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IN THE LAB

Frame Rigidity

Crispin Mount Miller

How rigid is a bicycle frame? How much difference is there among different frames, and what are the consequences? Few other questions about frames intrigue cyclists as much as these, but good answers have seldom been available. Like many other aspects of bicycle engineering, frame rigidity is a subject that has been buried in folklore and mythology.

Some time ago we discovered that several people had independently thought of the same configuration for a frame rigidity testing jig. Among the people in this club were Gary Klein, Gary Fisher, John Schubert, and me. We were scattered around the bicycle industry and didn't all know each other, but we'd all wished for the same kind of machine.

A Different Kind of Machine

Our idea was to simulate riding stresses by loading a bicycle frame as a rider would — by pressing on the pedal — and then measuring how the frame deflected under the load. The frame would have to be supported in a realistic fashion, with dropouts and head tube not clamped rigidly in place, but allowed to move somewhat, as they do when a bike is ridden.

In this respect, our machine would differ from the few rigidity testing machines known to exist inside the bicycle industry. Most manufacturers test rigidity by clamping the frame down and poking sideways on the bottom bracket shell. This is adequate for some kinds of comparisons, but it doesn't address all the subtle questions that our pedaling load simulator would answer.

Building such a machine was too time-consuming and costly for any of us, but a cooperative effort made it possible. Gary Klein and John Schubert collaborated on a design over the telephone, and Klein built "Tarantula I" in his framebuilding shop. *Bicycling* magazine purchased the machine from Klein and it now sits in our bike workshop. We have done a few tests with the machine; in this article, I'll present an analysis of how and why the machine works and what questions it can answer for us.

Need to Isolate Results

The fundamental purpose of the machine's design is to apply loads to a frame in ways that resemble normal use, but to isolate the results: to sort out, from a bike's various deflections under load, what portion is due to deflection of the frame, and not of the wheels, drivetrain, or anything else.

To perform such measurements reliably, a testing machine must provide well-controlled, repeatable ways to do three things: support and hold the frame being tested; apply force with a known magnitude, location, and direction; and measure deflections of specific parts, in specific directions.

The support must be designed to minimize extraneous motion that would contaminate the readings. This machine's design accomplishes this principally by making all the supports many times as rigid as the object being tested, so that deflections of the supports are negligibly small; and also by arranging the support structure so that any deformations that do occur do not affect the measurements.

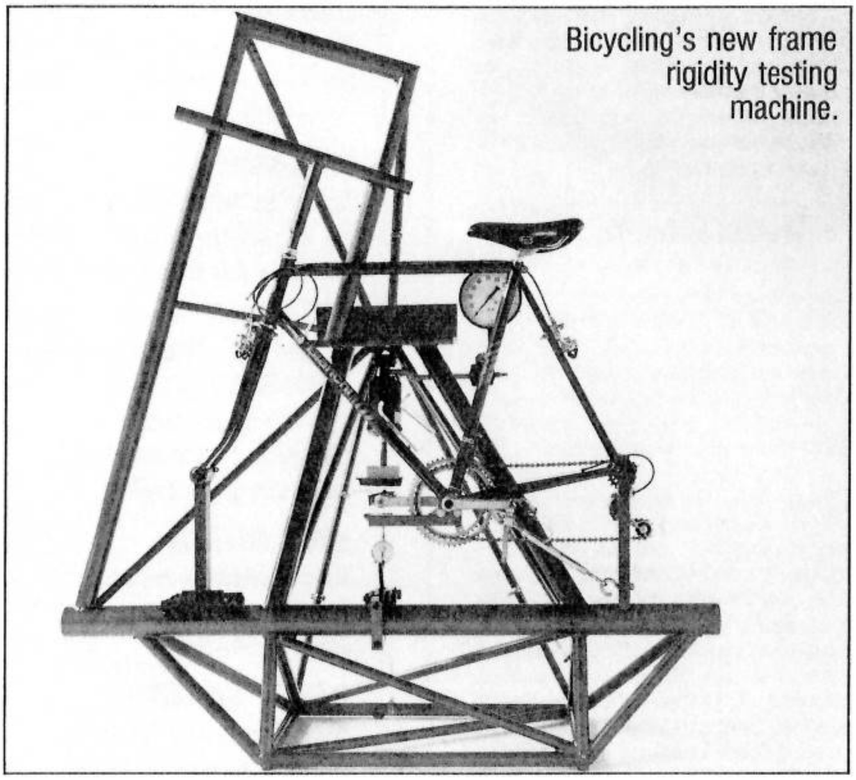
The principal support for the bicycle is a rail representing the ground, consisting of a steel pipe three inches in diameter and five feet long, three-dimensionally braced by several welded struts of smaller steel pipe.

The bicycle sits on this support rail on a pair of one-by-two inch steel pillars installed in place of wheels. These pillars are fastened to the bicycle frame's dropouts, not to the testing machine; at the bottom end they are simply notched to sit on the support rail. They simulate perfectly rigid wheels that have perfect traction (against lateral motion) on the ground. They are free, however, to move in certain limited ways (as rigid wheels would) so that they don't improperly restrain the motion of the frame itself.

The front pillar is equipped with a freely rotating "axle" at the top end and a "roller

IN THIS ISSUE

skate" foot at the bottom, so that it can move forward, as a real wheel would, when the fork flexes forward under a load. The rear pillar simply stands still on the support rail and is bolted solidly to the dropouts. This pillar has two "rear sprockets" welded immovably to it (with teeth staggered $^{1}/_{4}$-inch to allow fine adjustment of chain and crank position) and is braced against the sprockets' torque by a turnbuckle that reaches to the bottom bracket from the lower end of the pillar. This rear pillar might seem to be immobile, but in fact it moves slightly with the frame, as a (locked) wheel would, when the rear triangle tilts forward or swings sideways under a load.


Bicycling's new frame rigidity testing machine.

(A vector diagram shows that the resulting pattern of forces due to the turnbuckle is equivalent to that for a bike with an "infinitely high" gear, i.e., with a rear sprocket whose radius is zero or — except for the force on the seatstays — to that for a bike with its rear brake locked. While this isn't completely realistic, the only difference for the frame turns out to be that the net vertical force on the bottom bracket is high by a few percent — about 12 percent compared to that for a bike in a 90-inch gear. This correction can easily be deducted from the readings and is a small price for the simplification it allows in the structure and operation of the machine.)

A spidery superstructure of additional steel struts extends above and behind the support rail. This upper structure provides lateral support for the bike being tested, and also offers a "place to push from" to apply testing forces.

Loading and Measuring

The machine applies controlled loads to the frame with a pneumatic cylinder supplied with compressed air through a finely adjustable pressure regulator. In its present location, the cylinder applies an oblique downward force to the right pedal. Other arrangements we're considering are to apply a vertical load to the seat, and to pull or push in various directions on the handlebars.

Once it applies the load, the testing machine measures deflections with a simple and direct instrument called a machinist's dial indicator: a dial face attached to a telescoping rod, with a hand on the dial that measures the telescoping motion in thousandths of an inch. This instrument can be mounted against any of several parts of the frame to measure specific deflections. By suitable locations of one or more cylinders and dial indicators, the machine can be used to measure numerous aspects of rigidity under various vertical, lateral, and pedaling loads.

Flexure under Heavy Load

As the present location of the cylinder might imply, the first question we are looking at is the classic one of frame flexure under a hard pedaling load. The piston is oriented to apply a force that simulates a hard push in a sprint: vertical when viewed from the side, and slanted ten degrees toward the midplane of the frame when viewed from the front or rear — as if a rider, standing up in a sprint, were tilting the frame a bit to the left while pushing straight down on the right pedal. The crank is positioned level, i.e., halfway through the downstroke; and the force is applied to the pedal at a point five inches from the midplane of the frame. (On most bicycles, this point falls approximately in the middle of the foot-bearing part of the pedal.)

Having applied the force, one has to choose which resulting deflection to measure. When the machine pushes down on a pedal, the frame displays several different motions at once: the fork tips flex forward and let the frame descend and tilt forward; the middle of the frame bows away from the piston; and the bottom bracket rocks sideways. All of these motions enable the pedal to descend somewhat without turning the rear wheel. Some of them have other implications as well, such as shock absorption or effects on steering. Each is a worthwhile effect to measure.

A more interesting approach, though, is to take measurements that predict the actual amount of energy the frame absorbs from a pedal stroke.

How Much Energy is Wasted

One of the most widely voiced complaints about frame flexibility is that it wastes energy, because, when the rider depresses a pedal, some of the rider's work must be invested to "wind up" the frame, instead of turning the wheel.

(At some later moment, the frame will "unwind" and release this energy; the extent to which this energy is wasted, or instead ultimately helps to propel the bike, is a subtle question whose answer depends on the way muscles function, and also on each rider's pedaling technique. I plan to address this question in a future article, but for the moment, suffice it to say that some portion of this energy does get wasted.)

Gary Klein, when he built the machine, equipped it to measure a frame's "wind-up" energy directly.

One way to measure energy is as work done on a moving object. "Work" in this sense is defined as the product of a force applied in a given direction and the distance the object moves in that direction while the force is exerted. For a constant force exerted parallel to the object's motion, this can be stated simply as

$$W = F\,X$$

where W = work; F = force; and X = distance.

If the force or direction of motion varies during the interval in question, the equation becomes more complex, and often must be expressed as a calculus integral. However, for certain elastic objects like springs — and, to a good approximation, bicycle frames — there is a convenient special case. When such objects are flexed, the force and distance bear a constant ratio to one another:

$$F = k X$$

where k is a constant called the "spring constant." For objects that exert varying forces in accord with this spring-constant equation, the work required to produce a given deflection is

$$W = \frac{1}{2} F X$$

$$\text{(often written as } W = \frac{1}{2} k X^2\text{)}$$

where F is the force *at full deflection* and X is the magnitude of that deflection.

The work done by the piston depressing the pedal, then, is half the product of the final force and the final pedal displacement.

But this figure, measured at the pedal, includes work spent to wind up the drivetrain, not just the frame; it includes crank flex, chain stretch, and other factors. This figure may be interesting as an evaluation of the whole bicycle (and so would measurements of wheel deflections) but it doesn't allow comparison of frames by themselves.

Where to Look

What's needed to determine the frame's contribution is to measure how much pedal motion is due specifically to frame deflection. This requires measuring the motion of the frame itself, not of the pedal, which is part of the drivetrain. But while the measurement must be made on the frame, the work equation requires that the measurement must describe the motion at the point where the force is applied — the pedal — and there isn't any part of the frame there.

This problem can be approached in various ways. The technique we have used so far employs a very direct mechanical approach — we measure the motion of a fixture on the bottom bracket that presents an appendage at the required location.

This fixture is a small arm that is clamped to the bottom bracket shell and supports a small plate, roughly horizontal, just underneath the pedal. The plate is oriented perpendicular to the piston shaft, so that a dial indicator placed under the plate, with its plunger in line with the piston, will read motion only in the direction the piston pushes.

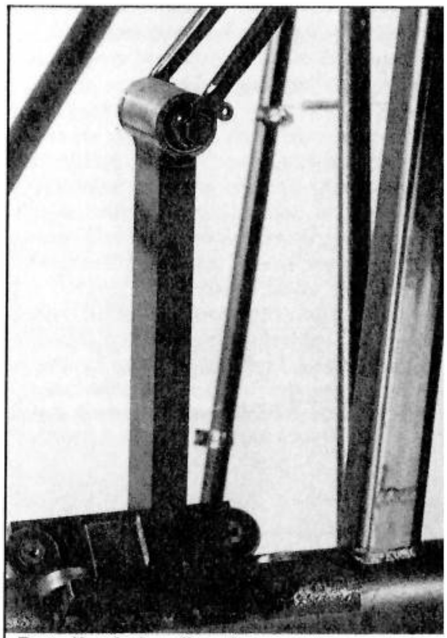
Because this plate is attached rigidly to the frame, it responds only to frame deflection and not to drivetrain deflection. But since its location is the same as a pedal's, it responds to angular deflections of the bottom bracket in the same way a pedal would. The motion of the plate, therefore, represents the desired measurement: *the portion of the pedal's motion due to frame deflection only.*

(If one wishes to simulate a gear less than the "infinite" locked-wheel case represented by this machine, the use of this plate requires one correction factor: if the rear wheel were *stationary* — i.e., did *not* rock forward with the frame, but rather stayed still in external coordinates, representing a true "zero" reference for forward propulsion — and the gear were finite, the crank would tilt forward a bit less than the frame would, because the chain would not move with the frame. To make this correction we place a dial indicator under each end of the lengthwise portion of the plate's mounting arm — this portion runs level and parallel to the wheelbase — and measure its tilt by the difference of the two vertical deflection readings. We then calculate the portion of the tilt which would not occur in the simulated gear[1], and correct the plate-motion reading by a corresponding amount. To be consistent in simulating the response to a finite gear, we also subtract the correction term that corresponds to the downward force from the turnbuckle mentioned earlier, since the net downward force on the bottom bracket determines both its downward motion and its forward tilt, though not its lateral motions.)

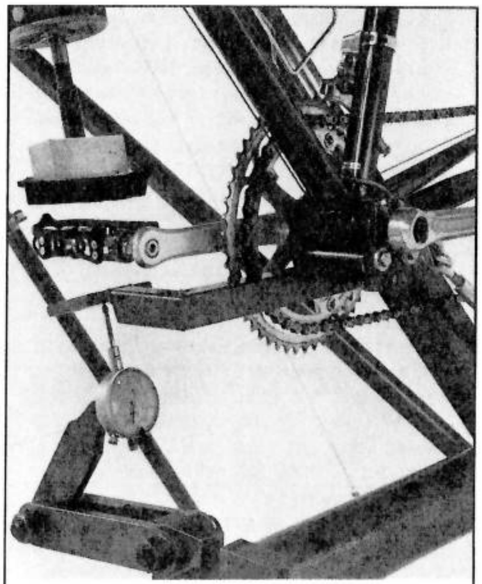
Predicting Pedal Motion

A more abstract technique which we plan to try is to predict the pedal motion mathematically by extrapolating from motions measured at the bottom bracket itself. Our planned method of measuring this motion is to attach a rectangular metal block, an inch thick and three inches square, under the bottom bracket, and align it with the wheelbase and midplane of the bicycle, and then place four dial indicators against selected points on its faces. These indicators will measure the motion and rotation of the bottom bracket in all the dimensions necessary to predict the resulting motion of the pedal; given the orientation and location of the piston shaft, we can then calculate the component of pedal motion along the piston's line of action.

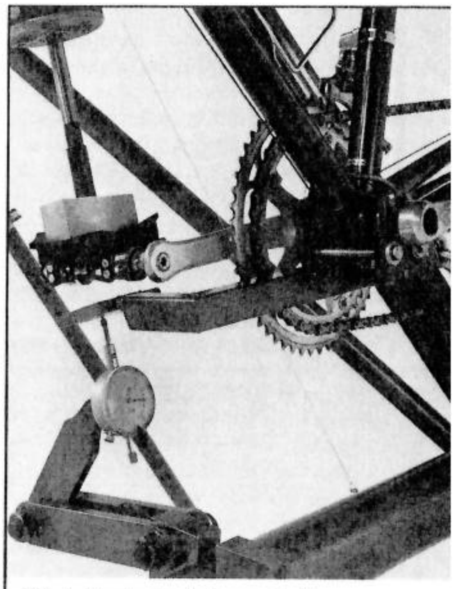
This technique may seem more complex, but we find it attractive because it's more versatile: in the course of determining the



Detail of the floating mount for the front dropouts.



Detail of bottom bracket area showing deflection under load: (Left) photo taken before loading;



(Right) photo taken during application of 200-pound load.

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[1] This portion is equal to the tilt of the frame multiplied by the ratio of rear cog size to chainwheel size: since a stationary rear cog would be rotating backward, relative to the frame, it would drive the crank backward (relative to the frame) a proportional amount. For example, a crank geared 52:13 would rotate in the frame 1/4 as much as the rear cog, so that its net tilt relative to the ground would be 25 percent less than the tilt of the frame.

pedal motion, it will also measure several motions of the bottom bracket, which are interesting in their own right; and it is more quickly adaptable to modifications in the location and direction of force applied to the pedal, since the only adjustments required are changes of numbers in the calculation formulas, instead of mechanical adjustments of the measuring device itself.

Initial Test Results

Our testing so far has been limited to three bikes, with about a dozen load cycles run on each, and with eight data points taken for each cycle. I can't make far-reaching claims about the validity of the test data until more cycles are run, but so far the results have been quite consistent and repeatable. (There's a small chance that the relatively few cycles I've taken will eventually turn out to be on one side of the scatter that a larger data base would display.)

Some interesting findings emerged when I finished and sat down with my calculator. (See Table 1.) I found numbers for the deflection energy ½ F X. Putting them in context is difficult because the *total* work done in a pedal stroke bears no fixed ratio to the maximum downward pedal force. Against the estimate in Table 1, though, which I consider reasonable, the steel frames' deflection energy is about one percent of the total work in a stroke; and the aluminum frame's is about 1½ percent. Contrary to traditional expectations, in this case the larger of the two steel frames is the more rigid one; but it weighs a good bit more, too.

But I also discovered various things about the geometry of frame deflection.

The first thing that struck me was the direction of the indicator plate's motion. Though the force applied in these tests was nearly vertical, the indicator plate's deflection is mostly horizontal.

The piston must swing sideways, following the pedal, more than it extends downward. (The energy calculations are corrected for this swing.) While there is still a moderate vertical motion at the indicator plate (directly below the pedal), angular extrapolations indicate that the vertical motion at the midplane of the bicycle is very small — about a tenth of the horizontal motion. Most of the plate's vertical motion is due to tilting of the bottom bracket, and not to downward motion of the frame.

Bottom Bracket Tilt

This mostly horizontal character of the plate's motion raised an interesting question. Tilting of the bottom bracket is often thought of as a rotation relative to the immediately adjacent parts of the frame, due to flexibility in the bottom bracket shell and the down and seat tubes. This local flexing is often suspected by people with narrow front derailleurs who find that the chain may rub when they pedal hard and not rub when they don't. (Deflection in the crank and spindle could also cause this effect, of course.)

The large lateral motion of the bottom bracket suggested a second source for the rotation: perhaps the whole rear triangle rotates rigidly (since it is tetrahedrally braced to a large extent) and the bottom bracket just happens to be the part whose rotation is measured.

This possibility seemed fascinating, but I lacked the measurements to check on it. All the measurements I had taken were of motions near the bottom bracket. Time did not permit me to do all the additional measurements I would have liked (a run of numbers takes almost a full day, and the press dead-

Table 1: Pedal-Related Deflections at 200-Pound Load[1]

	Deflection of Indicator Plate (inches)						
	in direction of force applied	horizontal	vertical	Vertical Deflection of Plate Fixture at Midplane of Bicycle (inches)	Spring Constant *k* for Type of Force Applied (pounds force per inch deflection[2])	Energy (½ F X) Absorbed by Frame (inch-pounds)	Absorbed Energy as a Fraction of Estimated Total Work Done in Pedal Stroke[3]
Bianchi Limited (23-inch frame, 170-mm cranks; frame: 4 lbs. 12 oz., fork: 1 lb. 11 oz.)	.285 ± .005	.476 ± .001	.206 ± .005	.039 ± .011	702	28.5	1.06 %
Medici Pro-Strada (18½-inch frame, 165-mm cranks; frame: 4 lbs. 1.5 oz.; fork: 1 lb. 4½ oz.)	.319 ± .011	.479 ± .002	.236 ± .013	.063 ± .014	627	31.9	1.23 %
Motobecane Prolight (24-inch frame, 170-mm cranks; frame: 3 lbs. 2½ oz., fork: 14½ oz.)	.417 ± .004	.731 ± .001	.286 ± .003	.050 ± .005	480	41.7	1.56 %

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[1] Load applied as described in text. Each value at 200 pounds is interpolated from the best-fit line from readings at four points ranging from 61.6 to 246.4 pounds, usually averaged from two runs.

[2] This figure is a rate and does not imply that this high a load was applied. Our maximum testing load was 300 pounds.

[3] Based on an assumed total work per stroke of maximum force × total vertical pedal travel, or 2677 inch-pounds for 170-mm cranks and 2598 inch-pounds for 165-mm cranks. The actual forces during a pedal stroke are much more complex, but information published by P. Cavanagh and I. Faria (in their book *The Physiology and Biomechanics of Cycling*, John Wiley and Sons, 1978) strongly suggests that this formula for total work per stroke approximates the upper limit approached by smoothly pedaling riders. For a rougher pedaling style (especially likely during a sprint) the work per stroke would be a smaller multiple of the maximum force, and the energy absorbed by the frame would be a larger percentage of the total work.

line had arrived), but I was able to make some quick checks of the seat lug and rear dropout motions on the Bianchi Limited. Because we do not yet have a fixture to hold the dial indicator in these positions, I took the measurements with a measuring tape.

From three runs' worth of tape measurements (Table 2), my tentative conclusion is that the effect exists, but it isn't the only source of bottom bracket tilt. Under this type of load, the rear triangle does rotate, almost rigidly, around an axis that runs approximately from the foot of the rear wheel pillar to the midpoint of the seat tube. The magnitude of the rotation is about 1.9 degrees under a 200-pound load.

This rotation can be expressed as the sum of two component rotations: one around a vertical axis and the other around a front-to-rear horizontal axis. The vertical-axis component — 1.6 degrees — agrees closely with the lateral rotation of the bottom bracket itself. The component around the horizontal axis, however — 1.0 degrees — is barely over half as great as the sideways-tilting rotation of the bottom bracket. Bottom bracket tilt, then, appears to be partly due to bodily rotation of the rear triangle, but almost equally due to the traditional culprit of flex occurring near the bottom bracket.

Pattern of Deflection

To the extent that the rear triangle does rotate, though, what pattern of deflection lets it do that? What part of the frame *is* being flexed? This is a subject for numerous future projects, of course; at this point, our analysis is largely conjecture. But the rear-triangle motion does imply certain things. I expect to find the following pattern:

The only parts outside the rear triangle are the top tube, down tube, and fork. If the rotation axis runs as the preliminary measurements indicate, it's almost parallel to the down tube. The rear triangle rotation therefore requires torsion in the down tube (and this torsion is made more severe by the additional rotation of the bottom bracket beyond that of the rear triangle). In addition, since the rotation axis misses the head tube (which is the more-or-less fixed restraint for the front of the frame) the top tube and down tube must both bend sideways to stay with the head tube. (The top tube will bear some amount of torsion, too, but not much, because it's largely crosswise to the axis of rotation.) Finally, the fork will flex sideways somewhat, allowing the head tube to follow the rotation of the down tube to a small extent.

So what does it all mean? We've learned some things, but the numbers don't tell the whole story; they answer some questions, but they always raise new ones. Some questions about where the flex takes place have been mentioned before. Others — particularly the question of how much deflection energy is lost and how much is put back into the drivetrain — keep popping up every time we sit down and talk about the machine. As we run more tests and analyses, we'll let you know with future *Bike Tech* articles.

Table 2

Lateral Deflection of Points on Rear Triangle under 200-Pound Load on Right Pedal (Bianchi Limited)

bottom bracket	+.294 ± .005
seat lug	-.31 ± .01
rear dropout	-.22 ± .01

(Average of three loading cycles. Deflection to left considered positive, to right, negative. Bottom bracket deflection measured with dial indicator, others with steel measuring tape; tolerances are maximum deviation of readings from mean.)

RESEARCH

In this issue we present the first of three installments of Dr. Van Valkenburgh's paper, which he presented at the IHPVA Scientific Symposium in November 1981. This installment contains the sections on ergometry and computer simulations; the remaining sections cover the areas of drag measurement, stability, and safety.

Getting the Numbers Right

Human Power Research Methodology

Paul Van Valkenburgh

Introduction

In their first four years of Human Powered Speed Championship competition (1976-79), the single-rider vehicles I built were able to finish in first place for two years and in second place for two years. However, these successes were relatively unrewarding for a number of reasons. First, the designs were empirical (intuitive, seat-of-the-pants, educated guesses) and not arrived at by standard engineering development practices. Second, the designs turned out to have fundamental problems with stability, drag, and human factors, and the solutions were not obvious (at the time). As a professional vehicle dynamics researcher involved in human power only as a hobby, I finally had to make a choice between recognition (more wins) and knowledge (research into human power basics). Obviously research interests won out over competition the past few years — partly because all that success and exposure was not paying off in increased profits or more clients.

While most of the specific knowledge I have gained over the past three years is not in reportable form, or is applicable only to a particular machine, there are reasons why the research methodology should be described here. First, there are some not-so-obvious possibilities for error in measurement by the inexperienced researcher using unsuitable equipment. And, if we are to learn anything by comparing data, it is important that we measure the same parameters, using the same methods, under the same conditions. The techniques and equipment described here are all well proven. I have used most of them over the past 20 years in research for the auto, truck, motorcycle, recreational vehicle, snowmobile, and race car industries, and in related magazine tests.* Regardless of the intended end result — be it practical everyday transportation or the setting of all-out speed records — there are five categories of research, and numerous subcategories of methods, as shown in Table I.

Ergometry

Although human power output has been well researched, most results are open to question because of the problems of human variation and unsophisticated measuring equipment. Even testing the same human being, it is difficult to get repeatability because of fatigue and learning, psychological, and environmental effects. However, it also appears that there is no human ergometer that either duplicates accurately the ordinary bicycle or records precise, instantaneous power output.

Poor simulation is due partly to the lack of accurate simulation of aerodynamic loads that increase with the square of velocity, and to the lack of realistic inertia simulation. Some aero loads have been simulated by the use of small fans, but these are not calibrated and are certainly not equivalent to standard bicycle air drag.

Inertia effects are a potentially more serious problem for accurate power research. The conventional Monark ergometer has a 20-pound flywheel which, because of its small diameter, barely simulates the inertia of a bicycle *without* a rider. Even if all other

Figure 1: Computer-equipped ergometer/ simulator for prone rider.

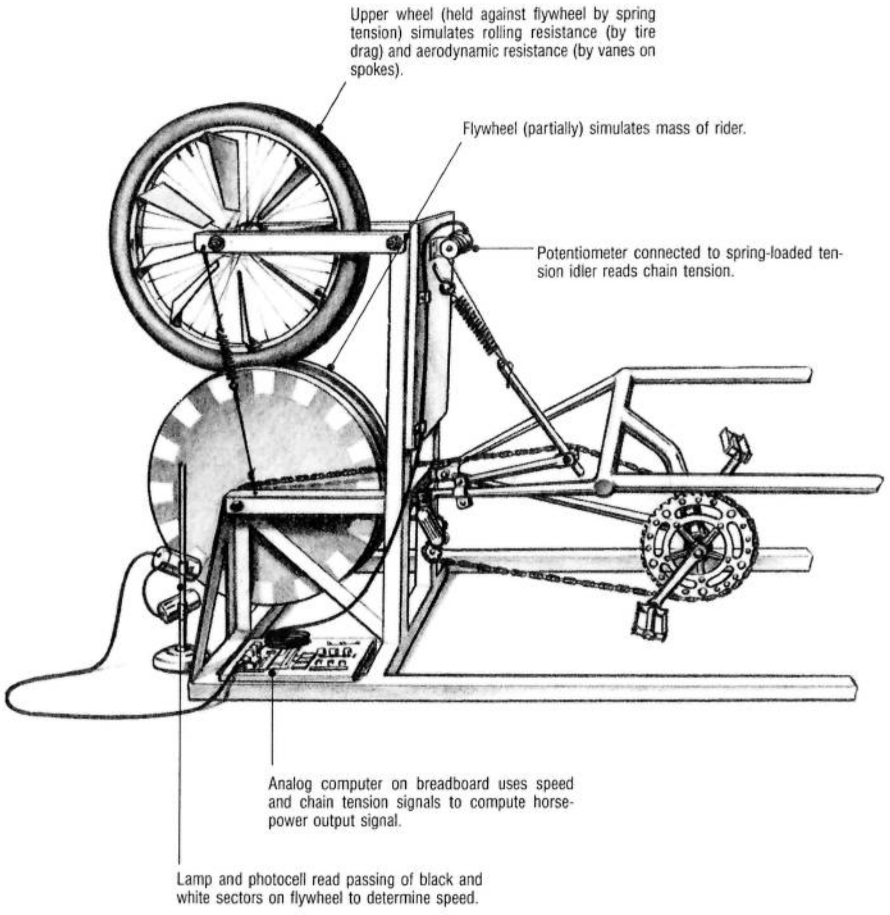


Table 1
Human Power Research Methodology

Air and Rolling Drag Measurement
- Wind Tunnels and Ground Planes
- Strain-Gauged Bodies and Drivelines
- Coastdown Recording Methods
- Air Pressure/Area Integration

Ergometry and Human Factors
- Water or Mechanical Friction Brakes
- Air Friction
- Flywheel Inertia
- Electric Motor/Generators
- On-Road Power Measurement
- Instantaneous Torque and Power Measurement

Stability Evaluation — 4Whl / 1R / 1Frt / Diamond Config.
- Overturn — Cornering, Off-camber slope
- Oversteer — Steady state, Transient
- Disturbance Response — Crosswinds, Bumps
- Braking — Straight, Turning

Simulations for Parameter Evaluation
- Digital computer
- Analog computer
- Full scale Simulator

Accident Protection
- Standardized Scenarios
- Standardized Instrumentation

forces (air and rolling drag) were accurately simulated, a rider could still accelerate many times faster than on a real bicycle. The mechanical friction load may be increased to simulate the inertia load, but this is highly unrealistic. To illustrate, consider the extreme of very slow pedal speeds. A high-drag, low-inertia ergometer will practically come to a complete stop as the pedals go over the top and bottom dead center, but this would not happen to a low-drag, high-inertia bicycle on the road. The same problem exists, with lower forces and speed fluctuations, but higher frequency, no matter how high the pedaling speed. It is possible that any reported close correlations between cycle ergometry and real-world riding situations are due to fortunate coincidence.

The major difference among all ergometers, dynamometers, or even exercycles is in their method of applying a load. Water brakes (pumps) are primarily used for large horsepower engines, where heat dissipation is the biggest problem. The Monark band friction brake, or for that matter, an ordinary drum, caliper, or disc brake, is more accurate at lower horsepower levels, but only to the precision with which it is applied as a function of velocity. Roller friction or small fan loads, which are used in commercially available exercycles, may be good for exercise but are useless for either measuring power or simulating road loads.

One attempt to overcome these problems with a *mechanical* solution is shown in Figure 1. In this case, the mass of a Monark flywheel was increased to almost 250 pounds, bringing its equivalent bicycle and rider mass up to about 70 pounds. This is still not acceptable, but a proper simulation would require spinning this flywheel up to about 1.7 times the real bicycle speed, or 85 mph in the case of the simulated HPV. Otherwise, the flywheel diameter or weight would have to be increased considerably. The safety problems of having such a large mass spinning at such high speeds should not be underestimated. At a 50 mph flywheel speed, the energy in this 250-pound wheel is equivalent to that of a 200-pound body falling eight stories.

Figure 1 also shows an attempt to simulate the linear increase of rolling drag and the square increase of air drag with velocity. The tire shown provides about the same rolling drag as two high-pressure tires, and the spoke blades were sized to match the air drag of a particular streamlined HPV. The accuracy of such a simulation can be verified through a coastdown of the apparatus, if the rotational inertia of the flywheel and bike wheel are known. In other words, the coasting time/velocity curve of the ergometer should match the coasting time/velocity curve of the simulated vehicle.

Electric motor/generator dynamometers with electronic feedback-loop controls are a far more sophisticated, precise, and expensive way of simulating loads and measuring power. The emissions test chassis dyno at

American Honda, for example (see Figure 2), is normally used to accurately simulate real road loads on all sizes of motorcycles for emissions tests in the lab. Regardless of the physical mass of the dyno rollers, the machine can be programmed with any predetermined static drag, rolling drag, aerodynamic drag, and simulated inertia. In other words, if the simulated cycle had *less* inertia than the dyno rollers, electric power would be used to *drive* the rollers during acceleration. While such a dyno might provide a very accurate simulation of a HPV (if the control figures can be set low enough), it is not suitable for measuring human power because of the lack of precision at such relatively low power levels.

Most ergometers measure power by holding either torque or speed constant, recording the non-constant, and manually multiplying the two after the fact. Some experiments, however, require immediate feedback of power-level information. In my preparations to evaluate hand-and-foot power, I constructed an electronic instantaneous horsepower indicator for the ergometer previously shown in Figure 1. This analog computer system consists of a digital speed pickup (triggered by a photocell reading the black-and-white intervals on the flywheel) with a conversion to analog signal, and a spring-loaded potentiometer which measures chain tension or pedal torque. A carefully calibrated breadboard analog computer combines these signals and sends the appropriate signal to a horsepower meter for the rider. The rider can therefore be given instructions to maintain constant levels of power output for given lengths of time, regardless of the continually changing output speed. It is a simple matter to tap off both the horsepower signal and wheel speed signal onto a two-channel strip-chart recorder, as shown in the following figures.

A single run with a severely compressed time scale is shown in Figure 3. The rider (Ralph Therrio) was instructed to increase his power output in 0.2-horsepower increments over 25-second intervals. Note that the machine was brought up to a 15 mph "push-off speed" before the test was started, and at the end the time scale was changed to better measure the coastdown slope. The terminal speed in this test was 42 mph.

An expanded-scale run is shown in Figure 4. In this case, the rider was instructed to "burn out" after the last 0.8 horsepower interval, giving a peak terminal speed of 49 mph (which is the speed the actual vehicle achieved). At this recorder speed, the instantaneous power fluctuations become obvious, regardless of the electronic damping (filtering) used. This damping can be seen in the dropoff slope of the power curve even though torque input was stopped instantaneously.

An evaluation of the phase relationship between hand and foot crank angles is shown in Figure 5. In this case the time scale was expanded again, and the signal damping was reduced. While the *average* power output is about the same in both cases, the upper power curve is more "spikey," showing the almost complete instantaneous loss of power as both hands and feet go over top dead center simultaneously. The lower curve shows a smoother flow of power when hands and feet are only 90° (or 270°) out of phase. Further expansion of the time scale is useful to measure torque variations with crank angle at high rpms.

All of these dyno-lab or ergometer simulations are interesting from a research standpoint, but too expensive and time-consuming to justify unless the rider can use the information. On-road power measurement can be more useful in that there is no question about realism. In fact, time trials are an indirect, long-term average measure of power which have been used since bicycling began. However, an instantaneous power indicator would be of more value to a rider, especially for "pacing," or intuitively allocating re-

Figure 2: Honda's motorcycle dynamometer/simulator being used to measure power on Brian Uchida.

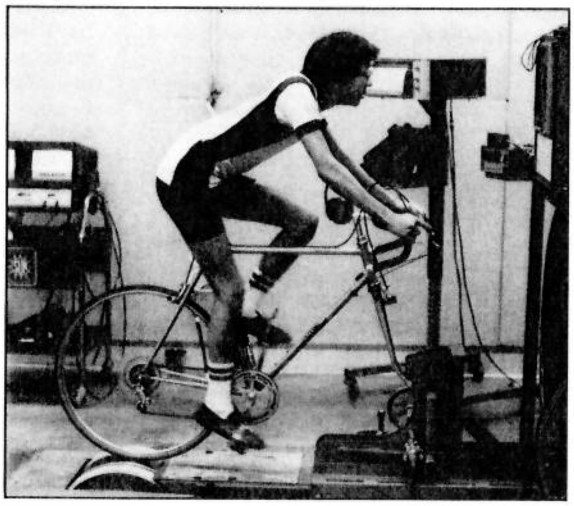


Figure 3: Ergometer output recording — one complete run, hand-and-foot powered with damped horsepower signal.

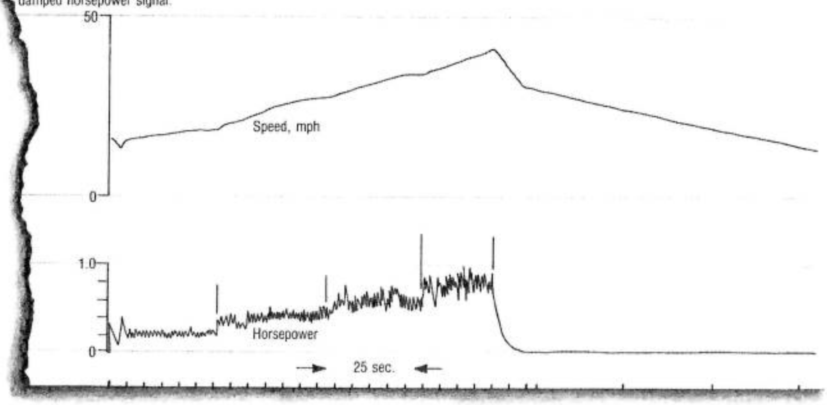
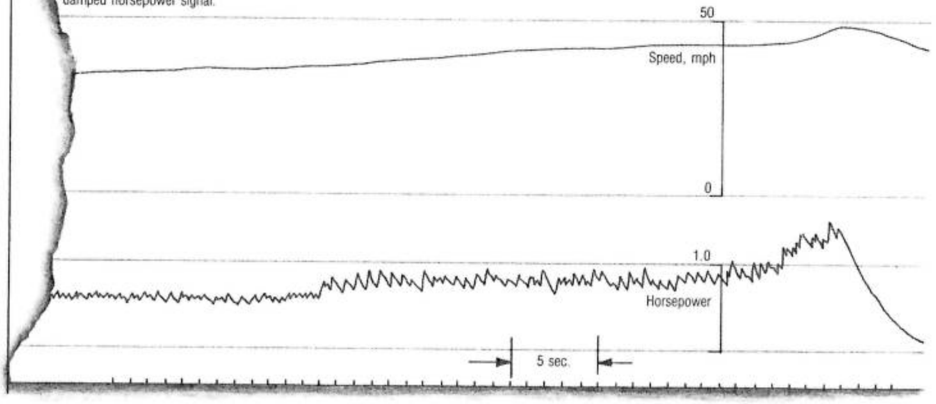


Figure 4: Ergometer output recording — expanded time scale, hand-and-foot powered with damped horsepower signal.



serve energy to last precisely the length of the task (race or tour), and no longer. The previously described system is easily adaptable to a precise, lightweight, on-board power meter.

Simulations

Computer simulations complement test data, and have become an important tool for the evaluation of vehicle designs and operating strategies. Any vehicle design is always a compromise, a collection of trade-offs between conflicting requirements, such as between low weight or aerodynamic enclosures. The only way to evaluate performance accurately as a function of parameter variations is to vary one characteristic while holding all other variables constant: power input characteristics, ambient conditions, vehicle configuration, etc. And the only way to control these variables is with mathematical simulations.

A number of teams and even non-competing enthusiasts have used digital computers to predict the speed performance of HPVs. The general equations are quite simple, and the computer requirements are minimal. (What is not so simple is coming up with the correct variables to use in the equations.) In general, however, these simulations have been used simply to make predictions or to determine the potential of multiple riders, and not to evaluate the relative effect of parameter variations. Once a designer determines that an X percent reduction in air drag is equal to a Y percent reduction in rolling drag, or a Z percent reduction in weight, then he knows where to concentrate his efforts.

Another use for computer simulations is to aid in evaluating different rider power output strategies. For example, Figure 6 shows a digital computer simulation which is similar to the ergometer data previously shown in Figure 3. By varying the increase rate of the power output, it is possible to determine the optimum rate, without introducing uncontrollable variables such as fatigue, learning, or rider power fluctuations. Of course it is necessary to gather adequate ergometric data to be sure that the power output figures are attainable. This also permits accurate lab performance comparison between a 160-pound rider with X horsepower capability and a 200-pound rider with Y horsepower capability.

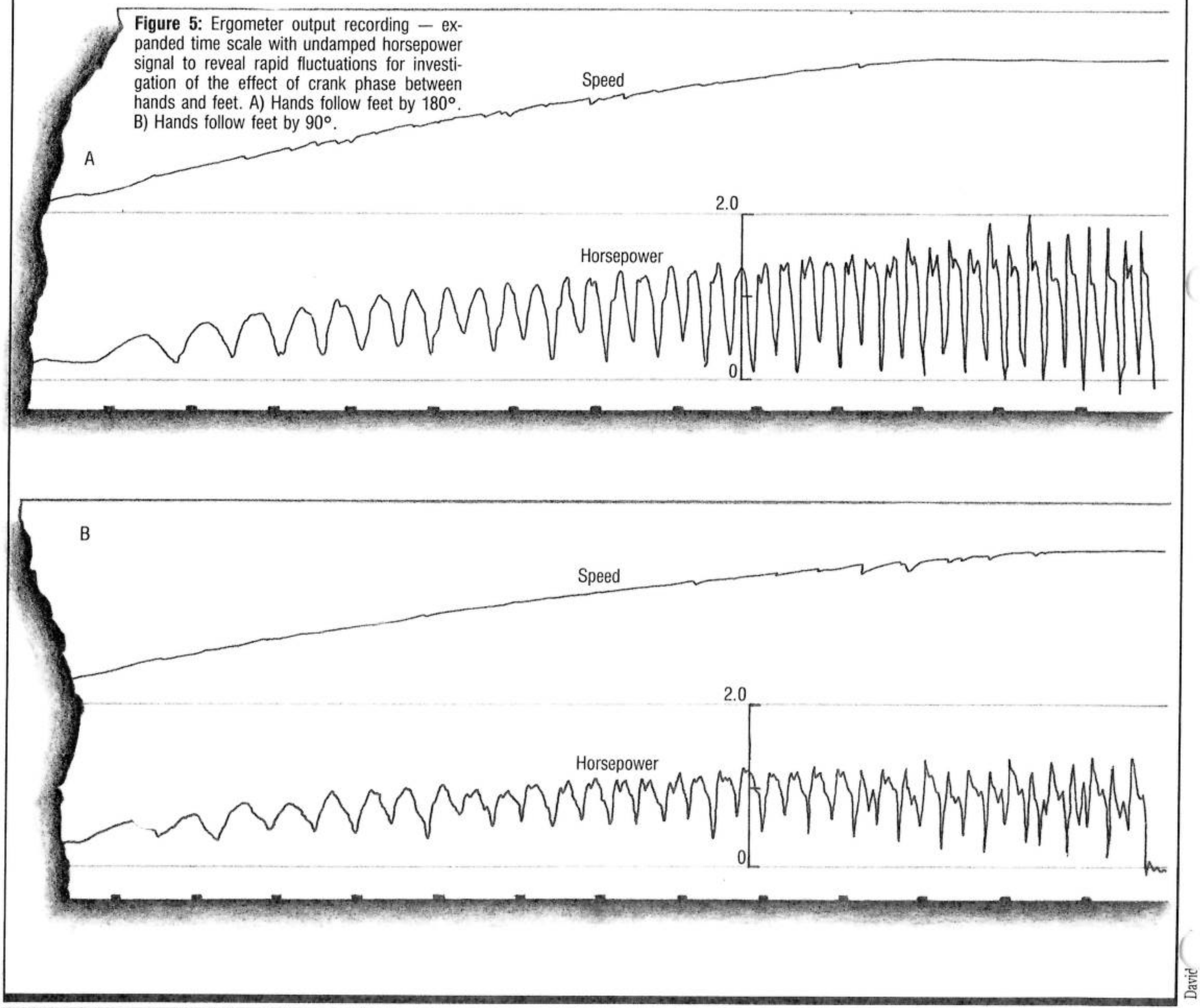


Figure 5: Ergometer output recording — expanded time scale with undamped horsepower signal to reveal rapid fluctuations for investigation of the effect of crank phase between hands and feet. A) Hands follow feet by 180°. B) Hands follow feet by 90°.

David

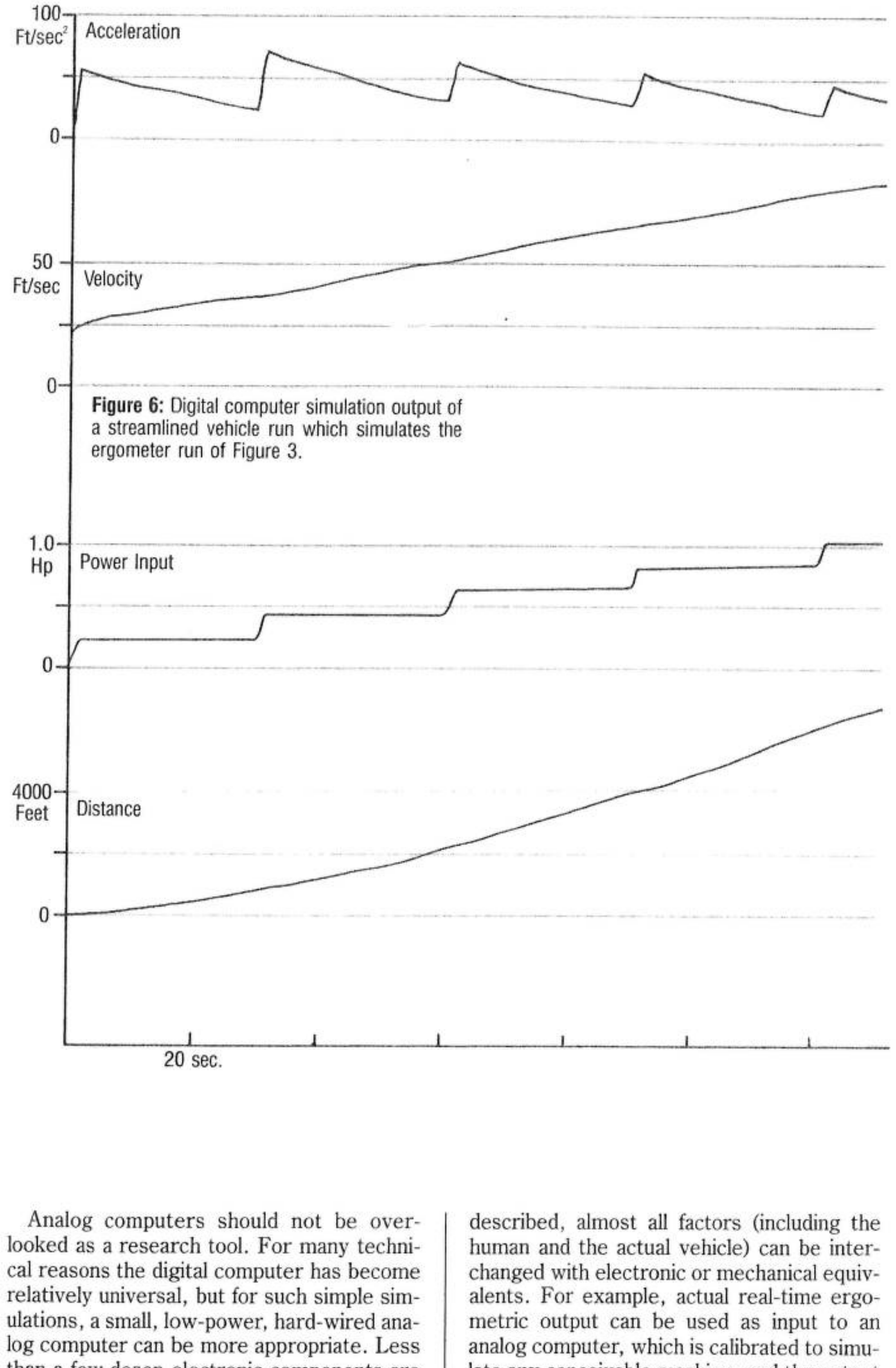


Figure 6: Digital computer simulation output of a streamlined vehicle run which simulates the ergometer run of Figure 3.

Analog computers should not be overlooked as a research tool. For many technical reasons the digital computer has become relatively universal, but for such simple simulations, a small, low-power, hard-wired analog computer can be more appropriate. Less than a few dozen electronic components are required, including a potentiometer for each of about five important variables. All of the necessary outputs can be plotted in real time just as the digital output shown in Figure 6. In fact, the device is similar to the previously described analog computer built to compute horsepower on an ergometer, and could be made small enough to fit in a pocket.

At this point, the research methodology has gone full circle. To perform a good simulation you need good drag and ergometric data, and to get good data you need a good lab simulator. A natural product of this situation is the full-scale simulator: given the mechanical and electronic hardware previously described, almost all factors (including the human and the actual vehicle) can be interchanged with electronic or mechanical equivalents. For example, actual real-time ergometric output can be used as input to an analog computer, which is calibrated to simulate any conceivable machine, and the output can be recorded in terms of speed or distance. In effect, this is what the previously described electronic feedback control motor/generator ergometer is — a programmable full-scale vehicle simulator. As a solution to the problem of finding acceptably flat and long courses on which to have speed championships, races could be held on such a machine. The only problem is the effort of determining appropriate drag coefficients for each competitor's vehicle.

**For more detail on all the tests and equipment mentioned here, see my book* Race Car Engineering and Mechanics *(Dodd Mead, 1976).*

On Some Much - Misused Terminology

Mario Emiliani

Editor: The folklore engineers of the bicycle world have traditionally abused a number of technical terms. Colloquial understanding of technical terms is sometimes so misleading that it becomes difficult for an enthusiast to understand a technical presentation. We hope this article will get us all speaking the same language and put an end to many common misunderstandings.

The following terms will appear frequently in Bike Tech. *Our contributing editor/ metallurgist Mario Emiliani has defined all the terms and indicated some preferred terms along with the reasons why they're preferred.*

Most of these definitions are too difficult to remember if you don't work with them every day (yet another reason for you to save this issue of Bike Tech *for future reference). But this article is more than a dictionary; just reading through it and contemplating the definitions will help you understand a lot about how metals behave. And our future articles will rely heavily on this understanding.*

General Terms

Alloy - A mixture of two or more elements.

Ferrous Metal - A metal which contains mostly iron.

Steel - An alloy of iron and up to 2 percent carbon.

Plain Low-Carbon Steel - A steel which contains only carbon and manganese as intentional alloying elements.

Low-Alloy Steel - A steel which contains up to 5 percent total intentional alloying elements.

Microstructure - A metal's structure, which is usually visible only under a microscope after special preparation.

Rigidity - This term will always be used instead of "stiffness" when describing the ability of a frame, wheel, crankarm, etc., to resist deflections caused by pedaling. More about this when we get to the modulus of elasticity.

Hot-Drawing or Hot-Working - Deforming a metal at temperatures which depend upon the metal. These temperatures are usually above about one-half the metal's melting point. For steels, hot working takes place between about 1350°F - 2200°F. Hot working is used to make large dimensional changes in a component.

Cold-Drawing or Cold-Working - Deforming a metal at temperatures below about one-half its melting point. For steels, cold drawing can take place up to about 1350°F. The purpose of cold drawing is to increase the strength of the metal, and/or to refine the shape of a part to conform to close dimensional tolerances.

Terms Related to Testing

Force or Load - The effort needed to accelerate a mass, that is, pounds or newtons.

Stress - The force per unit area on an object; i.e., pounds per square inch (lb/in^2) or kilograms per square millimeter (kg/mm^2).

Strain - The amount a material deforms in the direction of a stress applied to it: stretching when tested in tension, compressing when tested in compression, or shear when tested in shear. Strain measurements are made on a portion of the test specimen called the gauge length. Strain is usually measured in terms of inches of deformation per inch of gauge length, or inches per inch (in/in). Shear strain is measured in terms of an angle.

Static - A state in which all the forces acting on a mass are in balance. Such a mass is said to be in equilibrium, or at rest. Many tests on materials are called static because the variations in testing parameters occur very slowly. A tensile test is considered a static test.

Dynamic - A state in which the forces acting on a mass are unbalanced, and vary continuously with time. An example of a dynamic test done on materials is a fatigue test.

Mechanical Properties - The tensile strength, yield strength, impact strength, fatigue strength, ductility, hardness, and modulus of elasticity of a material. Several of these properties (defined below) are illustrated graphically in Figures 1 and 2.

Tensile Strength - The maximum stress a material can withstand in tension. The tensile strength is Point 4 in Figures 1 and 2.

Yield Point - The tensile stress beyond which significant permanent deformation will take place. More accurately, it is the point at which the stress-strain curve begins to deviate from linearity. The line 0 to 1 in Figures 1 and 2 is the linear portion of the stress-strain curve, Point 1 being the yield point.

An important thing to remember is that Point 1 in Figure 1 is where *significant permanent yielding begins*. This is not to say that yielding doesn't occur at lower stresses - it does; it's just hard to detect.

Yield Strength - This is the stress at which a material exhibits a specified deviation from linearity. Some materials display a small dip in their stress-strain curves just beyond the yield point. The uppermost portion of the curve is taken as the yield strength. This is shown as Point 2 in Figure 1.

Some materials (including most of the high-quality steels used in bicycle tubing) don't exhibit a definite yield strength, so we have to arbitrarily define one. For these materials, the stress-strain curve doesn't dip after the yield point. The curve keeps rising smoothly.

To define a yield strength for these materials, we add a line to their stress-strain graphs, as seen in Figure 2. This line is parallel to the line 0-1 but offset 0.002 in/in to the right. The point at which this line intersects the stress-strain curve is taken as the yield strength (Point 3, Figure 2).

Ductility - The ability of a material to deform permanently without breaking. This property is usually measured by the percent elongation, which is the percent a material permanently deforms relative to a portion of its original length.

A material with a high percent elongation is termed ductile, while one with a low percent elongation is termed brittle. The value of percent elongation at which a material is considered ductile or brittle varies among materials, and depends on what the material is going to be used for. Ductility is influenced by cold working, heat treatments, and alloying elements.

Elastic Deformation - Strain which occurs between Points 0-1 in Figures 1 and 2. Materials stressed in this region will never take a significant permanent deformation.

Plastic or Permanent Deformation - Strain which occurs beyond Point 1 in Figure 1, or beyond Point 3 in Figure 2. Materials stressed in this region will take a permanent set.

Modulus of Elasticity or Stiffness - This property is a measure of a material's ability to resist deformation by stresses below its yield strength. It varies considerably among materials, but is fairly constant for particular metals. For example, the moduli of elasticity of steel, titanium, and aluminum are 30 million lb/in^2, 17 million lb/in^2, and 10 million lb/in^2, respectively. These values don't vary appreciably regardless of alloy content, heat treatment, or mechanical working.

The word stiffness, as applied to the modulus of elasticity, should never be confused with the rigidity of bicycle frames. They are two entirely different things. The rigidity of a bicycle frame varies, and depends upon the inside and outside diameters of the tubes and the geometry of the frame. The modulus of elasticity is independent of material dimensions.

The modulus of elasticity, customarily called "E," is found by determining the slope of the linear portion of the stress-strain curve (see Figures 1 and 2).

Hardness - A material's resistance to plastic deformation, usually measured by making an indentation in the material. Hardness tests are good indicators of a material's tensile and yield strength, and have the added attraction of being easy to do.

Impact Strength - The amount of energy needed to break a material. If a material can absorb a lot of energy and deform plastically, the material is said to be "tough."

Fatigue - Failure of a component due to the application of repeating stresses. Fatigue failures are progressive, in that the repeating stresses must be applied enough times that they create cracks large enough to cause failure.

Fatigue Strength - The maximum stress a material can withstand for a specified number of cycles without failure. For this term

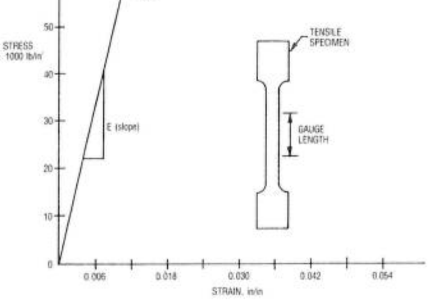


Figure 1. A typical stress-strain curve for plain low-carbon steels. Point 1 is the yield point; Point 2 is the yield strength; Point 4 is the tensile strength; and E is the modulus of elasticity. 0 to 1 is the linear portion of the stress-strain diagram.

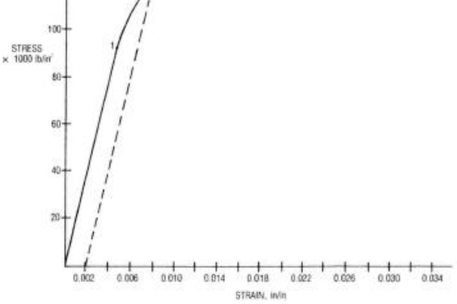


Figure 2. A typical stress-strain curve for high-strength steels and aluminum alloys. Point 1 is the yield point. The intersection of the dotted line and the stress-strain curve, Point 3, is the yield strength of 0.002 in/in strain. Point 4 is the tensile strength.

to mean anything, both the stress level and the number of cycles must be stated.

Fatigue Limit - The maximum stress level a material can withstand for 10 million cycles without failure. Only a few metals, most notably steels, exhibit a fatigue limit.

Slip - The process by which plastic deformation occurs. Slip is simply rows of atoms sliding over each other due to shear stresses.

Terms Related to Brazing

Brazing - A process which joins metals by heating them to a suitable temperature, then introducing a non-ferrous filler metal (the brazing alloy). The filler metal has a liquidus above 840°F, but below the solidus of the base metals. (Only non-ferrous metals have such a low liquidus.) A characteristic of brazing is that the filler metal is drawn into close-fitting surfaces by the phenomenon of capillary attraction.

Base Metals - The metals which are joined together.

Liquidus - The lowest temperature at which a metal is liquid. Sometimes a component of a metal melts first, leaving the remaining metal still solid or slushy. Liquidus refers to the lowest temperature at which the *entire* alloy is liquid.

Solidus - The highest temperature at which a metal is completely solid.

Silver Brazing Alloy - This term is preferable to silver solder since soldering is a completely different joining process. The confusion between soldering and brazing occurs because the upper temperature limit of soldering is near the lower temperature limit of brazing (around 840°F).

Silver Brazing - This term will be used instead of silver soldering for the above reasons.

Brass Brazing Alloy - This term is preferable to "bronze brazing alloy" because there aren't any bronze brazing alloys. Some brazing brasses (alloys of copper and zinc) contain about one percent tin, and as a result people called them bronzes. In 1978 the American Welding Society recognized that "bronze" was misleading, and changed its filler metal specifications to "brass" where applicable.

Brass Brazing - This term will be used instead of bronze brazing for the above reasons.

Heat-Affected Zone - A region of base metal adjacent to the area joined, whose mechanical properties are altered by the heat.

Overheating - Most people use this term, as it applies to the joining of bicycle frames, to refer to a supposed impairment of the steel's mechanical properties due to excessively high heat. Usually, excessive heat is thought of as temperatures beyond those recommended by the tube manufacturer. But tests I have done show that high-quality bicycle tubing can withstand temperatures much higher than the manufacturers recommend, with (apparently) few ill effects (see *Bicycling*, September/October 1981).

Overheating is a term more accurately applied to the brazing alloy than the steel. Brazing alloys have a narrow range of temperatures at which they can be used successfully. If the brazing temperature is higher than the upper limit of this range, constituents of the brazing alloy will become volatile and burn off. Because of the locally high pressure created when the brazing alloy is overheated, some of the brazing alloy is driven between the grains of the steel. This can weaken the steel. In addition, burning the brazing alloy will alter its chemical composition, which in turn may affect the strength of the joint.

Natural Convection - The way brazed bicycle joints are cooled. It's simply to let the joint cool by itself in still air at room temperature.

Welding - Joining two metal objects by heating them to a temperature which allows the base metals to fuse together without the need for filler metal. Often, though, a filler metal (welding rod) is used.

Terms Related to Heat Treating

Heat Treatment - Controlled heating and cooling of a metal to obtain certain mechanical properties. Time is a very important factor when heat treating metals.

Annealing - A general term describing a heat treatment designed to soften (and consequently, weaken) a metal. Variations of this term are used to describe the extent to which the metal is softened.

Normalizing - A heat treatment for ferrous alloys which involves heating the metal above about 1350°F, then cooling it in air by natural convection (usually to room temperature). This is the heat treatment given to steels brazed at temperatures beyond about 1350°F.

Tempering - A heat treatment used to make a metal tougher. This is done, for example, by heating a steel to between approximately 1100°F and 1350°F for a period of time. This is the heat treatment given to steels brazed at temperatures below about 1350°F. The time period depends on the specific alloy and on the thickness of the object (thicker pieces take longer for the center to reach temperature).

Grain Size - Metals are made up of many microscopic crystals called grains. The grain size of a metal determines its mechanical properties; the grain size is determined by alloying, and heat and mechanical treatments.

BOOK REVIEW

Fahrradtechnik: *A Very German Approach to Bicycle Engineering*

John S. Allen

Fahrradtechnik: Konstruktion, Fertigung, Instandsetzung (Bicycle Engineering: Design, Fabrication, Assembly and Adjustment); by Siegfried Rauch and Fritz Winkler. (Bielefelder Verlaganstalt KG, Bielefeld, Federal Republic of Germany, 1980) 306 pages, 263 illustrations.

This book belongs on the shelf of any person who takes an active interest in the subjects covered in its title. The many illustrations convey considerable information even if you don't speak German: if you want more information, use the illustrations as your table of contents and find a German-speaking person to translate.

Both authors have worked as engineers in major bicycle manufacturing firms in Germany and Holland. The emphasis of the book reflects their experience. The third of the book on materials, design considerations, and techniques related to mass production of bicycle frames is quite thorough, but the other two-thirds on components is less complete.

The book brings together, and relates to bicycles, much information that is usually found only in general engineering manuals: tables of different types of steels with their compositions and properties; a look at the geometry and stress relationships in welded and brazed joints; and a survey of welding and brazing materials and techniques. The book includes many engineering drawings, with dimensions, of frames and frame parts, gleaned directly from the drafting departments of major German bicycle manufacturers. Such drawings are not available to the public anywhere else, as far as I know. They give an unparalleled insight into major bicycle manufacturers' design decisions and into the manufacturing process.

The authors demonstrate a strong understanding of materials science and manufacturing technology. This strength is evidenced by their discussion of frames and the manufacture of handlebars, stems, machine-built wheels, and some other bicycle parts. There is a substantial but appropriately cautious discussion of the present and future uses of plastics and other synthetic materials in bicycle construction.

Unfortunately, the authors' discussion of bicycle components is not as thorough or as careful as their treatment of frames. However, this is such a large topic that it cannot be treated thoroughly without a separate book. There are many theoretical discussions about components, and these provide some interesting insights. For example, the authors show how the rubbing between adjacent balls causes greater wear and friction in a full-race ball bearing than in a bearing with a retainer.

However, the authors repeat many longstanding myths. For instance, they state that serrated rims provide better wet braking; that wheel rims become oval under weight load; and that normal sidepull brakes push the rim sideways while the cam-operated Weinmann "Synchron" does not. The authors seem to be out of touch with recent research efforts, and sometimes fail to examine what they are saying in the light of basic mechanical principles.

Nonetheless, there is a lot of useful material here. Though the illustrations in the components section are mostly copied from manufacturers' parts catalogs, they give a wide-ranging survey of various design concepts and brands. Where else would you get to see an exploded view of a Union generator without destroying your own generator?

As an American reading this book, I must comment on its European, specifically German, approach. The very idea of a comprehensive book for public consumption about the theory and practice of manufacturing a commercial product is something very German, which I like. There's an honest motivation to make information available, to back it up with theory, and to organize it for whoever may find it useful. Contrast this with the narrow, trade-secrets approach which is all too common in U.S. industry!

The European perspective is also evident in the survey of types of bikes at the beginning of the book. The description of German bicycle types points out the differences in the evolution of bicycle styles between Germany and the United States. The average German cyclist still rides a bike very much like the Raleigh Tourist, called the "Tourenrad" (touring bicycle). In increasing steps of fanciness are the Sportrad (sports bicycle) — like the Raleigh Sports, more or less, though sometimes with derailleurs; the Sport-Rennrad (sports-racing bike), like our common multi-speeds with wired-on tires; and the Rennrad (pure racing bike). The authors sharply define these categories according to frame geometry and components. However, there is no mention of differences in geometry between a bike used for day riding and one used for loaded touring.

Most adult German cyclists still ride the Tourenrad or Sportrad for rugged, plodding transportation on their cobblestone streets. Contrast this to the United States, where riders went from lightweight, single-speed bikes of the 1890s to the imitation-motorcycle children's bikes in the decades when only children rode, to the lightweight multi-speed bicycles of today.

Lightweight, multi-speed bicycles are clearly still regarded as something a bit exotic by the authors of *Fahrradtechnik*. The authors mention several times that a normal bicycle speed is 15 km/h (9½ mph). Three times in the book, they state that the ideal pedaling cadence is 40 to 60 rpm! One of these times is in the book's last three pages, which are an apparent afterthought about *racing* (the drawings on these pages aren't numbered, among other clues). True, 40 to 60 rpm is the most efficient cadence for riding at very *slow* speeds on a Tourenrad — but it is far from the best for fast riding. The authors seem to inhabit a very German and commercial ivory tower. If they ride bicycles at all, they must ride Tourenräder (that's the German plural). I've said it before: many bicycle designers don't ride bicycles! (See *Bicycling* magazine, May 1982, p. 146.)

Also notably European (and commercial) is the authors' perspective on new developments. They do mention all of the new products of major world manufacturers here — the Shimano freehub, the new Sachs three-speed hub designs, the aluminum-frame mass-produced Kettler bikes (Touren-, Sport, and Sport-Renn-). But outside the area of materials science, there is little in the book about truly new engineering developments. Particularly lacking is mention of developments from the United States, like sealed bearing hubs, Klein frames, fat-tire multi-speed bikes (good on cobblestone streets, by the way), recumbent bicycle design and racing, or sports physiology. There are a few pages on BMX but again, the perspective is outside-looking-in.

At the end of the book is a list of firms which contributed information used in the book, and another list of manufacturers of products mentioned. Then 23 pages of advertisements for bicycles and bicycle equipment. No bibliography and no index. This reemphasizes the point that the book is compiled from commercial sources, not academic ones.

Aside from the engineering information it contains, this book is important because it reveals both the strengths and weaknesses of the bicycle engineers' perspective. There has been too little dialogue between major manufacturers' bicycle engineers, on the one hand, and bicycle riders and academics, on the other. This book is a welcome contribution to that dialogue.

DESIGN CRITERIA

Would Transmission Covers Be a Drag?

David Gordon Wilson

They used to be called "chain cases." The rather massive enclosures of pressed steel sheet almost-hermetically kept the elements from the chainwheel and rear sprocket. The cotter pin on the chainwheel crank could be adjusted through a little sliding door or the whole chainwheel could be examined by removing a circular cover, which fitted into the main structure like a cocoa-can lid. At the rear there were several separate pieces which had to be removed before the tire could be changed.

Because chain cases were fitted to only the heaviest of bicycles, they came to be associated with the least adventurous types of bicycles and bicyclists. But their users had real advantages. The enclosed chains and sprockets would last for years of daily use in places where rain and grit would require two complete transmission sets a year for unprotected bikes. A benefit equally interesting to me is that chain cases may improve the energy efficiency of derailleur-equipped bicycles.

The modern equivalents I am thinking of would be better called transmission covers. There would be no attempt to make them complete enclosures. Rather, they would protect the chain, sprockets, and derailleur mechanism from the direct streams of dust or gritty water and mud thrown by the wheels. The covers would be molded from one of the resins used for soft-drink bottles, such as polycarbonate. A conservative estimate of the total weight, including the fittings for mounting, is 250 grams, or about half a pound. (It should be possible to make them considerably lighter than this.) Would they require more or less energy from the riders?

We can put this problem into the bicycling-power equation* (see box). By inserting numerical values typical for a "sports" type of ten-speed commuting or touring bicycle, we can find the power required to ride on the level at 8 meters/second (about 18 mph) and up a 5-percent grade at 5 meters/second (11 mph). We can assume an average mechanical efficiency of 0.95 (chain not too dirty but not quite clean either), and then determine how much this power-transmission efficiency would have to improve in order to compensate for the added mass of a transmission cover:

Power (watts) for bicycling in no-wind conditions	On Level at 8 meters/second	Up 5% Grade at 5 meters/second
Bare Chain	160.16	269.14
With Transmission Cover	160.23	269.72
New Mechanical Efficiency Required	95.04	95.20

It is obvious that the added mass of a transmission cover would have an almost negligible effect on the power required, even for a relatively fast uphill grind. The increase in transmission efficiency required to compensate for the added mass — in other words, to lead to exactly the same power requirements at the same speed — is only a fifth of a percent, even for the uphill case.

The increase in efficiency that is likely to result from a clean chain and cogs, as opposed to a chain and cogs of average dirtiness, is two percent.

One can conclude that many riders have been much too concerned with shaving the last gram off their machines. It is appropriate to do so for sprint racing on the track. But for commuting and touring, components that add mass but reduce aerodynamic or mechanical losses, such as fairings and transmission covers, pay for themselves many times over in terms of the energy spent.

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*From Frank Rowland Whitt and David Gordon Wilson, *Bicycling Science: Ergonomics and Mechanics,* second edition, MIT Press, due out Sept. 1982.

Power to propel a bicycle is given by:

$$\dot{W} = \frac{C_v}{\eta_{mech}}[\Sigma mgC_r + \Sigma mg\frac{s}{100} + 0.5C_dA\rho\,(C_v + C_w)^2]$$

with terms defined below. Numbers in the right-hand column are typical values chosen for use in the example.

$\dot{W}$	= power required, in watts	
ηmech	= power-transmission efficiency from pedals to wheel	0.95
Σm	= total mass of bicycle and rider, in kilograms	85.00 kg without trans. cover 85.25 kg with trans. cover
C_r	= coefficient of rolling resistance for wheels	0.004
g	= acceleration due to gravity	9.81 meters/sec^2
s	= upslope of road, in percent (a downslope would be negative)	0.00 for level case 5.00 for uphill case
C_d	= coefficient of aerodynamic drag for bicycle and rider	1.00
A	= frontal area of bicycle and rider, in square meters	0.40 m^2
ρ	= density of air, in kilograms per cubic meter	1.225 kg/m^3
C_v	= bicycle groundspeed, in meters per second	8.00 m/sec for level case 5.00 m/sec for uphill case
C_w	= speed of head wind, meters/sec. (a tailwind would be negative)	0.00

INVENTIONS

This Bike Steers with Both Wheels

John S. Allen

Long-wheelbase, low-slung two-wheeled vehicles have some problems with steering and stability. Because the rear wheel takes longer to follow the front when turning a long-wheelbase vehicle, the longer wheelbase requires greater steering corrections to maintain balance.

In low-slung vehicles, like the recumbents raced at the International Human Powered Speed Championships, a given sideways displacement results in a greater lean angle and therefore a greater falling-over torque. Like a stick balanced vertically on a finger, the lower the bicycle, the harder it is to keep balanced.

In side winds, with a wind fairing, a two-wheeled long-wheelbase recumbent can become very hard to control. This problem has been evident in every IHPVA competition, and has led more and more teams of contestants to build and ride tricycles.

But tricycles also have their shortcomings. They impose heavy lateral loads on wheels, and they are wider which leads to more air resistance. Because of the width limits of human powered vehicles used either to win races or to serve as practical transportation, tricycles cannot be very stable. They will roll over before they would skid sideways, unlike, for example, a typical automobile. In the IHPVA competitions, tricycles as well as bicycles have rolled over.

Inventor Milton W. Raymond, of Cambridge, Massachusetts, is working on a solution to these problems: a bicycle on which both wheels are steerable.

A graduate of the Massachusetts Institute of Technology (MIT), Raymond worked for many years as a researcher in MIT's department of mechanical engineering. More recently, he has worked as an independent consultant and has undertaken independent research projects on solar energy, building insulation, and the design of motorized and human powered vehicles. He is a confirmed, long-time utility cyclist.

Raymond says parallel steering of the two wheels makes it possible to correct balance equally rapidly on bicycles of all lengths.

"When both wheels steer parallel, the wheelbase effectively goes to zero," he points out. It is possible to establish a lean more quickly to begin a turn, and the bicycle does not have to swerve as far to the side opposite the intended direction of the turn. This is an advantage in emergency maneuvering.

Two-wheel-steered bicycles are not entirely a new idea, Raymond notes. In Archibald Sharp's 1886 book *Bicycles and Tricycles,* there is a picture of a tandem consisting of two large wheels, one behind the other, linked by a frame tube that connects the tops of the two forks — as if two unicycles were joined together. As with unicycles or the usual high-wheeler bicycle of that time, the riders sat atop the wheels, and the cranks were attached to the wheel hubs. The front wheel was steerable, and the rear one may have been.

More recently, in the 1970s, the Swing Bike®, a children's novelty bicycle, was marketed. It was similar to a conventional modern bicycle, except that the rear wheel, chainstays, and cranks pivoted as a unit from a "headset" above the rear wheel. Raymond test-rode a Swing Bike® and became convinced that its principle was useful for more than stunt riding.

"I rode it in a tight circle around a five-foot card table," Raymond recalls. "The large steering motion was with the rear wheel, but the corrections that kept balance were with the front wheel."

On a long-wheelbase bicycle, slow-speed maneuverability is a special problem. Raymond points out that slow-speed stability and a small turning radius are important on crowded streets and paths. Although he wants his bicycle to have an aerodynamic advantage over a conventional bicycle, he also insists that his bicycle handle well enough to be practical for transportation.

Raymond eventually wants to build a bicycle with stressed-skin construction, like an airplane. The skin of most streamlined human powered vehicles has been only a covering, with a triangulated framework inside. Greater strength, significant crash protection for the rider, and lower weight are achievable with stressed-skin construction.

But the first prototype, now under construction, will have a frame of conventional steel tubing. This heavy prototype will test theories and mechanical details to be refined later. In order to permit testing of long-wheelbase performance, the bicycle will be a tandem, with both riders supine and facing forward.

The drive system on this prototype is especially interesting. The rear wheel of the bicycle will be able to pivot through almost

360 degrees on its fork so that handling can be tested over the widest possible range. No conventional universal joint can handle more than about 45 degrees of steering, so Raymond is using a linear ratchet drive.

Four cables for the drive and one for the rear brake all loop over pulleys and then are fed directly down the middle of the rear fork steerer tube.

A future version of the two-wheel-steered bicycle will probably use a more conventional two-stage chain drive with a universal joint. For now Raymond wants to determine by experiment that no advantages will be lost though the limited steering angle of that mechanism.

Pedals on the prototype now being constructed will be pivoted from above, like the pendulum of a clock; Raymond believes that a foot motion that rises at the ends of the stroke is more comfortable in the supine position. If this idea proves true, a similar pedal arrangement will be used on the next machine, except that connecting rods will link the pedals to a chainwheel.

The first steering arrangement to be tried on the prototype will link the front and rear wheels so that they can only be steered parallel to each other. With this arrangement, the bicycle will travel, on average, only in a straight line, and the riders will steer only to maintain the balance.

Once this arrangement has been tested, a double pivot will be installed at the center of the handlebars. Turning them like normal handlebars will steer the front wheel alone, and rocking them so one end is up and the other down will turn the wheels parallel to each other. Steering will be tested first with the bicycle coasting, and then with the riders pedaling. Raymond figures that stability will decrease as the steering is made more complicated, but he hopes to achieve hands-off stability in all cases.

Raymond has already built and successfully ridden one test bicycle, a unique supine recumbent in which the rider faces the rear. Raymond concedes that the "backwards-facer" is not practical for road use; even with the best frontview mirror he could devise, the angle of view was not wide enough for safety. He does note that improvements in television technology might change this situation by the beginning of the next century.

Still, the "backwards-facer" fulfilled its purpose: to test stability under the most challenging conditions possible for the rider. Fork rake and head angle were adjustable over a wide range. This bicycle will be described in more detail in the second edition of Whitt and Wilson's book *Bicycling Science* (scheduled for publication in September 1982).

The "backwards-facer" contributed valuable information toward the design of the present test bicycle. Raymond is now at work in the machine shop, building the two-wheel-steered bicycle. It may lead to radical changes in our thinking about bicycle handling and design.

SHOP TALK

Hook-Edge and Straight-Side Tire and Rim Compatability

John S. Allen

The widespread availability of high-performance wired-on ("clincher") tires and rims has been a boon for cyclists but a complication for the bicycle industry. Tires with identical markings may require different rims, and rims with identical markings often require different tires.

Most bicycle mechanics are familiar with the notion of using hook-edge rims with foldable tires and wider straight-side rims with wider wired-on tires. But there's more to it than that. Some interchanging is possible, however, and it isn't always obvious why this works some times and not others. Here's the how and why:

Straight-side rims, as the name indicates, have flat inner sidewalls. The tires used on these rims are centered by the bead seats of the rim. (The bead seats are the shoulders at the bottom on either side of the rim.) The tires are held in place by their bead wires, which resist the tendency of the tires to expand under inflation pressure.

Hook-edge rims have thickened ridges at the edge of the inner sidewall. Air pressure traps the tires' bead wires under the ridges, thus centering the tires and holding them in place.

So far, so good — except that there has been quite a bit of crossbreeding between the two types in recent years.

The 27 × 1¼-inch and 700C sizes, originally the straight-side sizes, have seen the introduction of several models of rims with hooked edges.

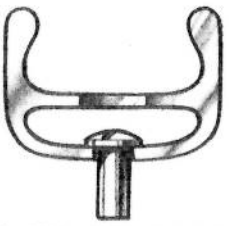
And in the 16, 20, 24, and 26 × 1.75/2.125 sizes, originally the hook-edge sizes, straight-side rims have been developed. The most common examples are the earlier Weinmann and Araya aluminum BMX rims.

Common wisdom suggests that one use only hook-bead tires (designated by decimal width markings such as 20 × *1.75*) on hook-edge rims, and wired-on tires (with fractional markings such as 27 × 1¼) on straight-side rims.

But there are now however, some 27 × 1¼-inch and 700C tires that should be used *only* on hook-edge rims. For instance, these are the Bib TS folding tires made by Michelin with Kevlar beads too stretchy to hold against air pressure. Specialized's Turbo tires also use Kevlar beads; however, Mike Sinyard, President of Specialized, indicates that these tires may be used on straight-side rims, as the beads are stronger than Michelin's. But if you want to play it safe — particularly if overinflation or high-temperature operation from braking on long downhills are likely — use hook-edge rims.

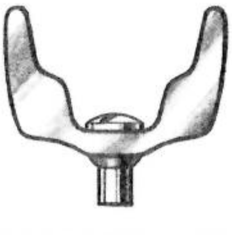
The Mavic Module E, Module 3, and other rims of similar construction have hook edges

Typical High-Performance Rim Sections

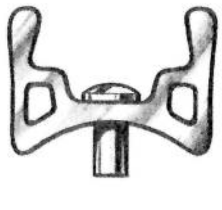


Hook-Edge (Mavic Module 3)

Combination
(Super Champion Model 58)



Straight-Side (Weinmann 210)



Inward-Slanted Sides-not a true hook-edge
(Weinmann A129 concave)

(Note: Only the inside profile of the rim determines whether it is hook-edge or straight-side. Outside profile may vary according to construction.)

but no bead seat. The absence of the protruding bead seat at the bottom of each sidewall makes it easier to install and remove tires. Once the tire is deflated, the bead drops right down to the bottom of the rim's channel: then one section of the bead can be pulled up over the edge. This is particularly helpful with the Kevlar-beaded tires, which tend to be made a little bit small to compensate for bead stretching. One caution about these rims: most of them have recessed spoke heads, and require a strong fabric rim tape to prevent the tube from protruding into the recesses. Velox makes such a tape; adhesive, duct, and fiberglass filament wrapping tapes have also been used successfully. Two layers of tape are advisable.

The Super Champion model 58, Rigida Alu, Rigida 1320, and many others rims have *both* hook edges and bead seats. These rims hold the tires most securely of all; they can even hold tires that are theoretically too wide for the rim. Super Champion makes the model 58 in a 650B size, too — a size commonly used on tandems with tires up to 47 mm (1¾ inch) wide. I've seen these tires successfully used on the narrow rims, though the tandem's owner complained that the ride was a bit "wallowy." Still, Super Champion model 58 and Rigida Alu are well suited for Specialized's new 27 × 1⅜-inch and 700 × 35c tires — and have also been used with tires as narrow as one inch. (But don't use one-inch folding tires on this rim; the rim is too wide.)

Since it is harder to install and remove tires from rims with bead seats, they should be used when versatility is more important than convenience. Also, with narrow rims, the valve of the inner tube may ride up on the bead seats. This leaves a void between the rim and the tube, around the base of the valve. The nearby (thin-walled) portion of the tube expands into this void and the tube blows out. One solution is to use molded valves rather than those with metal nuts holding them to the tube. Presta valves are preferable. If Schraeder valves are used, build a ramp of bathtub caulk extending to the nearest spoke holes and rising to the level of the bead seats around each valve. Before inflating a tube, make sure that the valve is pulled out until its base bottoms on the rim or the bathtub caulk.

Weinmann concave rims have a semi-hooked bead — actually, just an inward-slanting sidewall. These rims are not recommended for Michelin folding tires. It is particularly hard to remove tires from these rims, as the center well is very shallow. Use thin fabric rim tape; in fact, such tape is the best choice with any narrow rim. Most rubber rim strips are too wide, and if you trim them to the right width (a tedious job using scissors), there isn't much strength left around the valve hole.

Now for the other crossbreed: hook-bead tires on straight-side rims. I have a pair of such tires (20 × 1.75) and rims on my Raleigh Twenty, and they work. It *is* necessary to take more care in mounting the tires, because the tires' hooked beads may not fit quite as well to the rims' bead seats. You might have to inflate a tire partway and then work around it with your thumbs, pushing the bead into place. Fred DeLong has described plastic rim adapters, but I've never seen them. It's probably best not to buy this rim/tire combination for a child who is likely to let the tires become underinflated, or fo someone who won't mount the tires carefully when repairing punctures. Since thes rims have narrow sidewalls, considerabl care is necessary in adjusting the shoes of caliper brake. Otherwise, there should be n problems, at least I've had none in 5,00 miles.

LETTERS

Fatalities from Collisions

I read with much interest David Gordon Wilson's piece in the pilot issue of *Bike Tech* on technical research needed in the field of bicycling. I certainly agree with the conclusion that an adequately funded research program would likely repay the investment many times over.

Wilson's statement at the start of the section on "Accident prevention" that "Most injuries, serious and otherwise, and most deaths to bicycle riders come from accidents in which no motor vehicle is involved" is partly in error, I think. The part dealing with injuries is correct; the part dealing with fatalities is wrong, to the best of my knowledge. In the United States, so far as we can tell, the overwhelming majority of bicyclists' deaths does in fact involve motor vehicles; around 1,000 of such fatal accidents have been reported in each of the past several years. It would surprise me if in any given year more than a few dozen bicyclist deaths were caused by accidents not involving motor vehicles (the problem that the latter type of accident is not uniformly reported complicates the task of arriving at a reliable estimate, of course). I certainly would appreciate seeing any contrary evidence you may have.

Ralph B. Hirsch
National Legislative Director
League of American Wheelmen
Philadelphia, Pennsylvania

David Gordon Wilson replies: Ralph Hirsch, as usual, seems to be correct that most bicycle fatalities come from collisions with motor vehicles. I was so convinced of the opposite that I did not give ground easily. I went to six agencies to get the truth. None has it: all confess that the data collection is very poor.

There seems to be no doubt that around 1,000 bicyclists are killed in motor-vehicle-related accidents each year. Although there is no good measure of those killed through encounters with dogs, gratings, potholes, bad brakes, and faulty forks, I now don't doubt that they add up to considerably less than 1,000 a year — thank goodness. Apologies!

Backpedal Rebuttal

I am moved to rebut the John S. Allen article entitled "The Boyd Brake Actuator Raises Some Issues of Bicycling Engineering" that appeared in the pilot issue of *Bike Tech*, Vol. 1, 1982.

The most successful inventions are those that are made to satisfy a perceived future need, for example, Sir Frank Whittle's jet engine, Chester Carlson's Xerox, George Dowty's liquid spring.

The growing energy crunch is going to persuade many people on this continent to use bicycles in the future for utility purposes, such as commuting, going to the store, etc. And as Scott Didlake said in his *Bicycling* article of July 1980 about riding in traffic, "the coaster brake is the most useful device ever invented for city cycling."

The results of an admittedly informal market survey which I conducted revealed, that if given their "druthers," somewhat more than 50 percent of the teenagers would have back-pedaling brakes on their multi-speed bikes, the vast majority of the mature men (over 30) would do likewise, and virtually all of the mature women would also. Indeed, many women told me that they refuse to ride 10-speed bikes because they only have hand brakes.

There are approximately 96 million mature people (ages 31 to 65 inclusive) on this continent compared with 103 million youths (ages 6 to 30). When the results of the above market survey are factored into these numbers, there obviously is going to be a substantial future market for multi-speed bikes that are equipped with a back-pedaling brake, and that is why I invented it.

Now to address some of the detailed points in John Allen's article. As he says, experienced bicyclists prefer an independently hand-operated front brake. I do not disagree. This they can have together with my pedal-operated rear wheel brake.

As to pedal-operated front and rear brakes, there may be some hesitation. But I have a prototype that is so equipped. It has the added feature that the pedal operation of the front brake is always milder than that of the rear brake, plus the emergency feature that the front brake can also be hand operated.

I agree with him also that promising, but not the most promising, applications of my actuator would be for hand-cranked machines for the handicapped and high performance recumbent machines; also for one-armed riders. But he forgot two very important applications; namely, "bicycles built for two" and tricycles.

The brake lock-up feature, when the bike is rolled backward, is a definite plus on steep hills as Fred DeLong stated. It also is a great convenience when leaning the bicycle against a wall or other object. It eliminates the need for the so-called "Jiffy Stand."

It is interesting that Mr. Allen should regard the wedge brake as "the weakest part of the invention." Those who have seen my prototype bicycles took the exact opposite view. The wedge brake is not the crude stirrup brake of yesteryear that works on the inside diameter of the rim. Rather, it is a simple, sensitive, positive yet very rugged brake that works on both the sides and inner diameter of the rim. When equipped with industrial brake pad material having a relatively small spread in wet and dry coefficients, it provides excellent braking under both wet and dry conditions. This is a *must* for utility bicycles.

As to toe clips and straps, not many utility riders will want them. And as for controlled panic stops, Scott Didlake stated in his article, "Most importantly, the coaster brake allows instant, reflexive braking. Though theoretically you might not be able to stop as quickly with a single rear coaster brake as you can with front and rear caliper brakes, in practice you stop more quickly because braking is an immediate reaction."

Mr. Allen's assertion that "an industry-wide adoption of the Boyd actuator to replace a rear hand brake would have an adverse effect on the bike handling skills and safety of the cycling population" is debatable. Only the future will settle this question.

Finally, to counter Mr. Allen's inference that I am an inexperienced bicyclist, let me say that I lived in Bermuda during part of my youth when bicycles were the primary means of transportation. And before leaving that paradise in the early 30s, I owned a bicycle with a Sturmey Archer three-speed gear and integral coaster brake together with a hand-operated front wheel brake. It is worth noting that the hand brake was rarely used.

Winnett Boyd
Richmond Hill, Ontario, Canada

Long Overdue

I congratulate you on a superb job with *Bike Tech.* It is long overdue that a publication of this type be available. Campagnolo-USA Inc. is initiating an aggressive campaign to educate dealers and their customers on the technical aspects of our products. We are glad that your company has also seen the need to equip the cyclist with such important information.

Jeff Davis
Technical Advisor
Campagnolo-USA Inc.
Houston, Texas

Plan Ahead

In response to your request for our input on the new publication *Bike Tech:* I think it's great and I can see some great things coming from it for dealers and individuals. My only comment: because *Bike Tech* is going to have so many timely and important articles over the years, could we start now and plan for the future usefulness of all *Bike Tech* issues by 1) coming out with a yearly (and updated yearly) *Bike Tech* index of previous issues, so we can quickly look up some technical point in a past issue; and 2) put holes in the left side so the issues can be kept in a loose leaf binder.

Keep up the good work.

Ralph Howard
The Bike Shoppe
Ogden, Utah

Editor: Thanks for the suggestions! We're looking into it.

Lessons of History

I am enthusiastic about the future of *Bike Tech;* however, technical information of this caliber may be hard to come by. So don't forget to look to the past for interesting information, and of course look to the future for exciting, interesting, and informative articles that can keep us updated with technological improvements.

Jim Gentes
Product Design
jim blackburn design
Campbell, California

Editor: You're right: new information on testing and research is frequently hard to come by. We're counting on the best people in the bicycle industry to write us about the work they're doing.

Let Us Hear

We'd like *Bike Tech* to serve as an information exchange — a specific place where bicycle investigators can follow each other's discoveries. We think an active network served by a focused newsletter can stimulate the field of bicycle science considerably.

To serve this function we need to hear from people who've discovered things. We know some of you already; in fact some of you wrote articles in this issue. But there's always room for more — if you have done research, or plan to do some, that you want to share with the bicycle technical community, please get in touch.

BIKE TECH

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