shows that simply waiting for the perfect tail wind will not enable you to win the DuPont Prize. But if all other conditions are right (e.g.: low-drag vehicle design, maximum legal downslope, etc.), that tail wind could be just enough to push you into the money.

Altitude and Temperature

Bicycle record-seekers are well aware that they can improve their times by racing at higher altitudes, and the Air Density Graph (Figure 9) shows why. For example, the air density at Denver (6000 ft altitude) is only 80% of that at sea level (with 60°F temperature at both locations), and this translates into a direct 20% reduction in air drag force. On a 90°F day, air density decreases by a further 4 to 5%.

How can we use this information with our four Speed Performance Graphs (Figures 5 through 8), which were based on standard sea level 59°F air, to calculate the vehicle's top speed? According to the equations given in the sidebar, it turns out that a given percentage change in air density has the exact same effect on the top speed as the same percentage change in the vehicle's effective frontal area (C_DA). For example, a 20% reduction in air density (going from sea level to Denver) has the same effect as a 20% reduction in effective frontal area. Thus the Vector Single's performance in Denver can be estimated from Figure 5 by looking at an effective frontal area of 0.4 ft^2, which is 20% smaller than its actual 0.5 ft^2. The result, following the heavy line of 1.0 hp input, is an increase in speed from 61.4 mi/hr to 66.0 mi/hr. It looks like we have a winner! But this assumes that the human engine could produce the same 1.0 hp in the thinner air. Kyle's analysis of speed records set at 6000 to 7500 ft altitude indicates that riders suffer a 5% to 10% decrease in power capacity, which partially offsets the 20% to 24% reduction in air drag forces.[14]

Chuck Champlin, of the IHPVA Rules Committee, is iffy on whether or not carrying breathing oxygen on board an HPV would

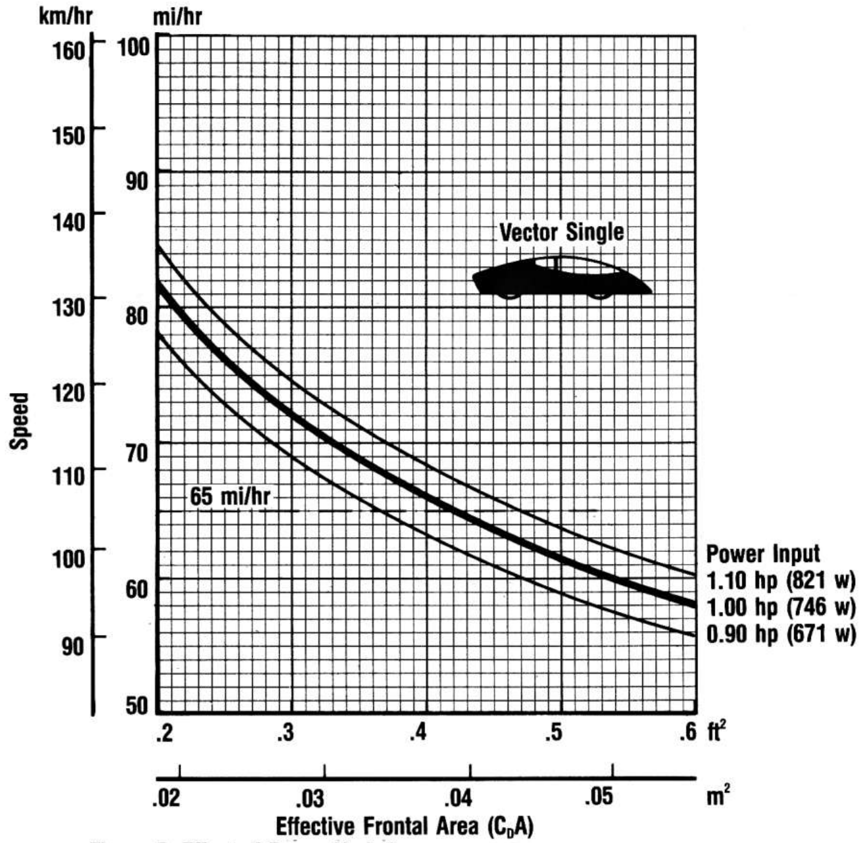

Figure 5. Effect of Power Variations

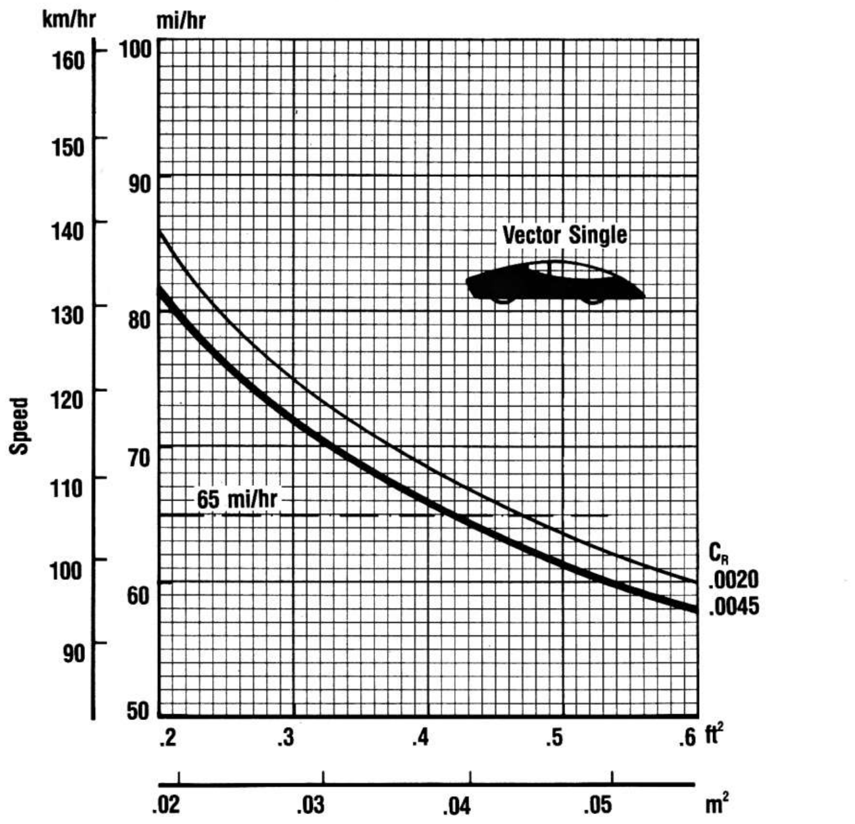

Figure 6. Effect of Rolling Resistance Coefficient (C_R)

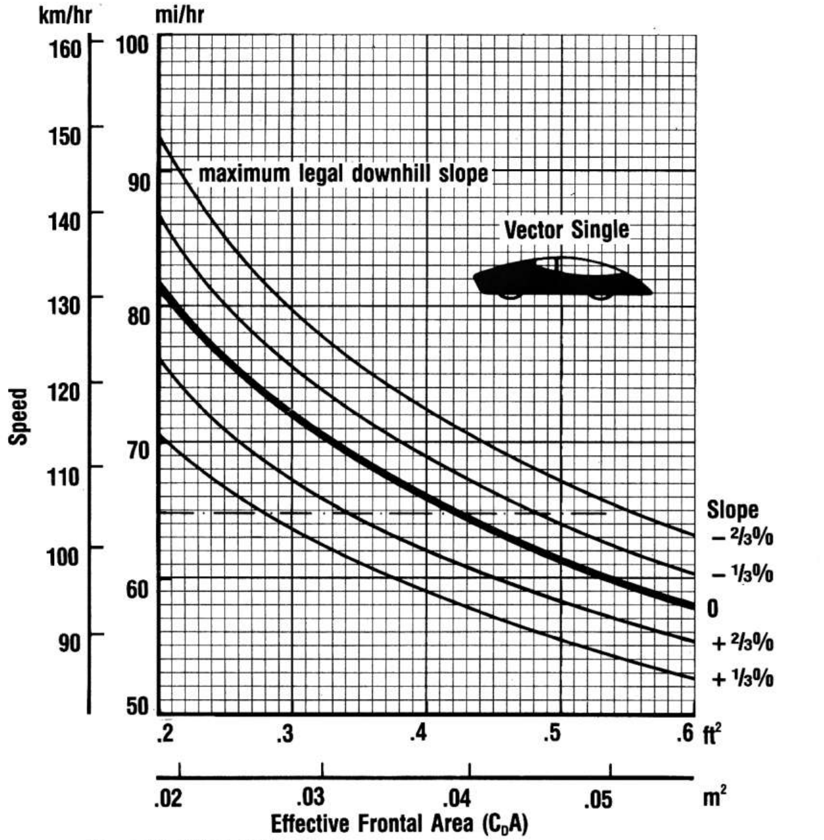

Figure 7. Effect of Slope

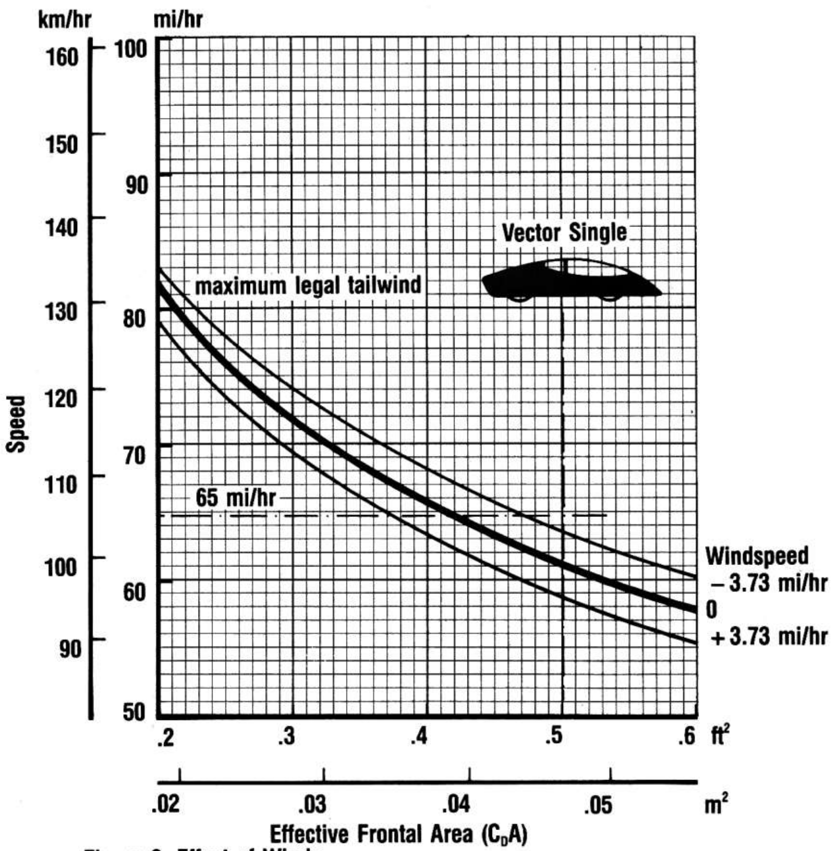

Figure 8. Effect of Winds

be in the spirit of the rules. Regardless, proper scientific training at altitude should acclimate the rider without supplementary oxygen to within a couple of percent of sea level performance, so it may be a moot point.

Winning the Prize

Up to this point, I've looked at how each main factor, by itself, affects the vehicle's top speed; what happens when we put them all together under the most favorable conditions? We'll have a real winner, I'd say. The existing Vector Single or any of its clones should be able to reach 65 mi/hr by using the legal "loopholes" available, with no need for new hardware design or new technology. Here's how:

- Select a top rider who can devote a month or two to a scientific retraining program in the specific vehicle for this specific task. How about recruiting a cyclist who almost made the Olympics and is still hungry for fame and glory? The rider must also train at altitude to acclimate to the thin air. This combined program should bring the athlete back to within a few percent of his sea-level power capability. Without such training, the human engine will be 10% under-capacity for the attempt.
- Select the right course. You must run at 6000 feet above sea level or higher, and find a course with close to the maximum legal downhill slope. The *Reader's Digest World Atlas* shows roads above 6000 feet in the states of Arizona, California, Colorado, Idaho, New Mexico, Nevada, Utah, and Wyoming.

A Vector Single operating at 6000 foot elevation at 60°F, on a maximum legal downhill slope with a rider who can produce 1.0 hp at that altitude and in that riding position will achieve 73.5 mi/hr!

Under these same (ideal) conditions, reaching 65 mi/hr to *just win* the prize will take a much *lower* sustained power input: only 0.7 hp, which a top athlete can produce for almost two minutes. To reach 60 mi/hr, the rider must produce 0.54 hp, which a top athlete could hold for some 10 minutes while covering 10 miles. Thus, there should be ample time to accelerate from 0 to about 60 mi/hr, without the rider exhausting himself before that final blast up to 65 mi/hr and the flash (lasting 6.88 seconds) through the timing traps.

The ideally sloped smooth road will be difficult to find, but roads at higher altitudes can be selected to compensate. Improving rolling resistance is not necessary, nor is improving the maximum tail wind condition. But note that the 65 mi/hr run, which required 0.7 hp in still air, would require only 0.61 hp in presence of a legal maximum tailwind. This slightly lower power level can be sustained for about 3.7 minutes by a top athlete, and this almost *doubles* the time available for acceleration up to 65 mi/hr, before exhaustion sets in.

Since the rules do not explicitly restrict competition to sites within the United States, consider that in La Paz, Bolivia, on a 90°F day, a top athlete could ride the Vector at 65 mi/hr on the maximum legal downslope with only 0.48 hp expenditure. If he were breathing sea level air, he could sustain this effort and the 65 mi/hr speed for as long as 40 minutes. Why be content to just break the record, when you can really demolish it! Anyone for an oxygen bottle?

A final comment: all the results calculated here and the equations in the sidebar, are based on a *constant* level of power input from the rider. These calculations do not account for the details of what happens while the rider is warming up and accelerating to top speed, and also ignore the very real fact that the rider's peak output can be diminished due to the fatigue he accumulates while accelerating. For example, I've shown that a 1.0 hp effort can propel the right HPV under the right conditions at 65 mi/hr; but top athletes can produce 1.0 hp for only about 30 seconds, while it can take a considerably longer time, on the order of 2 to 5 minutes, to accelerate the vehicle from 0 to 65. This problem should be treated as a golden opportunity for collaboration between a physiologist and a mechanical engineer to produce some useful "pacing" guidelines for the rider. In any case, the speed performance graphs in this article, despite the limitations I've mentioned above, should be accurate enough for setting the correct priorities to produce a winning design.

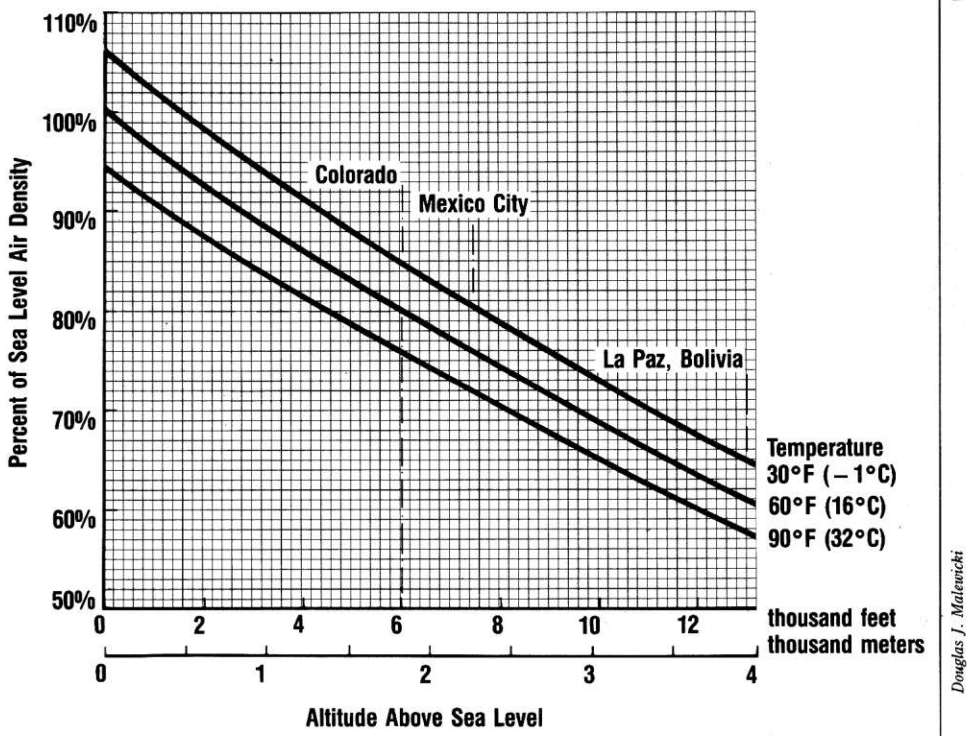

Figure 9. Effect of Altitude and Temperature on Air Density (based on data in Refs. 12 and 15)

The Winner

If you're a realist like me, you might conclude that the time, effort, and resources needed to win the DuPont Prize are far in excess of the rewards you'd receive. But watch out for a small group of college students who are willing to devote countless hours to building their vehicle, surveying their sites, and then living in tents next to that perfect road in the mountains, with their dream machine and one almost-burnt-out, Olympic-class cycling buddy. They'll do it, and come out $15,000 richer with fame, glory, and quite a story to tell!

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BOOK REVIEW

The Custom Bike . . . Demystified

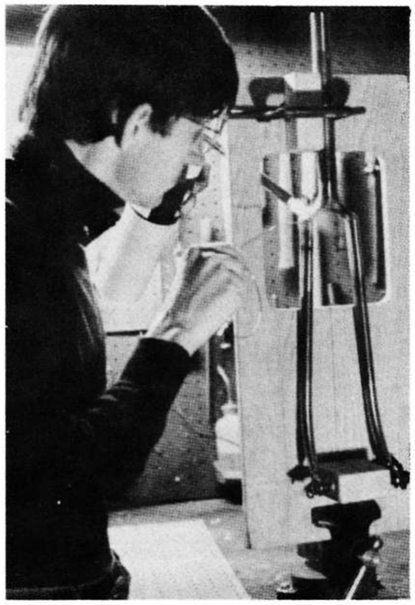
Angel Rodriguez

Designing and Building Your Own Frameset (An Illustrated Guide for the Amateur Bicycle Builder)
Richard P. Talbott, P.E.
Second Edition, 1984. 161 pages
$26 postpaid from:
The Manet Guild
Box 73
Babson Park, MA 02157

This book is essential reading for first-time framebuilders, and for cyclists who are thinking about having a frame custom-built for them. In my own framebuilding business, I know that there's a tremendous curiosity on the customer's part about the work that goes into his or her particular frame. In fact, many of my customers actually want to stand by and watch their frame being built — a request that builders seldom agree to, for many reasons. This book provides a good close-up look at all of the basic steps that go into framebuilding. If you're buying a custom frame, this book will help you communicate with your framebuilder. And if you're thinking about building your own frame, this book will get you started.

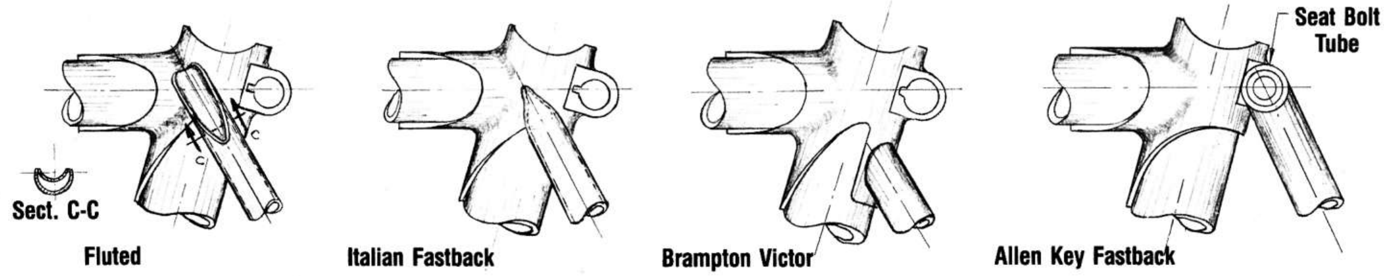
In this second edition of his book, Talbott has not changed the text very much from the original 1979 edition, but he's made major improvements in the graphics. The new edition includes over 120 clear photos and a dozen technical drawings showing every step in the framebuilding process. (See illustrations accompanying this review.) Talbott has updated his table of professional custom framebuilders, listing over 70 names and addresses. He also lists over 50 professional frame painters, and ten sources for framebuilding supplies such as tubing, lugs, and brazing materials.

Chapter 1, "Frameset Design Principles," is the weakest section of the book be-



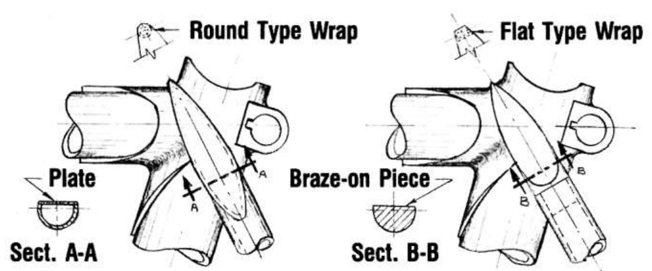
Brazing the Crown/Blade Joints

Thoroughly heat the joint to proper temperature (you may need two torches plus some heat reflectors), and feed rod into the joint crevice. (P7.27) Braze one blade at a time starting at its outside surface and finishing on the inside. A final caution: the jig is combustible so do not be careless with the torch. The jig will be of little use if you incinerate it on your first pass (I almost did). (P7.28) After brazing, set the fork assembly aside in a draft-free area, and let it cool while it is still clamped in the jig.



Fluted **Italian Fastback** **Brampton Victor** **Allen Key Fastback**

SEAT STAY ATTACHMENT DESIGNS (Not to Scale)



Full Wrap Using Flat Plate **Full Wrap Using Braze-on Piece**

CONSTRUCTION NOTES

Partial Wrap and Full Wrap Around Designs (Only full wrap is illustrated.)

Either design may be fabricated by beveling the stay ends, then brazing on flat plates. A popular and much easier method is to purchase prefinished, beveled, braze-on pieces, then braze them to straight cut stay ends. In the full wrap around design, beveled ends are left extra long, heated, then tapped with a hammer to form an overlap on top of the lug. When stays are brazed to the lug, extra brazing material is used to build up the overlap, and it is then filed to either a round or flat shape. For partial wrap designs, bevel can be made any length desired.

cause it is based on the C.O.N.I. publication *Cycling,* an out-of-date Italian book that is hard to find and even harder to understand. Ten, or even five years ago, the C.O.N.I. book was the state of the art in design measurements. Today, we have more exact methods of determining frame dimensions, such as The Fit Kit system (see *Bicycling,* May 1983). In addition, it would have been helpful for the author to include a sample measurement worksheet like the ones that many framebuilders use. Worksheets make systematic taking of measurements and annotation of desired braze-ons easy, so that nothing will be omitted during the drawing, purchasing, and construction steps. It's also worth noting that Talbott's discussion of frame design does not venture into structural analysis. Questions like, "What are the forces on the down tube?" or "How strong must the head tube be, and why?" are not mentioned. Maybe it's just as well, because discussions of these questions could easily fill a book by themselves. Despite these limitations, Talbott conveys a clear qualitative sense of how the completed frameset must perform, which the novice should find worthwhile.

The heart of the book is the hands-on section, Chapters 3 through 12. Here, Talbott sets forth a step-by-step procedure for building a conventional steel frame with brazed lugged joints. Talbott's system of simple brazing jigs, built with common shop materials, will be very helpful to the novice builder. This section is so well organized and clearly written that anyone who can master the brazing process (the hardest part, according to Talbott) can complete a frameset with a minimum of wasted effort and "headscratching."

When I spoke with Talbott, he pointed out that building your own frame is not an economical thing to do. He says there is no way to justify the expense of building just one frame, and the methods he uses are not production methods. If you add up the cost of all the necessary tools and supplies, and compare that to the price of a custom frame, you immediately understand that the real reason for building your own frame is for the joy of having done it yourself.

Talbott says that his main purpose in writing the book was to dispel the mystique which surrounds framebuilding. There is too much of what he calls the "decal philosophy": A way of thinking about frames as a mixture of art and magic — the attitude that if the name on the frame is right, nothing else need be questioned. Talbott wants to give cyclists the tools to design and build their own frames, and more than that, he wants cyclists who have no intention of building frames to understand the basic construction steps and design approaches used by builders.

Angel Rodriguez is a professional builder of bicycle and tandem framesets, and owns R & E Cycles Co. in Seattle, Washington.

PHYSIOLOGY

Finding Your Own "Optimum Aerobic Cadence"

Robert L. Boysen

Editor's Note: The question of optimum cadence has a fairly disreputable history. As recently as ten years ago, many physiologists were baffled as to why racers were successful with high cadences that were, to the physiologists, not efficient. It turned out that the physiologists were basing their argument on lab experiments with isolated muscle fibers, while the racers were guided by what they knew worked for them in competition; a classic case of two parties "talking past" each other. Then the physiologists turned to more realistic measures of the intensity of exertion (oxygen consumption, heart rate, and blood lactate levels), and still said that racers were spinning too fast to be efficient. This controversy was resolved only after it was realized that terms like "efficient" and "optimum" were being used in inconsistent and sometimes poorly defined ways by various writers on the topic.

At this point, most of the confusions have been ironed out. Han Kroon (in June 1983 Bike Tech*), David Gordon Wilson (in December 1982* Bike Tech *and in his book,* Bicycling Science, *MIT Press, 1982), and John Forester (in April 1983* Bike Tech *and in his book* Effective Cycling, *MIT Press, 1983), to name just three, have reviewed many of the previous studies and clarified most of the troublesome issues.*

We can now safely say that the "most efficient cadence" is known, from practical experiments, to lie within the 70 to 100 RPM range, for many common cycling situations. To get a more precise fix on your own "most efficient" cadence in your own cycling situation, turn to Robert Boysen's article printed here. Boysen's simple procedure, developed while analyzing data on hill-climbing cadences (see the "Ideas and Opinions" section in this issue), uses minimal equipment and should tell you a lot about yourself.

Boysen uses the term "optimum aerobic cadence" to mean that cadence which minimizes the cyclist's heart rate, at a specified and constant level of power output at the pedals. By "optimum," he means "most energy-efficient" in the sense that the cyclist obtains the greatest result (maximum speed and distance) per unit of muscle power expended. A synonymous term, from the language of exercise physiology, is "energy-economic cadence."

It's true that "optimum" can mean more than just "efficient." After all, one reason for learning to spin (using high cadence and low muscle force) is to reduce the risk of knee injury. And in competitive racing, constraints such as strategy, pacing, and drafting enter the equation. Energy efficiency may have little meaning for the racer; he doesn't care if he's exhausted at the finish, as long as he wins! But a large number of cyclists, particularly tourists and commuters, have a great interest in traveling the longest distance with the least effort. For these situations, the most efficient cadence is indeed the "optimum aerobic cadence" defined here.

Robert L. Boysen is President of the Western Jersey Wheelmen Bicycle Touring Club, and cycles about 7,000 miles per year. He holds a B.S. in Mechanical Engineering (Rutgers) and an M.S. in Management Engineering (NJIT), and works as Director of R & D in Polyolefin Specialties for Union Carbide Corporation.

While reading Alan Hammaker's article, "Perspectives on Gearing," in the May 1984 *Bicycling,* it occurred to me that most serious cyclists already have the equipment they need to determine their optimum aerobic cadence. Mr. Hammaker obtained some very interesting data on the effect of cadence (and gear ratio) on hill climbing with the use of nothing more complex than a hill, a bicycle, a friend, and a watch.

This article describes a simple method I've developed for determining optimum aerobic cadence; anyone with access to a stationary cycle, torque wrench, and heart-rate monitor can collect his or her own data. The numbers reported here were obtained on the author at his present level of fitness. Other individuals can expect to obtain different numbers, but should see the same patterns and trends as I describe below.

Stationary Cycle

For collecting the data, I used the following straightforward method: I recorded my heart rate while pedaling an indoor stationary bicycle at various cadences and torque settings. From this data, I could easily calculate the heart rate increase per unit of power output at each cadence and torque setting. Plotting these data on graph paper showed that the curves do indeed exhibit a minimum point, which I could identify by visual inspection.

The stationary cycle that I used, the Schwinn *Excelsior,* has no calibration for torque, and has no instruments other than a "speedometer." I borrowed a torque

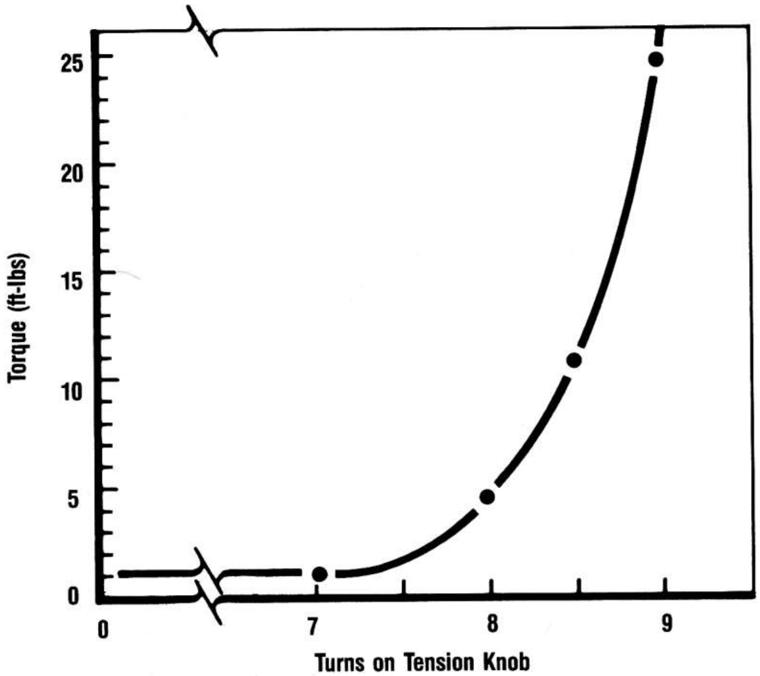


Figure 1: Torque Calibration of Stationary Cycle

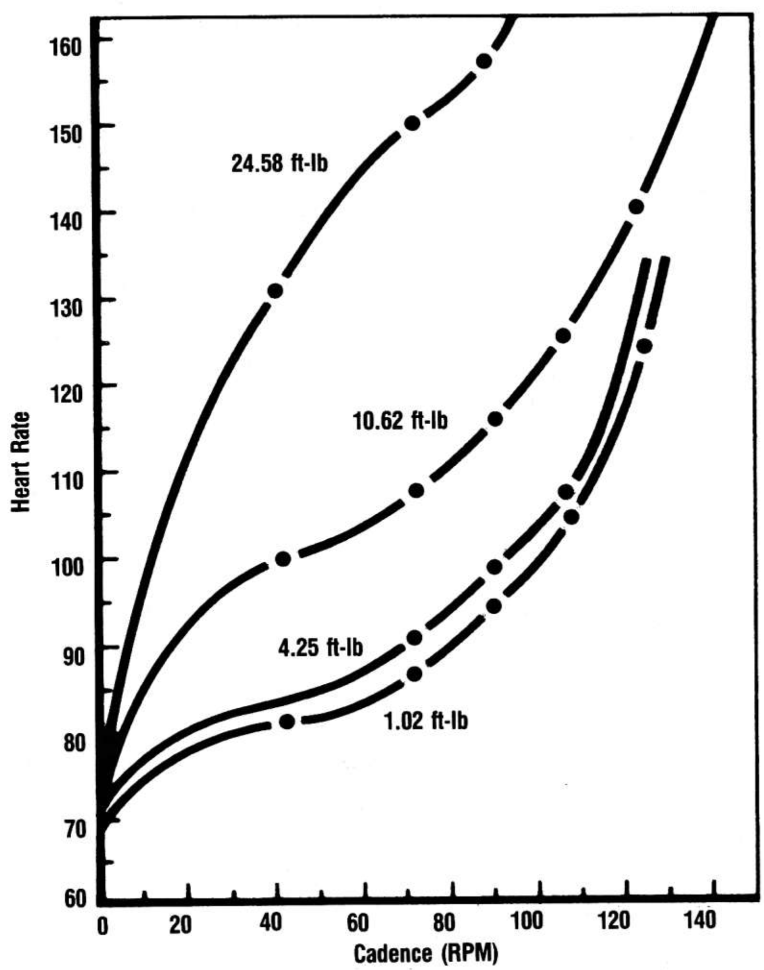


Figure 2: Measured Heart Rate versus Cadence at constant torque

George Retseck

wrench (the 0 to 50 ft-lb type used by maintenance mechanics) to measure the torque required to turn the pedals of the stationary cycle at several settings of the tensioning knob. The tensioning knob sets spring tension on a friction brake. The torque wrench was attached to the cycle by removing a pedal and threading a bolt to the crank arm. The torque wrench was then fitted to the bolt. The resulting calibration curve is shown in Figure 1.

To test whether the friction brake maintained constant torque regardless of speed, I rotated the crank with the torque wrench at various speeds and noted the resulting torque. I found that speed had no measurable effect on torque of the friction brake, which is fortunate because it greatly simplifies the subsequent calculations. After the data-collection session, I rechecked the torque calibration curve and found no measurable differences. Thus, any wear or heating of the friction brake that might have occurred could be safely ignored. Other brands of stationary bike might yield different results on these two preliminary tests; it's always best to check.

To measure heart rate, I used a Sears "Digital Electronic Pulse Monitor" with an earlobe transducer. Any reliable monitor could be used. After several short sessions of pre-exercise, my heart rate was taken with the monitor. A quite consistent "base" of 70 beats per minute was found. The rate tended to drop rather quickly after an exercise session to 70 and remain there for several minutes, after which it began to drop slowly. My usual *minimum* rate is about 53.

The main testing went like this: A torque was pre-set with the tensioning knob and kept constant through a series of test runs at several cadences. To obtain each data point, I pedaled at a constant cadence as indicated by the cycle "speedometer," until the heart rate stabilized at a steady value (plus or minus two beats) for about three minutes. It took anywhere from five to fifteen minutes of pedaling for the heart rate to reach this equilibrium. Cadence was held to about plus or minus one RPM during the test, and heart rate was monitored continuously. After each test run, I rested until my heart rate returned to 70 before starting the next test. In total, I did seventeen test runs, recording heart rate at most combinations of five cadences (42, 72, 90, 108, and 125 RPM) and four torque settings (1.02, 4.25, 10.62, and 24.58 ft-lbs). It's worth noting that I was pedaling in the sitting position throughout the tests. None of the conclusions of this article should be applied to the standing or any other position, without running further tests.

Curiously, at moderate exercise levels, my heart rate tended to overshoot the final equilibrium value, followed by a smaller undershoot, et cetera, finally approaching an equilibrium level. Classic feedback control systems used for process control in industry act in the same manner.

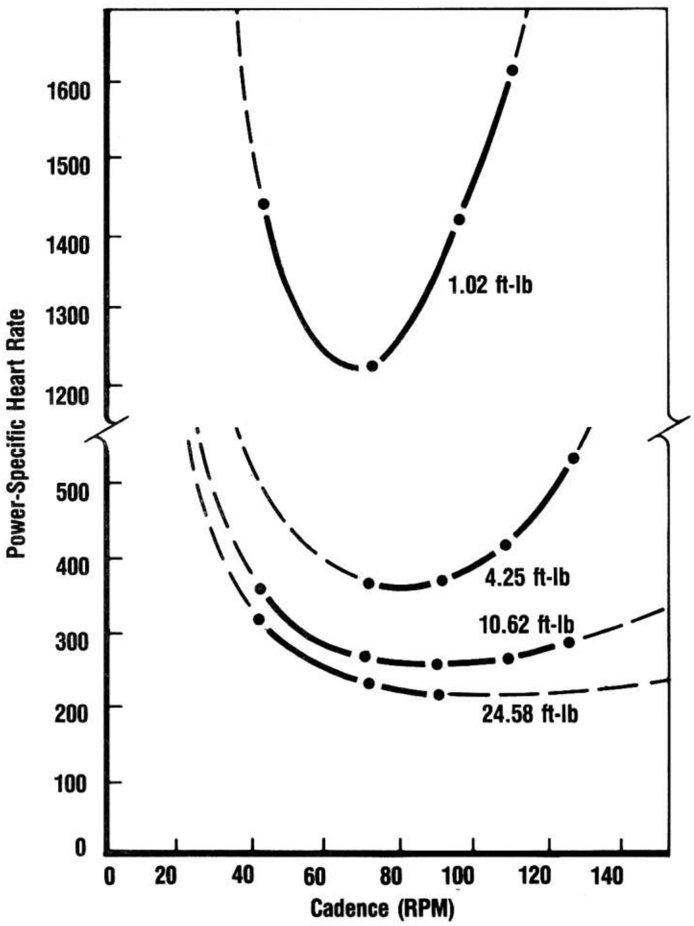


Figure 3: Power-Specific Heart Rate versus Cadence at constant torque

George Retseck

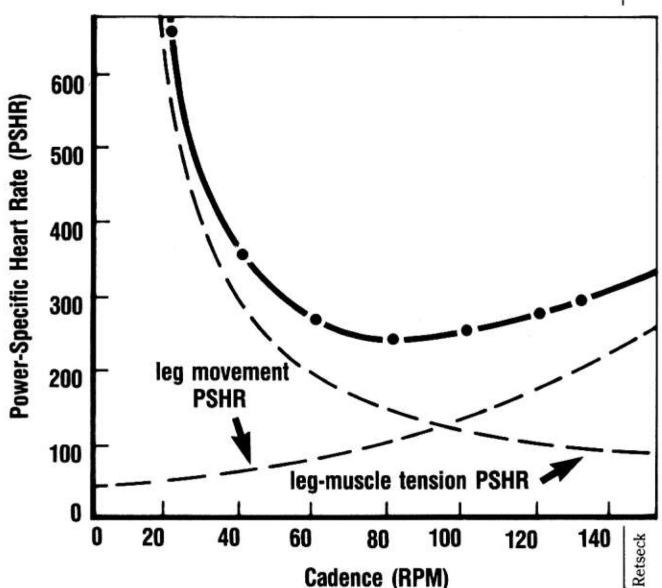


Figure 4: Power-Specific Heart Rate (at constant torque) shown as the sum of two hypothetical components: leg-muscle tension and leg movement.

George Retseck

The data I obtained are shown in the accompanying table and are plotted in Figure 2. I measured several of the data points out of sequence to determine whether my increasing fatigue was affecting the results. As far as I could tell, this effect was negligible.

Heart rate measured at various cadences and torque settings on stationary cycle.

Cadence (RPM)	Torque (ft-lb) 1.02	4.25	10.62	24.50
42	81.5	—	100	131
72	87	91	108	150
90	94	98	117	157
108	104	106	127	—
124	124	124	140	—

Note: Resting heart rate = 70

The "S" shape of the curves in Figure 2 is the first clue that an optimum cadence probably exists for each torque level. S-shaped curves have what's called an "inflection point" where the curvature changes from concave downward to concave upward. This is precisely the condition that's needed for an optimum (in the mathematical sense of a minimum) to exist.

Power-Specific Heart Rate

For each of the heart-rate data points, I could calculate the power being transmitted to the bicycle. Power depends *only* on torque and cadence, by the formula:

$$\text{Power} = \text{Torque} \cdot \text{Cadence} \cdot 2\pi / 33000$$

where power is measured in horsepower, torque is measured in foot-pounds, cadence is measured in revolutions per minute, and the 2π and 33000 are numerical constants. (To convert horsepower units to watts, multiply by 745.7.) For the data points I collected, power ranged from 0.008 to 0.421 hp. I don't mind admitting I had a fairly hard time producing over 0.421 hp for ten minutes.

To determine the optimum aerobic cadence, I conceived of a new factor called "Power-Specific Heart Rate" — PSHR for short. This factor is defined as the increase in heart rate (above resting rate) divided by the rider's horsepower output, as follows:

$$\text{PSHR} = \frac{\text{Heart Rate} - \text{Resting Heart Rate}}{\text{Horsepower Output}}$$

I calculated the PSHR for each of the heart-rate data points, and plotted the results in Figure 3 as PSHR versus cadence at constant torque. Since readings were taken at four separate torque settings, four separate curves result. I was pleased to see that the minimum point on the four PSHR curves fell at a cadence between 70 to 90 RPM, which is the range that other studies have found to be "most efficient" or "most preferred" by the rider.

But what do all these PSHR numbers tell us? From the definition of PSHR, it's clear that a cadence which minimizes PSHR will minimize heart rate for a given level of power output. Heart rate is a good indicator of the muscular effort being expended by the cyclist. And horsepower output is a perfect indicator of the rate of progress of the cyclist under any specific set of road conditions (wind, slope, air drag, etc.). Thus, riding at the cadence which minimizes Power-Specific Heart Rate results in the most distance traveled with the least exhaustion, for any given level of power output. In other words, it's up to the rider to choose how hard he wants to work; say, 0.05 hp for a leisurely tour, or 0.2 hp for a short intense workout. Once the level of power output is chosen, the rider's individual curves of PSHR versus cadence indicate which cadence to use to get the maximum results (distance traveled) from the muscle effort expended. This is the meaning of "optimum" in the term "optimum aerobic cadence."

Fine Tuning

The shape and location of the curves in Figure 3 suggest some interesting conclusions about optimum aerobic cadence:

—Optimum cadence increases with increasing torque. In my own case, optimum cadence is 70 RPM for very low torques (1 ft-lb), increasing to about 120 RPM for high torques (24 ft-lbs).

—The curves become quite flat at very high torque levels. For example, at more than 24 ft-lbs torque, any cadence between 70 and 140 (and perhaps even higher) would yield the same near-optimum level of efficiency.

—Cadences much below 50 are disastrous to cycling efficiency.

The general shape of the curves in Figure 3 would likely be the same for all cyclists, but the actual location of the optimum aerobic cadence on each curve will probably be different for different cyclists, and even for the same cyclist if his or her level of physical fitness changes. In fact, the PSHR curves such as plotted in Figure 3 could provide a useful tool for fine-tuning an aerobic training program, or for comparing different riders of different pedaling styles. (Editor's note: Is anyone interested in comparing non-circular chainwheels or cam-driven linkages using this procedure?)

Why an Optimum Cadence?

I tried to understand why an optimum energy cadence exists, by the following reasoning. Minor projections of the data show that: (a) heart rate increases with increasing cadence even at zero torque level, and (b) heart rate also increases with increasing torque even at zero cadence. Item (a) can be interpreted as "it takes more energy to flail your legs faster, even with no useful output." (You would get tired at 150 RPM cadence even if the chain were disconnected.) Item (b) can be interpreted as "isometric exercise raises your heart rate, even though nothing moves." (Did you ever try, unsuccessfully, to push a car uphill?)

In concert with this explanation, the PSHR curve can be thought of as the sum of two other curves illustrated in Figure 4. These two hypothetical curves are: (a) PSHR due to leg movement alone (no-load spinning), which increases with increasing cadence, and (b) PSHR due to simple muscle tension (isometrics), which decreases with cadence at constant torque.

My next project is to try to substantiate these two curves by experiment. I can measure heart rates under no-load spinning conditions (at various cadences), and under isometric conditions (at various torque settings), using the same stationary bike and pulse monitor equipment. After all, it's easy enough to take the chain off the stationary bike, and to push against the torque wrench. I hope this data will result in curves similar to the hypothetical ones sketched in Figure 4. If it does, I'll have some basis for expressing the power-specific heart rate as the sum of two components:

$$\text{PSHR} = \frac{\text{Isometric Effort Heart Rate} + \text{Leg Movement Heart Rate}}{\text{Horsepower Output}}$$

In fact, I expect this relationship will have the following form:

$$\text{PSHR} = \frac{a \cdot (\text{Cadence})^x + b \cdot (\text{Torque})^y}{c \cdot \text{Cadence} \cdot \text{Torque}}$$

where the letters a, b, c, x, and y designate numerical constants to be calculated by a curve-fit to the experimental data.

Note: Due to space limitations, the test report on crankset flexibility, originally announced for this issue of Bike Tech, *has been postponed until the next issue.*

IDEAS & OPINIONS

High-Cadence Data Questioned

Editor's Note: This discussion had its beginnings on a steep hillside in Montreal, when Alan Hammaker was taking measurements to find whether climbing in a 14-inch gear or a 40-inch gear left him more exhausted at the top. He found that his heart rate was lower when he used a higher cadence (hence a lower gear ratio), with the comparison being made at the same levels of power output. He concluded that lower gear ratios made for more "efficient" hillclimbing, and published the result in May 1984 Bicycling.

Robert Boysen read the article, but wasn't convinced that Hammaker's data supported his conclusion. Boysen didn't necessarily disagree with the conclusion itself; he just wasn't happy with the statistical basis for the argument.

The upshot of all this is the two letters printed here: they both make good points about practical matters to consider when collecting and analyzing physiology data. After reading these letters, we're inclined to say that Hammaker's conclusion still stands, (i.e., it really is less effort to spin uphill in the 14-inch gear, rather than stomp up in the 40-incher), but we'd like to see more convincing data. In fact, Hammaker is planning another round of low-gear testing with better instruments, more riders, more repetitions, etc. We'll keep you posted.

And the other upshot is Boysen's discovery of a quantity he calls "power-specific heart rate": his article in this issue of Bike Tech, *in the "Physiology" section, suggests how to use this quantity to find the "most efficient" cadence at any power level.*

In the article titled "Perspectives on Gearing" in the May 1984 issue of *Bicycling,* Alan Hammaker reaches the conclusion that ultra-low gear ratios, and hence high cadences, result in greater pedaling efficiency while climbing steep hills. The hill-climbing tests which provided the data for Mr. Hammaker's analysis were done carefully enough, I think, but Hammaker's analysis of the data appears to be faulty. A proper analysis would reveal that Hammaker's data show no direct relationship between cadence and pedaling efficiency. In any case, more tests should be run before reaching a final conclusion.

I have plotted in Figure 1 all the bicycle hill-climb data presented by Mr. Hammaker. Heart rate is plotted versus horsepower generated. The cadence at each data point is indicated by the small number near each point. If the conclusion that heart rate is dependent on cadence (in addition to horsepower, of course) were supportable, a fairly clear pattern of cadence numbers would emerge. All the higher cadence numbers should lie near the lower dashed line, while all the lower cadence numbers should lie near the upper dashed line. This is obviously not the case. In fact, we have two points with almost identical horsepower and heart rate, but one shows a cadence of 41, the other a cadence of 63. Also, the cadence point marked 57 lies well above the point marked 58 — the opposite of what is needed

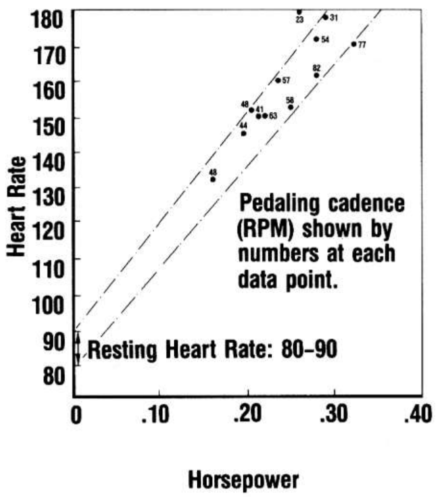


Figure 1: Heart rate versus horsepower produced by the rider. Data from hill-climbing tests reported by Hammaker in *Bicycling*, May 1984.

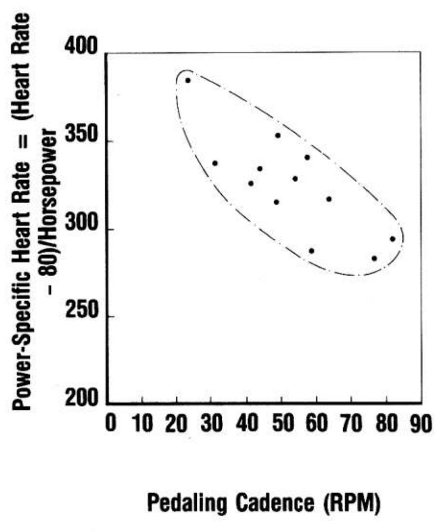


Figure 2: Power-Specific Heart Rate versus Pedaling Cadence, calculated from data shown in Figure 1.

George Retseck

to support his conclusion.

The only conclusion supportable by the data is that heart rate (at a given horsepower output) is independent of cadence. The indicated advice to the cyclist is to choose any cadence that feels good between 30 and 80.

To obtain a further check of the data, I invented a factor — let's call it "Power Specific Heart Rate" (PSHR) — which is equal to the heart rate (in excess of 80 resting heart rate) per unit horsepower output. (Note: See the article by Mr. Boysen in this issue of *Bike Tech* for more details.) I have plotted this factor against cadence in Figure 2 using a resting heart rate of 80 as reported by Hammaker. If the data supported the conclusion that heart rate efficiency improves with increasing cadence, a clear correlation should appear on this plot. However, no such correlation is apparent.

Again, the only valid conclusion is that heart rate is independent of cadence at a given power output.

I have read often that "higher cadence is better cadence," but I have yet to see any definitive supporting data. Can it be that the statement is a confession of "faith," rather than fact? Does anyone have the data?

Robert L. Boysen
Lebanon, New Jersey

Alan Hammaker responds:

Mr. Boysen's thoughtful analysis stimulated me to reread the literature I have on cadence, and to take a twentieth look at my data.

I would like to say at the outset that my article makes no pretensions at scientific rigor, and in the text one reads that it is a "tentative study" which "suggests" certain possibilities. My desire is that its publication would stimulate a more thorough effort which might reveal more conclusive results.

The shortcomings of the article are due less to insufficient analysis of the data than to insufficient data to analyze. Statistical analysis of physiological data requires far more measurements than I was able to take, and requires greater rigor in regard to reliability and validity. After all, I did this study essentially alone: I was the rider, time-keeper, and pulse-taker, except for the occasional help of a few friends. Pulse-taking is notoriously inaccurate, though I have taken pulses for many years in a medical setting. Instrumentation, as the article suggested, is a means to improve this aspect of data-collection for future studies.

Rigorous scientific studies have shown that the link between high cadence and high efficiency is more than just an unfounded "belief." These studies also point out limits to how fast a rider can spin and still maintain highest efficiency. Efficiency begins to decline above 80 to 85 rpm or thereabout. I suggest the following articles:

1. Diego Gueli and Roy J. Shephard, "Pedal Frequency in Bicycle Ergometry," Canadian Journal of Applied Sport Sciences, *Vol. 1, 1976, pp. 137-141.*

2. David Gordon Wilson, "The Performance of Machines and Riders on Hills," Bike Tech, *Vol. 1, No. 4, December 1982, pp. 4-5. (See particularly Fig. 1, which also appears on p. 66 of the 2nd edition of Wilson's* Bicycling Science.*)*

3. Han Kroon, "The Optimum Pedaling Rate," Bike Tech, *Vol. 2, No. 3, June 1983, pp. 1-5 (excellent bibliography and discussion of why racers spin faster than what mechanical efficiency would dictate).*

4. Ron Shepherd, letter to Bicycling, *July 1977, p. 71. "Our task is to explain how the described phenomenon happened: why were younger riders, closer to their physiological prime, riding much higher gears with lower cadence on a protracted steep gradient,* unable *to maintain the same power output as an older cyclist spinning low gears?"*

I would like to make the following points about my article and Mr. Boysen's critique:

A. By using pulse, I was employing only an indirect measurement of oxygen uptake, (though reference no. 1 above shows their close correspondence). Determination of actual pedaling efficiency requires direct measurement of oxygen uptake and carbon dioxide production.

B. My article addresses only efficiency on hills, not the larger general question of efficiency under all "normal" cycling conditions. My tests were done on an unusually steep gradient, and I don't believe we yet know how this compares to riding on the "flats," — different influences of wind resistance and deceleration due to gravity.

C. The hill I used in Montreal was just long enough for the pulse to attain a plateau, or "steady state" of adaptation to the work load. Definitive studies will have to employ much longer rides to eliminate any doubts as to reaching a physiological plateau.

D. Han Kroon (reference no. 3.) indicates that efficiency of cadence varies with work load. His figure 1a "shows that with increasing power output the rider has to increase the pedaling rate as well (as pedaling force) in order to obtain the highest possible efficiency." The important conclusion to be drawn from this is that one must compare efficiency at similar levels of power output. This is what I attempted in interpreting the data in my article.

E. I would agree with Mr. Boysen as to choice of any cadence between 30 and 80 that feels good — if the gearing allows the choice. In my test, the 14.5- and 18.3-inch gears allowed the rider that choice. I believe that gears within the 30-inch range (and above) would not be comfortable for most riders on long, steep hills such as our test hill. Another point: With 45 pounds of baggage in a 39.9-inch gear on our test gradient, any cyclist trying to spin at 60 rpm would have to produce a continuous 0.64 horsepower — shades of Eddy Merckx in Mexico City! Most of us mere mortals cannot do this — the point being that the high gears, relative to the gradient, restrict the rider's choice. Why not use a lower gear, spin faster, and ride up the hill at a similar speed in relative comfort? I found the 22.5 cadence agonizing — certainly not something I would choose on really long hills on a protracted tour.

F. I cannot explain all the problems Mr. Boysen found in his plot of heart rate versus horsepower (Figure 1). Measurement inac-

curacies certainly enter the picture. The 57 and 58 cadences he points out as being reversed could be related to the measurements, but I wouldn't expect a cadence difference of 1 rpm to reveal very much difference in efficiency.

If we do restrict ourselves to comparing close power levels, however, moving to the right of the 57 and 58 cadences we see that the next closest power level, at a cadence of 23, certainly has a higher heart rate. Similarly, on the upper right end of the graph, the link between lower cadence and higher heart rate is evident.

G. I tried a least squares curve-fit of Mr. Boysen's data in Figure 2, which plots "Power Specific Heart Rate" against cadence. Even though the number of data points (12) is really too small for a reliable regression analysis, my calculations netted a slope of −1.4, using several different regression equations.

(Editor's note: It's significant that the calculated slope is a negative number: this indicates that higher *pedaling cadence means* lower *power-specific heart-rate, and thus lower aerobic exertion needed per unit of power delivered. You can see this in Figure 2 by noting that the data points are not randomly scattered around the chart, but fall in a broad band from upper left to lower right. A statistical number called the correlation coefficient* (r) *shows how strong this relationship is. For Hammaker's 12 data points in Figure 2, the linear correlation coefficient is −0.82, according to our calculation. An* r *value of −1.00 means a perfect linear relationship, while an* r *value of 0.00 means no relationship.)*

All of this suggests that the issue is not dead, and that for climbing long steep hills, ultra-low gears and higher cadences really are more efficient.

George Retseck

Anodized Rim Stiffness: Bending vs. Compression vs. Spray Paint

The article in the April 1984 *Bike Tech*, "Anodized Rims are More Rigid," tells only part of the story. The author's basic point is correct: adding a layer of anodizing about 0.001 inch thick *will* increase the stiffness of the rim, since the stiffness of the anodizing is greater than that of the aluminum alloy. But his evaluations cover axial compressive loads only, while the rim is actually experiencing *bending* in addition to axial compression. Chris Juden's article in the same issue, for example, deals entirely with the bending loads. So I reworked the calculations to see how anodizing affects the rim's stiffness in bending.

The bending stiffness is proportional to E × I (Modulus of Elasticity times Moment of Inertia), so I calculated these quantities for both the unanodized rim and the anodized one, and compared the results. Unfortunately, the calculations are much more complicated than for the simple compression load.

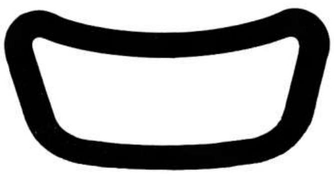


Figure 1: Fiamme Red Label Tubular rim. Cross section area = 0.1031 in^2.

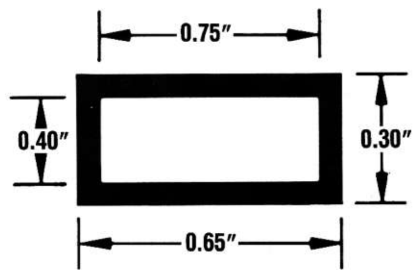


Figure 2: Rectangular approximation to Fiamme Red Label rim (unanodized).

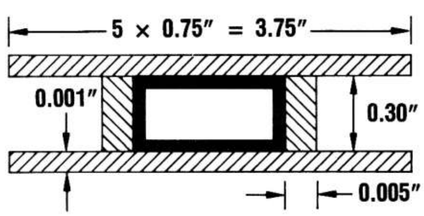


Figure 3: Fiamme Red Label rim with anodizing 0.001 inch thick. To calculate moment of inertia, the anodizing is increased in width by a factor of 5, since the anodizing is 5 times stiffer than aluminum. Total moment of inertia of anodized rim = $2.8923 \cdot 10^{-3}$ in^4 (14% increase over unanodized).

For the unanodized rim, I used the standard beam calculation given in many engineering texts. An assembly of simple shapes (rectangles, circles, et cetera) is used to closely approximate the rim's cross-sectional shape and size. (See Figures 1 and 2.) One easy method for measuring the rim's cross section is to hack-saw a section out of the rim and use it as a "rubber stamp" to transfer the shape onto fine graph paper (20 squares per inch). The rim's total moment of inertia is found by summing the moments of inertia of the simple shapes, taking care to calculate all moments of inertia about the cross section's centroid.

For the anodized rim, I used the standard technique for dealing with what's called a "composite beam" (a beam made of two materials). The extra stiffness is calculated by converting the anodized area to an equivalent area of aluminum, but with extra *width*. For anodizing five times stiffer than aluminum, the width of the anodizing must be multiplied by five. (See Figure 3.) The new effective moment of inertia can now be calculated by treating this transformed cross section as though it were entirely aluminum, since the effect of five times more width is the same as the effect of five times more modulus of elasticity.

I have done the calculations for two shapes: a hollow rectangle whose dimensions approximate a Fiamme Red Label tubular rim's cross section, and a much more complicated approximation of a Super Champion clincher rim. The tubular rim showed 14% increase in bending stiffness due to anodizing, and the Champion clincher rim showed a 27% increase, assuming that the anodizing applied to both rims was 0.001 inch thick.[1] These percentages agree fairly well with the result given in the April 1984 *Bike Tech.* (The author reported a 21% increase in compressive stiffness due to an anodized layer of approximately the same thickness.) However, the agreement is entirely by coincidence! Remember that bending stiffness and compressive stiffness are two different animals!

My second comment concerns the interpretation of the numbers once they are correctly calculated. The rim is but one part of the total system, which includes tire, rim, spokes, hubs, bearings, et cetera. The deflection (or lack of it) sensed by the rider is that of the entire system, and increasing the *rim's* stiffness by 27% will certainly not increase the *system's* stiffness by 27%. In fact, since tire deflection is probably 30 times rim deflection, I would guess the overall change, due to anodized rims, would be unmeasurable by the rider. In other words, riders who are faster on anodized rims might be just as fast if the rims had been spray-painted a dull grey.

Frank Krygowski
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[1] Editor's Note: To cross-check these calculations, we compared Chris Juden's measured value of bending stiffness for the unanodized Super Champion clincher rim ($3.2754 \cdot 10^{-3}$ in^4) against Krygowski's calculated value ($3.5838 \cdot 10^{-3}$ in^4). The two numbers differ by about 9.4%, which is reasonably close, given the approximations of Krygowski's cross-section plotting method.

newsline

INTRODUCING "NEWSLINE"—A NEW *BIKE TECH* FEATURE: The latest developments in cycling technology will be highlighted regularly on this page in *Bike Tech.* We see a steady stream of technical news items that *Bike Tech* readers should know about: items such as test reports, research projects, patents, inventions, new books and standards, and conference reports. But, for one reason or another, many of these items are not suitable for a regular *Bike Tech* article. So we created "Newsline" to bring the best of these items to you while they're still fresh. We'll publish the highlights, along with access information (names, addresses, phones, prices) so you can follow up on your own if you're interested. And we welcome your contributions to "Newsline," too. If you come across information that's technical, new, and interesting to *Bike Tech* readers, send it in. We'll pay $10 for each contributed "Newsline" item we publish. We're working to make *Bike Tech* an even better information exchange for the bicycling technical community, so let us hear from you soon. *Robert G. Flower, Jeff Davis, Jim Redcay, Susan Weaver.*

HELMET UPDATE: POLYSTYRENE LINERS SHOW BEST IMPACT PERFORMANCE IN CANADIAN TESTS: Helmets manufactured by Bailen, Bell, MSR, Norco, Protec, and Skid-Lid were tested in the Biomechanics Laboratory at the University of Waterloo, Ontario, with funding from Fitness Canada, a government agency. In the tests, each helmet was fitted on a headform and dropped on the front, rear, side, and corner from heights of 1.00 and 1.75 meters. An accelerometer in the headform measured peak acceleration, from which the helmet's capacity to cushion the shock of a direct impact was calculated. The test is similar to those run by the Snell Foundation and reported in *Bicycling* (March 1983). The Canadians found that helmets with expanded polystyrene liners transmitted much less impact to the headform than did those with soft foam liners. But the performance advantage of polystyrene disappeared when the helmets were dropped a second time on the same spot. Researchers believe that the polystyrene liners were crushed by the first impact and didn't bounce back. They also found that all of the helmets provided much less protection against impacts to the corner of the helmet, compared to direct impacts on the front. Factors of weight, ventilation, comfort, and security of fit were not tested. ("Impact Performance of Bicycle Helmets," by P. J. Bishop and B. D. Briard, *Canadian Journal of Applied Sport Sciences,* Vol. 9 #2, 1984, pages 94-101).

ANSI Z-90 STANDARD NOW AVAILABLE: In March 1984, the American National Standards Institute (ANSI) gave final approval to its voluntary standard for bicycle helmet performance (ANSI Standard Z-90.4: *Protective Headgear for Bicycle Users*). The Standard's requirements include that each helmet must reduce the impact of a fall from one meter height to less than the 300-G limit. In the future, consumers can expect to see helmets appearing with stickers stating that they pass the ANSI test. Copies of the Standard are available for $9.00 from ANSI, 1430 Broadway, New York, NY 10018. Telephone 212/354-3300.

NEW CONSUMER GUIDE FROM WABA: A handy pamphlet, *A Consumer's Guide to Bicycle Helmets,* is now available from the non-profit Washington Area Bicyclist Association. The *Guide* rates 14 helmets from "Excellent" to "Fair," and explains what to look for when buying a new helmet. Single copies are available free with SASE from WABA, 1332 Eye St., NW, Washington, DC 20005.

WALNUT HULLS CLEAN ALUMINUM BEST, SAYS NASA: Walnut hulls are the best abrasive for cleaning aluminum structural components prior to painting, according to a technical report from NASA's Marshall Space Flight Center. Samples blasted with walnut hulls showed no compressive stress of the surface, while samples blasted with abrasives such as silica sand, silicon carbide, or garnet showed considerable warpage due to compressive stresses of 24 to 33 thousand psi. Although the NASA report deals with aluminum components used in aircraft and space vehicles, its results could be useful to builders and refinishers of aluminum bike frames. The quality of surfaces repainted after blast-cleaning with walnut hulls, says NASA, was equal to that of a first-time painted surface, with no loss in structural properties. (For further information, order NASA Technical Support Package #MFS-27012, by Wendell R. Colberg and Charles H. Jackson, free from NASA Scientific and Technical Information Facility, P.O. Box 8757, Baltimore-Washington International Airport, MD 21240. Telephone 301/859-5300.)

Mark Lenny

SHIMANO UNVEILS "NEW DURA-ACE" LINE OF RACING COMPONENTS: Fundamental re-thinking of how each component must function "in real racing conditions" is the basis for the new line, according to John Uhte, Technical Manager of Shimano Sales Corporation (California). The "New Dura-Ace" series includes derailleurs (front and rear), shifters, brakes, freewheel, crankset, pedals (see illustration) hubs, and headset. Direct interchangeability with other brands of components, including Campagnolo, is possible with most of the New Dura-Ace parts, according to Uhte. Other features are said to include lubricant-impregnated nylon sleeves and titanium-nitride coating at most points of moving contact, to minimize friction. New bearing-seal designs were used in the pedals, crank, and axles, to resist the effects of mud and vibration typical in European road racing. The New Dura-Ace components will be available in the U.S. in February (Shimano Sales Corporation, 9259 San Fernando Road, Sun Valley, CA 91352).