Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

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PROTOTYPES

Molded Composites: The Next Step in Frame Design?

Getting Ready for the '88 Olympics

The *Bike Tech* Editors

In the aftermath of the 1984 Olympics, Mike Melton, builder of Raleigh's glued aluminum "funny bikes," predicted that the next wave of Olympic machines will make extensive use of graphite and composite fibers in the frame[1]. He didn't say exactly *how* these frames will be made, but we are now beginning to see a few clues as to what he might have meant.

Frames built of composite tubes are not big news anymore, of course. The Alan "Record Carbonio", the Vitus "Carbone" series[2], and the Peugeot PY 10 FC (assembled by Bador)[3] are three examples of the composite-tube design that have been mass-produced for several years. The tubes of these frames are made of carbon-fibers or a woven mix of carbon and Kevlar fibers; the fibers are bonded together by a "resin matrix", usually a two-part (chemically-curing) epoxy. The frame is then assembled by gluing the tubes into cast lugs, usually using a one-part (heat-activated) epoxy adhesive. From a distance, these frames all look like the conventional 7-tube steel or aluminum variety.

But there's another way to get the lightweight strength of carbon and Kevlar fibers into a bike frame: *molded composite* construction. With this method, there are no tubes; the frame is "all one piece." And, as you can see from the photos in this article, you'll never mistake such a frame for anything else.

[1]Bicycling, *March 1985, pp. 104-112.*
[2]Bicycling, *December 1985, pp. 75-77.*
[3]Bicycling, *March 1985, pp. 96-102.*

Dan Darancou's prototype: a Kevlar mat lay-up construction with a flat carbon fiber layer in the center plane.

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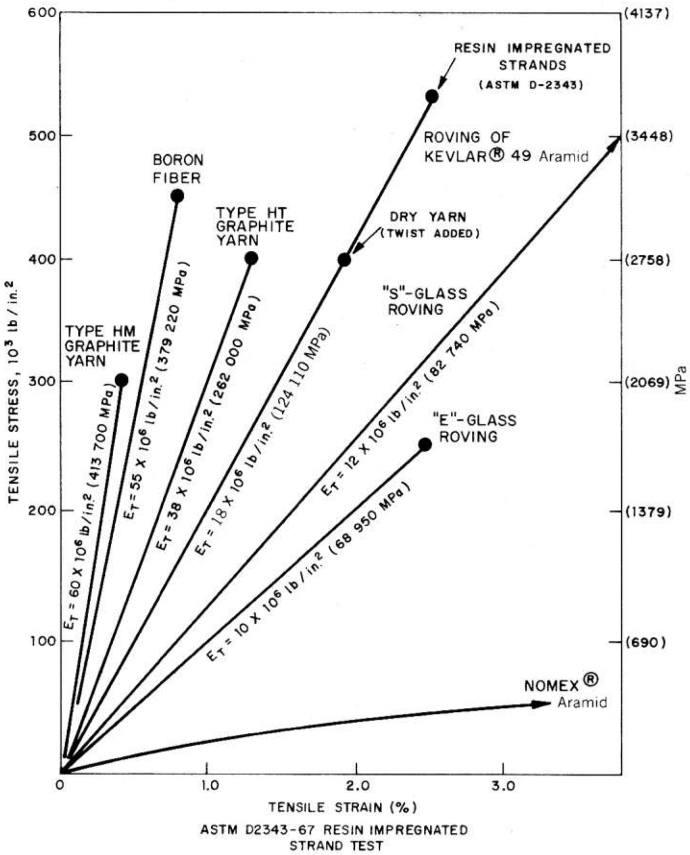

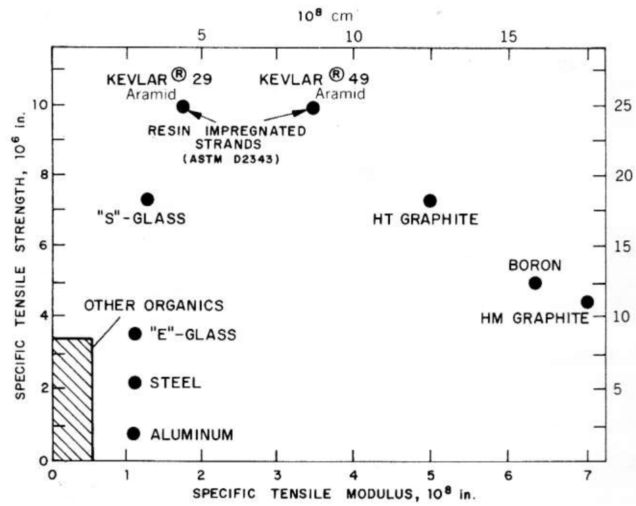

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Tensile properties of typical reinforcing fibers.

At left: Stress vs. Strain plots.

Above: Specific Tensile Strength and Specific Tensile Modulus (tensile strength and modulus divided by density).

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The main advantage of molded construction is that the frame's shape, cross section, and wall thickness can be "tailored" at every point to exactly match the strength and stiffness requirements at that point. For example, bending moments are typically much higher at the ends of the tubes, where one frame member joins another. This is exactly why double-butted tubing was developed; to put more material at the joint areas to resist the higher loads. But with molded composite construction, you are not limited to just one or two discrete steps in wall thickness, as you are with double-butted tubes. Instead, the wall thickness can be varied *continuously* to match the continuous distribution of loads.

Molded bike frames are certainly not a new idea. In the 1970's, a few molded fiberglass prototypes were built, but they were too flexible and/or too heavy to be practical. The problem was not in the molded construction method, but rather in the choice of reinforcement: glass fiber, the only material cheap enough for bike frames, was simply not stiff enough with respect to its weight. If the frame had enough glass fiber to be rigid, it was too heavy.

Highly Specific Properties

The solution to this problem appeared in the early 1980's: high-modulus materials like carbon fiber and Kevlar became available at relatively low prices. What does "high-modulus" mean? Basically, it means exceedingly strong and stiff, not only in absolute terms but also with respect to the material's own weight. In the accompanying figure, the stress/strain properties of various fiber types are plotted. The slope of each line represents the material's elastic modulus in tension (E_T). Note that Type HT graphite yarn, typical for bicycle applications, has a tensile modulus of 38 x 10^6 psi, which is about the same as that for garden variety CrMo steel frame tubing; the modulus of Kevlar 49 yarn is about half of this value (18 x 10^6 psi).

The figure also shows the materials' *specific* tensile properties, that is, the modulus and tensile strength *per unit weight*. For HT graphite, the specific tensile modulus is roughly *five times* that of steel, while its specific tensile strength is about 3½ times that of steel. Compared to aluminum, HT graphite is about *seven times* stiffer per unit weight. The implication, in theory at least, is that a graphite-fiber frame could be made as strong or as stiff as a steel one, and yet have only about 1/5 to 1/3 of the weight.

In practice, the picture is less rosy. For one thing, the epoxy resin matrix, needed to hold the fibers in place, adds considerably to the weight but almost nothing to the strength. Still, the advantages of high-modulus fiber materials are significant. Considering that graphite and Kevlar are already commonplace in other types of sports equipment (tennis rackets, skis, and fishing poles, for example), it's more than likely that molded-composites will play a role in the next generation of bicycle frames.

Here is a brief look at two molded-composite prototypes; they illustrate the late-1985 state-of-the-art quite well.

The Darancou Design

Dan Darancou[4], now a designer in General Motors' Pontiac division, hand-built the machine shown here for a student design project last year. The frame is made of two "half-shells" of Kevlar 49 fabric, and is filled with urethane foam, with a planar layer of graphite fiber sandwiched in the middle.

We found the project interesting, not because of the bike's outrageous shape, but because the fabrication process Dan used, *hand lay-up*, is fundamental in all molded composite construction. Here is a step-by-step description of the procedure:

—The starting point is to make two clay models (a left half and a right half) of the exact size and shape of the finished frame. At this stage, it's easy to sculpt the clay into whatever aerodynamic cross sections or flowing curves are desired. Accurate measurements, using templates and calipers, are essential to insure symmetry.

—Next, molds are made by pouring a non-shrink plaster slurry over the two clay models. Hemp fabric is pressed into the plaster for reinforcement. When the plaster cures, the clay is scooped out of the molds, and they are then ready for making multiple copies of the frame.

—Next, Kevlar fabric is cut into appropriately shaped strips (ceramic scissors are essential), and are saturated with epoxy resin. The main trick here is get the right amount of resin into the fabric; too much resin means excess weight, not enough means poor bonding.

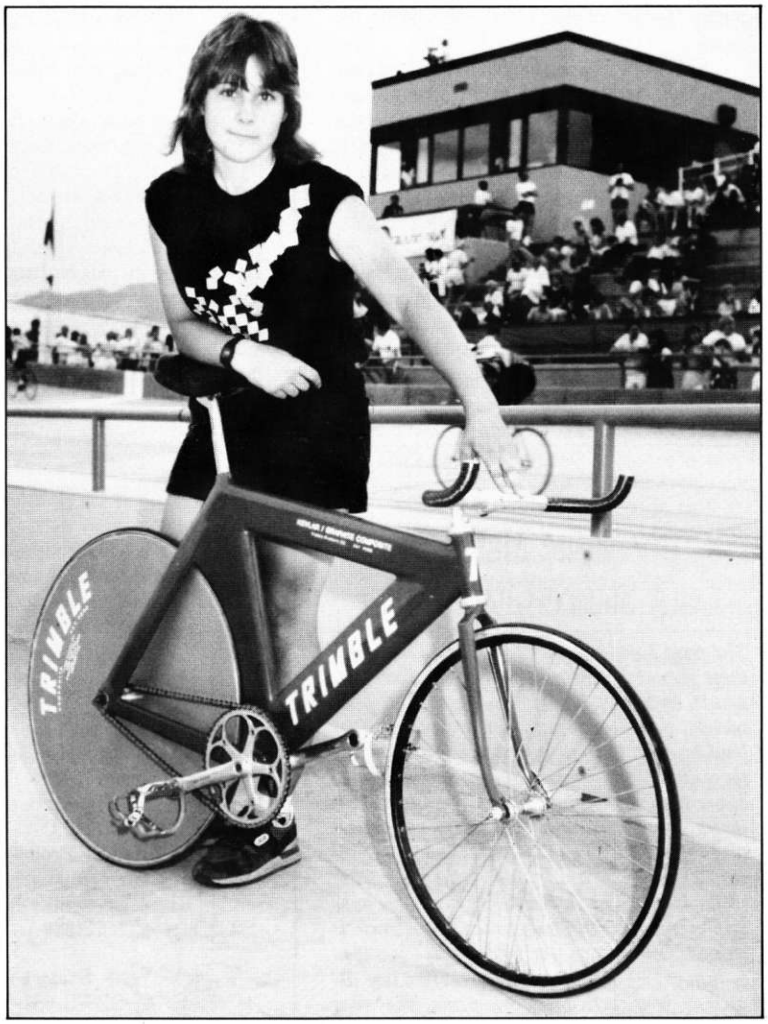
—The saturated Kevlar strips are pressed into the two molds. Several layers are built up, with extra thickness in areas of greater stress. When the epoxy fully cures, about four days later, the two Kevlar-fiber "shells" are removed from the molds, ready for assembly.

—Aluminum inserts are now placed at the hard points: bottom bracket, dropouts, headset, and seat. Hollow guide tubes are installed for routing brake and shifter cables *inside* the frame.

—Each half of the frame is now filled with closed-cell urethane foam, then shaved flat at the mating surface. Finally, epoxy-soaked carbon-fiber strips are placed on the mating surfaces, and the two halves are pressed together until cured.

Dan admits that it takes a long time to build a frame this way. He spent about 400 hours just to make the plaster molds, and a further 200 hours to do the resin lay-up. But if you're making three or more identical

[4]*Daniel Darancou 32600 Concord St. #708 Madison Heights, MI 48071*



Two Trimble Bikes: Heidi Hegg with the 12 lb. pursuit version (above), and the 20 lb. time trial version (below).

frames, for example, Dan figures you could justify the effort that goes into making the molds.

The big advantage to molded construction, Dan says, is that you can get strength and stiffness properties that are impossible any other way. In his next frame, Dan plans to incorporate "structural cables" of Kevlar or carbon inside the molded frame. These cables will be *pre-stressed* and held in a tensioning fixture while the resin cures.

By now, it should be clear that composites offer some interesting new design options. But is it really practical to make bikes this way? The work of Brent Trimble suggests that it is.

The Trimble Machines

Brent makes structural-composite parts for small aircraft at his one-man machine shop operation in Anchorage, Alaska.[5] He started building bikes about three years ago, "as a hobby," he says. To date, he's completed five frames. He sold the last three of them to top-class riders including Steve Hegg and his sister Heidi (see photos). But Steve Hegg resold his frame. . . . not because he didn't like it, but because the second buyer, the United States Cycling Federation, wanted to check out Trimble's design for use in the 1988 Olympic bikes (see interview in sidebar). Not bad for the fifth frame from an "amateur" builder.

Trimble uses essentially the same hand lay-up procedures as Dan Darancou, described above. But he uses mixed-weave fabrics (averaging 25 percent carbon-fiber, 75 percent Kevlar) in a computer-calculated lay-up pattern. He says that it's important to "keep the carbon fibers in tension," and that stiffness, not strength, is the controlling design factor.

Many of Trimble's methods are taken directly from his aircraft work. His frame

[5] *Trimble Products Company*
8025 Sundi Way
Anchorage, AK 99502.
Ph. 907-243-7120

Composite Materials: A Source Directory

The most popular topic of letters to Bike Tech *these days is composite materials. Everyone wants to know how to build carbon-fiber wheels, or where to buy Kevlar pre-pregs, or how to cure heat-setting epoxy. For some of these questions, there are no hard and fast answers yet. The commercial sources of composite frames (Alan, Vitus, Peugeot, for example) and their suppliers (TVT and Bador, for instance) are reluctant to talk about production methods in detail. Indeed, they are likely to be improving their techniques as experience is gained. In any case, the field is still wide open to innovators of all persuasions. Here is a list of resources, with brief comments, that may provide some answers to your questions.*

—**"Human-Powered Vehicles Source Directory,"** compiled by Mike Eliasohn. **Human Power** (Technical Journal of the IHPVA), Vol. 4, #4, Fall 1985, pages 10-25. [See especially Category 4 ("Construction Materials"); here is a hard-core list of more than 60 hardware suppliers, mostly industrial, many wholesale, of the specialized foams, metals, plastics, fittings, and tools needed to work with composites.] **Human Power** is available by subscription ($15/yr, quarterly) from:
International Human-Powered Vehicle Ass'n.
PO Box 2068
Seal Beach, CA 90740

—**Composite Basics.** A.C. Marshall (1985, 212 pp., $30) [Solid introduction: core materials/honeycomb sandwich, fibers/fabrics, molding and tooling. The publisher, T/C Press, also lists a huge selection of other interesting titles like **Handbook of Surface Preparation** (594 pp, $40.), **Technology of Carbon and Graphite-Fiber Composites, Advances in Adhesives** (1983, 306 pp. $56.), and dozens of others. We have not seen all these volumes, but the general tone sounds like an industrial-training approach that should contain some well-tested procedures. Ask for the complete catalog of books and literature searches.]
Technology Conference Publications
PO Box 842
El Segundo, CA 90245

—**KEVLAR Bulletin K-5** ("Characteristics and Uses of Kevlar 49 Aramid Organic Fiber"), **KEVLAR Brochure #E38532**, and **KEVLAR UPDATE** Newsletter.
KEVLAR Special Products Dept.
DuPont Company
3879 Excelsior Center Building
Wilmington, DE 19898

—**Scotch-Weld Structural Adhesives** (Bulletin #Z-SWPB-631-VP), **Innovative Adhesive and Sealant Products for Industry** (Bulletin #78-6900-0203-1), and **Technical Data Sheet for Epoxy Adhesive Series #2214** (Bulletin #Z-2214S). [3M's Scotch-Weld #2214 series is a family of widely-used industrial heat-setting one-part epoxies. They cure at 250 to 300 degrees F, and are available in quantities as small as 6 oz. tubes. There is evidence that this type of adhesive is used in manufacturing the Vitus 979 aluminum frame. The 3M Bulletins listed here are a good source of data on joint design and surface preparation for bonding a variety of materials.] Bulletins are available from:
3M Company Adhesives, Coatings,
and Sealers Division
223-1N, 3M Center
St. Paul, MN 55144

—**FIBERITE Composite Materials Selection Handbook.** (Detailed technical specifications on Kevlar/carbon/fiberglass composites in form of fabrics, tapes, and prepregs).
Fiberite Company
501 West Third Street
Winona, Minnesota 55987

—**Encyclopedia of Composite Materials and Components.** Martin Grayson, Editor. John Wiley & Sons, Inc., New York, NY. 1983. (1161 pp., $125.) See especially the chapters on "Carbon Fibers and Fabrics" (p. 221+), "Aramid Fibers" (p. 97+), and "Laminated and Reinforced Metals" (p. 609+). [This is probably the single most complete source on the chemistry and physics of composites. You may not actually want to buy it, but spending a few hours with it in the local engineering library would be a great help if you're buying materials and dealing with industrial suppliers.]

—**Composite Materials Handbook.** M.M. Schwartz. McGraw-Hill, Inc. New York, NY. 1984. (672 pp., $62.50) Available from McGraw-Hill and ASM.

—**Fabrication of Composite Materials: Source Book.** M.M. Schwartz, editor. 1985. (432 pp., $54.) Available from ASM (ask for their complete catalog):
American Society for Metals (ASM)
Metals Park, Ohio 44073

—**Design, Fabrication and Mechanics of Composite Structures** (reference materials for Seminar of May 1, 1984, Arlington, VA). Brian Jones, editor. 1984. (352 pp., $150.) [State-of-the-art aerospace goings-on.] Available from ASM (see above) or:
Technomic Publishing Company
851 New Holland Ave., Box 3535
Lancaster, PA 17604

—**Primer on Composite Materials: Analysis** (second edition). John C. Halpin. 1984. (187 pp., $25.) Available from ASM or Technomic Publishing Company. [All mathematics, matrix and tensor algebra. An excellent source if you're working on design equations for composites, or need some "acceptable" quick and dirty shortcuts.]

cross sections, for example, are derived from low-drag airfoil profiles. And his lay-up process uses "pre-pregs" (fabric sections pre-saturated with a controlled weight of resin at the factory), a standard aircraft building procedure. But Trimble is reluctant to discuss further details until his patent application, now pending, is granted. In any case, it's clear that the small-scale aircraft industry has already developed the materials and methods that bicycle framebuilders can use.

We rode the Trimble time-trial bike pictured here, serial #1 out of Trimble's mold, and found it acceptably stiff and comfortable. It is a bit heavy for its class (20.55 lb. with two disk wheels), but a few pounds could easily be shed by switching the steel fork to aluminum, and using a spoked front wheel. The real low-weight story is the pursuit bike: it weighs the same as the 12-pound Olympic aluminum funny bikes. The next batch of frames will weigh even less, Trimble says, thanks to a narrower cross section.

Trimble is also working on an all-composite all-terrain bike, and an all-composite front fork. He says he has "barely scratched the surface" in applying composite technology to bike design, and we're inclined to agree. Composite construction, whether molded, tubular, or a hybrid, might be just what's needed to make Mike Melton's prediction of a nine-pound track bike come true.

The View from Colorado Springs

Steve Bishop, Head Mechanic for the US National Cycling Team at the USCF training camp in Colorado Springs, made these comments to Bike Tech *about the Trimble bikes.*

BT: *What were your experiences with the Trimble bikes?*

SB: We had three different bikes out here this past summer, and they were all carbon fiber and Kevlar composite work. One of them had fully enclosed front and rear triangles, and one of them had just a closed rear triangle. One of these bikes was used down in the sports festival in a kilo and also in a pursuit event. Heidi Hegg has one and Kit Kyle, who's about the same size, rode her bike and liked it a lot.

We had a road bike here too, and everybody was surprised how well it runs. It had a Vitus fork, and was a really fun to ride. It is a different shape than the pursuit bikes that we got later in the summer though.

BT: *How do the composite bikes ride, compared to your standard lightweights?*

SB: There were interesting parts on each one of these bikes, and each one rode differently. But I have to say that they were all on the flexible side. I don't mean to be negative about them, because I think they were a really good effort for the first batch of all-composite bikes. I'd even say the road bike rode better because it was on the flexible side. But in the pursuit bike, it seems that the front triangle could be beefed up a bit.

BT: *Could they add more material and still keep the weight down?*

SB: Probably. One of designs was incredibly light, and we all definitely feel like going with the lightest possible equipment. It's to our advantage because of being able to accelerate the bike faster. But the lightest bike didn't seem to have enough material to be really rigid, so it may have to be beefed up. Maybe internally, or by adding different materials. It's all new technology, and these are just the very first efforts. The people seem to know their materials and processing and do a fine job of construction. All the bikes had an excellent finish and surface.

BT: *How important are the enclosed triangles?*

SB: There seems to be a big improvement in the aerodynamic characteristics. This still has to be measured with lab tests and wind tunnel information. But I'm sure you'll see a lot of designs in the future with the rear triangle enclosed from the seat tube. The seat tube, the seat stay, and the chain stay are all enclosed and the wheel fits inside. You get a lot more strength in the rear triangle. I think they are on the right track with the basic enclosed design.

BT: *Are molded composites really going to challenge the place of aluminum and steel in bike frames?*

SB: I'm sure of it. Look at the aircraft industry and motor racing industry. They are all racing with the composite materials. All the Indy cars have composites in the chassis. That really changed the way those cars worked. They got much faster cars immediately just because of the extra rigidity and weight savings.

BT: *How much difference will a composite frame make?*

SB: It depends mainly on the weight savings. The more weight you save, the more advantages there are. There's so little weight to a bike frame to begin with, it's hard to reduce the weight much more. A half pound [savings] is significant and a couple of pounds is pretty extraordinary. But now the weight of aluminum bikes is the standard. Still, I think we can push the envelope a bit more and squeeze something out of the new fiber materials. It's not going to drop a couple more pounds again, maybe just a pound or a half-pound. A lot of people will choose the [enclosed triangle] aerodynamic design and live with more weight, thinking that the bike moves through the air faster. I think there will be significant advantages to these enclosures.

DESIGN

Bicycle Chains

Materials, Chain Wear, and Lubrication

Mario Emiliani

Bicycle roller chains must be strong, durable, reliable, easy to maintain, and inexpensive. These requirements might seem easy to satisfy, but they're not. This is why modern roller chains are made from steel, and why their design differs little from that developed some 450 years ago by Leonardo da Vinci. And while today's roller chains work well in many applications, they seem heavy and even antiquated for modern lightweight bicycles.

Other materials could be used to make bicycle chains. A titanium or aluminum alloy chain, for instance, could be several ounces lighter than the typical 380 gram (13 oz) steel chain. Even composite plastic/metal chains, or all-plastic chains, could someday see widespread use. But before any of these become practical, some major advances in design and manufacturing technique will be needed. In any case, the final test for a new chain design will be whether it works as well as existing steel chains do.

In this article, we will look at steel bicycle chains, their performance and limitations, and the opportunities for using new materials in the future.

Steel

Most bicycle chains sold today are made entirely of steel, since few other materials are as strong, resistant to wear, easy to fabricate, and inexpensive, as steel. A wide selection of steel alloys, with a variety of heat treatments, is available to manufacturers of bicycle chains. Practical constraints, however, limit their choice to a few specific materials.

Low cost is a prime requirement for a bike chain, since it must be replaced often. Thus, stainless steels and other so-called "high alloy" steels are not used, since they contain large amounts (i.e., more than 5% to 10%) of expensive alloying elements like chromium, nickel, and molybdenum.

Two other prime requirements for chains are strength, to resist high operating stresses, and hardness, to resist wear. For-

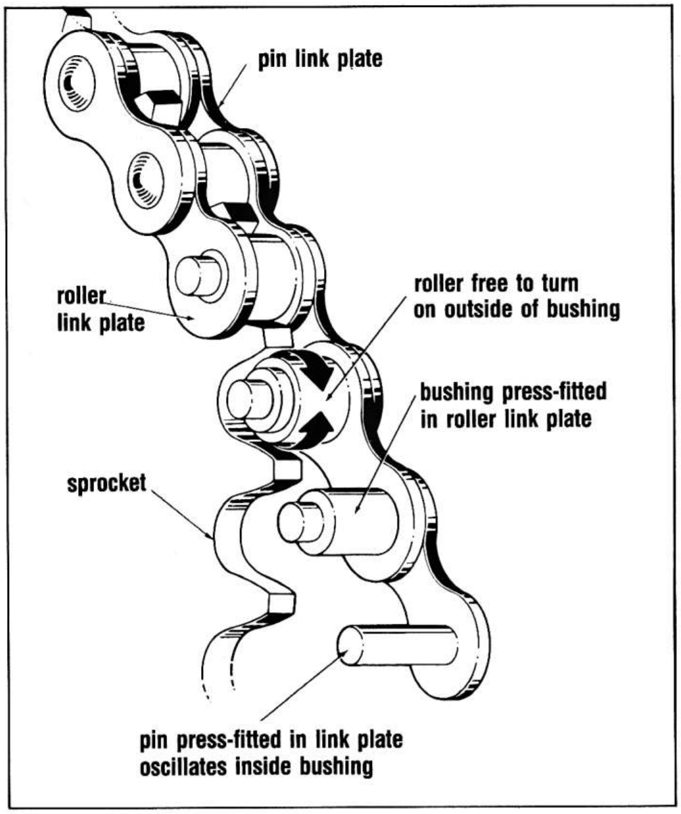


Figure 1: A standard roller chain. (Adapted with permission from Ref. 1)

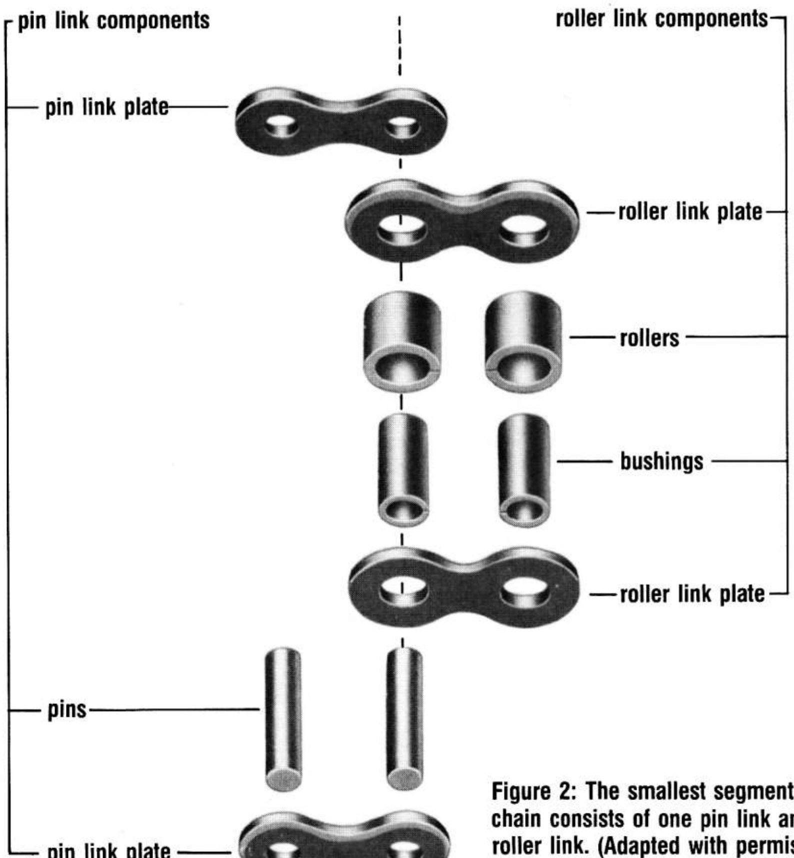


Figure 2: The smallest segment of a roller chain consists of one pin link and one roller link. (Adapted with permission from Ref. 1)

tunately, these properties are inseparable: the stronger the material, the better it's wear-resistance.

An outstanding combination of strength and moderate cost is found in the so-called "low alloy" steels (they contain less than about 2% of the expensive alloying constituents). This class includes the AISI 4140 and 4130 steels (the material commonly used in bicycle frame tubing).

Fortunately, some of the least expensive varieties of steel, namely the "plain carbon" steels such as AISI 1040 and 1060, work well in a bicycle chain. These steels contain about 0.6% to 1% carbon, and are in the same class as AISI 1010 and 1020, which are often used for frame tubing in inexpensive bicycles.

Most bicycle chains currently on the market are made from plain carbon steel because, besides its low cost, its strength and hardness are adequate. It is true that a low-alloy steel would be stronger and harder than plain carbon steel, *provided* that both received the same heat treatment. Its also true that a plain carbon steel, *if properly heat-treated*, could almost equal the properties of some low-alloy steels. For this reason, in trying to compare the various brands of bike chain, it is not sufficient merely to know the chemical composition; the complete history of processing and fabrication must be known.

It is not practical, in this article, to analyze every make of bicycle chain in such detail. After all, there are many brands worth mentioning (including the new ATB chains), and a minimum of four non-redundant parts per link would require testing. Instead I'll use the popular Sedisport as an example when I talk about how chains withstand wear.

Roller Chain Design

Chain drives of various forms were known for at least 2000 years, but da Vinci's designs were the first ones put to practical use. Even then, chains were expensive and difficult to make. And because the quality of steel available at that time was poor, early chains often wore out after a short period of use. It wasn't until 1895 that roller chains came became truly practical, when they were first introduced on the rear-wheel drive "safety" bicycle. Better quality steel and this new application brought a renewed interest in roller chain design and its other potential uses.[1]

The chains we use today are remarkably similar to those on the early bicycles. The

[1] ***Design Manual: Roller And Silent Chain Drives*** *(3rd ed.), by Jackson and Moreland; Washington, DC: Association of Roller and Silent Chain Manufacturers; 1958. The current version of this manual is* ***Chains for Power Transmission and Material Handling*** *(1982), available for $20. from: American Chain Association, 152 Rollins Ave., Suite 208, Rockville, MD 20852 (301-984-9080).*

standard roller chain is made from two basic sub-units: a **roller link** and a **pin link**, which are spaced alternately along the length of the chain (see Figure 1). When adjusting a chain's length, both a roller link and a pin link must be added (or removed). Since the pitch (pin-to-pin distance) of bike chains is a standard 1/2 inch (12.7 mm), length adjustments must be made in discrete 1-inch steps.

Figure 2 shows the smallest segment of chain (one roller link and one pin link) in detail. Note that this segment consists of *ten parts*. Thus, the typical 56-inch bike chain contains some 560 individual pieces: perhaps more than all the rest of the parts of the bike put together! A medium-priced chain today costs about $8., so you're paying less than 2 cents per piece; a tribute to the economies of mass production.

The plates are stamped from sheet metal, the bushings and rollers are made by rolling up small sections of sheet metal, and the pins are simply small rods. Each link is held together by press-fitting the bushings and pins into the roller and pin link plates, respectively. Each roller link and roller is sized so that it will move easily between each fixed pin link. This gives the roller chain the flexibility it needs to freely engage with the sprocket.

So-called "narrow" chains like the Sedisport are different in three major ways from the "standard" roller chain just described. First, the Sedis chains have no separate bushings at all. Instead, the rollers roll directly on integral "bushings" that are stamped directly into the roller link plates. Thus, the smallest segment (i.e. two links) of a Sedis chain contains only eight parts.

The second difference is that the chain width (i.e. length of the pin) and height of the Sedis chain are less than in regular roller chains. These smaller dimensions, coupled with close tolerances, allow 6-speed freewheels to be used on standard 120 mm wide rear chainstays. The table (Figure 3) shows some dimensions of the narrow Sedisport compared to two regular width chains.

The third difference is that the narrow chain has more side-to-side play compared to regular bike chains. For example, I measured 4.1 cm side-play over 15 links in a new Sedisport chain, compared to only 2.6 cm in a new Regina Oro. The Sedis has greater side-play because the roller link plates overlap each other less than on the Regina Oro. This is the reason for the Sedisport's much talked-about "smooth shifting" characteristic over narrow gear ranges, and its poor shifting over wide gear ranges. Finally, the Sedisport's roller link plates are flared at the edges, to improve the chain's ability to engage with sprocket teeth during shifting.

The design of Sedisport chains seemed quite novel when it was first introduced several years ago, but it isn't really new at all. The same general design (except for the flared roller links) is at least 89 years old, and can be seen on page 400 of Archibald Sharp's book, **Bicycles & Tricycles**[2].

Figure 3: Selected dimensions of popular derailleur chains.

Dimension	SEDISPORT	REGINA ORO	REGINA TITANIO
nominal chain pitch	12.7 mm	12.7 mm	12.7 mm
pin length (chain width)	7.3 mm	8.1 mm	7.9 mm
roller plate: width	4.4 mm	4.5 mm	4.3 mm
thickness	1.1 mm	1.0 mm	1.0 mm
length	20.9 mm	23.1 mm	23.3 mm
pin plate: width	6.7 mm	6.7 mm	6.9 mm
thickness	1.0 mm	0.95 mm	1.0 mm
length	20.8 mm	20.1 mm	20.0 mm

Chain Wear

Of the many wear processes which conspire together to remove metal from your chain, the major malefactor is *abrasive wear*. This type of wear occurs when "hard" particles (typically sand) become trapped between two sliding surfaces (see Figure 4). The small size of these particles (typically 0.0002 to 0.010 inch) makes them virtually invisible, but allows them to easily settle into even tight-fitting joints. The particles then gouge metal out as the parts slide past each other.

To make matters worse, the products of abrasive wear cause further abrasion. In time, the gouged-out metal fragments accumulate and do their own share of gouging, while the larger sand particles are crushed into smaller pieces, each with fresh, sharp cutting edges. Clearly, the best way to minimize abrasive wear is to keep the "invisible" sand out in the first place.

Bicycle chains are also subject to *adhesive wear*, but this is much less of a problem than abrasive wear. Adhesive wear occurs when the layer of lubricant on the surfaces is either too thin or is absent altogether. When the two surfaces were pressed together, the high points come into direct contact and become, in effect, welded together. When the surfaces are later moved apart, the high points remain welded together, and small pieces of metal are torn away from the adjacent surface in the process. In bike chains, adhesive wear removes much less metal than abrasive wear, because there usually is enough lubricant to prevent it.

[2] ***Bicycles & Tricycles,*** *by Archibald Sharp; Cambridge, MA: The MIT Press; 1977. Reprint of the 1896 edition published by Longmans, Green; London.*

A Closer Look

Figures 5 to 9 are scanning electron photomicrographs showing parts of my own Sedisport derailleur chain. Chemical analysis showed that all parts of the chain were made from a plain carbon steel, perhaps AISI 1050. I was surprised at how little wear I found on the chain. It had about 3000 miles on it, and I hadn't given it particularly good care. It's true that I rode it mainly in dry weather, but the only cleaning I gave it was an occasional wipe and a relubrication when it seemed necessary.

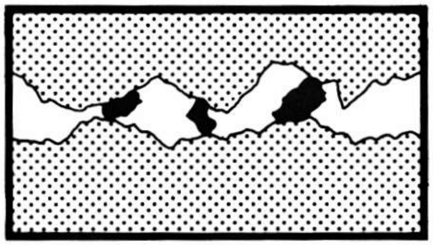


Figure 4: Abrasive wear starts when hard, sharp particles are trapped between sliding surfaces. These particles cut metal from both surfaces, and the metal fragments contribute to further abrasive wear.

**Editor's Note: Stresses on the chain can be estimated using the following formulas:*

1. *radius of front chainwheel = chain pitch x gear teeth / (2 Π)*
   Example: radius of 52T chainwheel = 12.7 mm x 52T / 6.28 = 105.1 mm
2. *Mechanical Advantage of front chainwheel = crank radius / chainwheel radius*
   = 170 mm / 105.1 mm = 1.62
3. *chain tension = pedal force x M.A. of front chainwheel = 250 lb x 1.62 = 400 lb.*
4. *shear stress across each pin (approx. 0.15" dia.)*
   = chain tension / (2 x pin cross-section area)
   = 400 lb / (2 x Π x diameter^2/4
   = 400 lb / 0.035 sq in
   = 11,300 psi
5. *compressive stress on pin's surface*
   = chain tension / 60% of pin's width x 20% of pin's diameter
   = 400 lb / 60% x 7.3 mm x 20% x 0.15"
   = 400 lb / 0.0052 sq in
   = 77,300 psi

(The factors 60% and 20% are approximations intended to represent the pin's "effective" area in carrying the chain-tension load.)

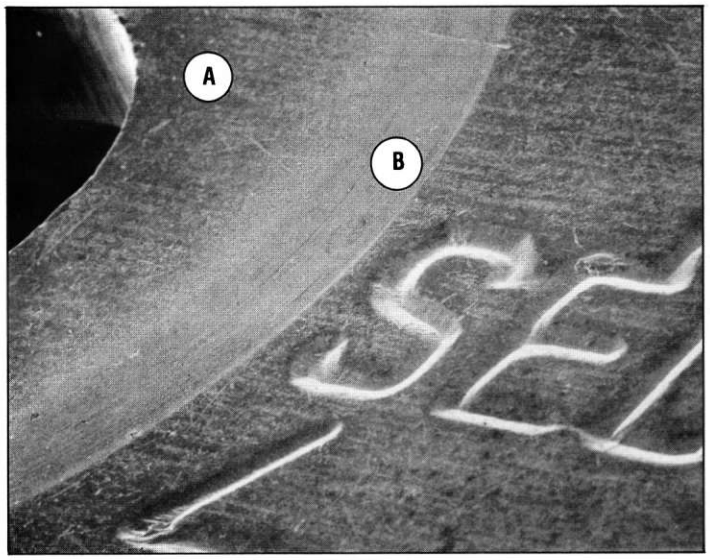


Figure 5: Chain misalignment is the cause of this uneven wear pattern on the pin link plate, where the roller link plate rubs against it. Note that area close to hole (A) is not worn, but the outer area (B) is. 40X.

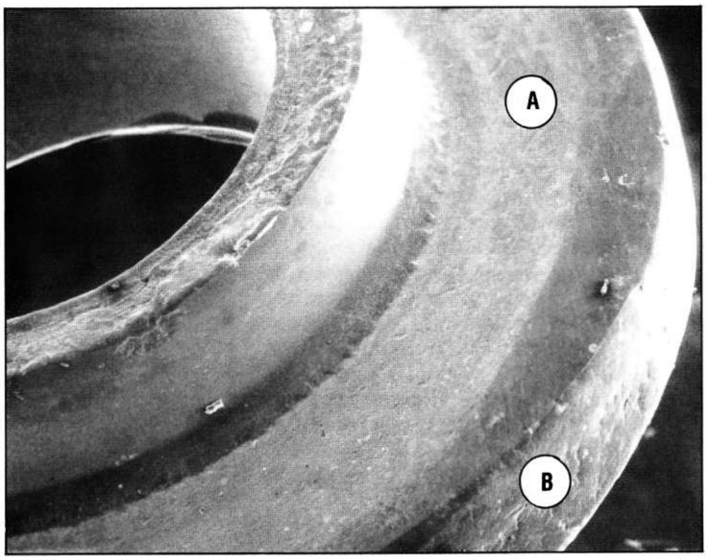


Figure 7: On this roller link plate, the worn region at A is expected, since this is where the side of the roller contacts the plate. The plate's edge (B) is noticeably fractured, indicating that it was stamped from sheet metal prior to heat treatment (when the metal was more formable). 38X.

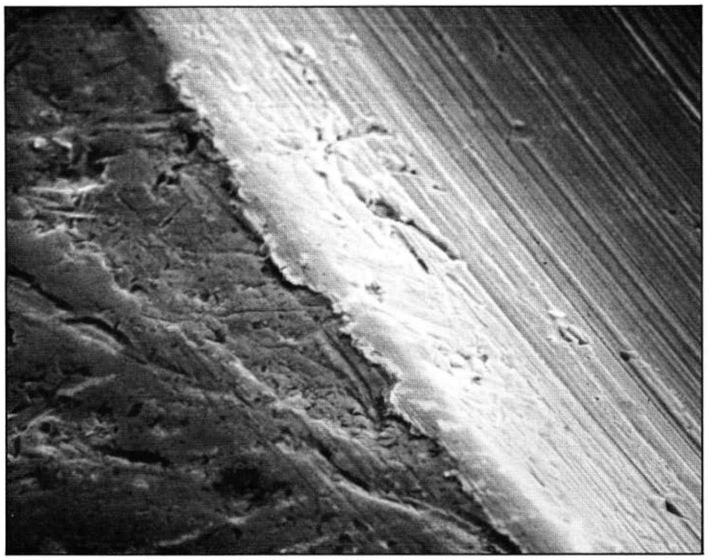


Figure 6: A closer look at the scoured area (B) shown in Figure 5. The deep gouges (upper right) are typical symptoms of abrasive wear. Note that the gouges are all approximately the same size and depth, an indication that the sand which caused the wear was crushed into small particles which did not decrease further in size. Note also the lip curling onto unworn metal (near center). 970X.

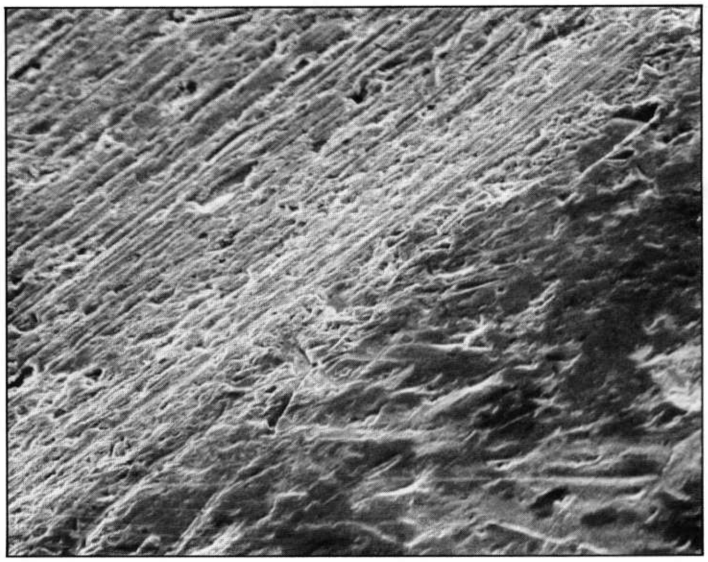


Figure 8: Close-up of the roller link plate shown in Figure 7. The scoured region (upper left) shows slight, uniform wear, an indication that the forces between roller link plate and roller are fairly low. The original surface finish of the chain, with no wear, is seen at lower right. 1000X.

Figure 5 shows the inner surface of a pin link plate. It is apparent that the outer third of the plate wore the most, and that this was due to chain misalignment (rubbing between the inner surface of the pin link plate and the outer surface of the roller like plate). A closer look at the worn region is seen in Figure 6.

Figure 7 shows the roller link plate and its integral bushing. The sides of roller link plate are worn over most of the surface where it contacts the sides of the roller. Figure 8 is a closer look, showing a scoured region with slight, uniform wear.

A polished cross-section of the pin (Figure 9) revealed that it had been electroplated. Chemical analysis of the surface of the pin showed a high chromium content. Chrome plating, as found on Sedisport and some other high quality chains, produces a very hard surface. This hard surface inhibits abrasive wear and, as a result, decreases friction between the pins and bushings. The chrome plate really seems to help; my pins had so little wear that the photomicrographs showed nothing of interest.

Pins are usually the most highly stressed part of the chain.* (However, if the centers of the pin link plates have holes drilled in them, *they* could be the highest-stress region.) In any case, chrome plating on the pins can prevent that incurable malady: "chain stretch."

Actually, "stretch" is a misnomer, since it implies that the chain stretches elastically like a rubber band. In fact, the chain elongates *permanently*, and the chain pitch (distance between pins) increases. The elongation is caused by wear: the outside diameter of the pins decreases and/or the inside diameter of the bushings and rollers increases. As little as 1/1000th inch change at each of these surfaces can make the chain almost 1/4 inch longer. Excessive chain stretch causes poor shifting: the chain no longer engages properly with teeth on the freewheel or chainring because each link is longer than the sprocket tooth spacings. In extreme cases, the stretched chain hops over small diameter freewheel cogs like a toad hops over a hot rock.

Coatings other than chrome plate are sometimes used on chains. For instance, I found by chemical analysis that the gold-colored Regina Oro chains are brass plated, while Shimano's silver-colored Dura-Ace UniGlide chains are nickel plated. In both cases, the electroplatings probably have some beneficial effects in reducing wear. Electroplated brass coatings are soft, so they serve as a solid lubricant. On the other hand, nickel plating is hard and, like chrome, reduces wear by virtue of this hardness. As the coatings wear off, of course, the wear resistance is lost.

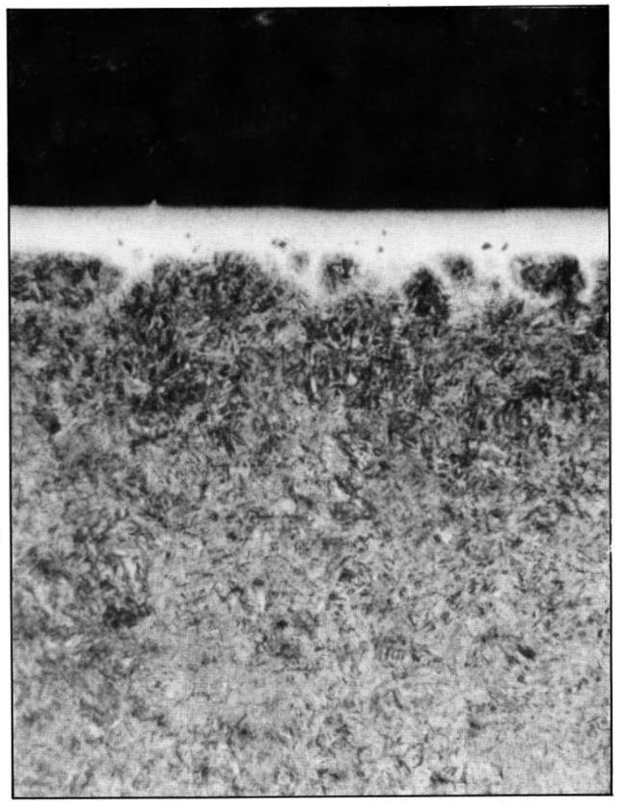


Figure 9: Cross-section of a pin from a Sedis chain, showing chrome plating on the surface. The plating is about 1/40th mm thick. Note how the chrome plating appears to have penetrated into the steel (i.e. the silvery whiskers). Apparently, the pin developed surface cracks due to high thermal stresses during heat treatment or quenching (fast cooling) when the pin was hardened. The pin was then plated, and the chrome filled into the cracks, producing whiskers below the surface. The surface cracks caused no problems during the lifetime of my chain, but they may be the cause of some otherwise mysterious chain failures. 270X.

Other Metals

What are the prospects for metals other than steels? To my knowledge, no major chain manufacturer currently sells anything besides steel chains. Nevertheless, titanium and possibly aluminum could be used in chains in certain circumstances and sold, I believe, at reasonable prices ($25-$50).

Aluminum is an obvious choice because it is only one-third the weight of steel, and certain alloys could be made strong enough, by proper processing, for sideplates. But few aluminum alloys are hard enough to take the abrasion that pins, rollers, and bushings receive. A workable design might use aluminum side plates with integral bushings (a la Sedis), plus steel rollers and pins.

Another factor to consider is sideplate rubbing due to chain misalignment. This might be reduced by hard anodizing the roller and pin link plates. (Anodizing produces a hard surface layer of aluminum oxide, about 0.02 mm thick, which helps resist wear.)

Such a chain should be used only with an aluminum freewheel (and aluminum chainrings, or course), since hard steel sprockets would quickly wear through the chain's oxide layer. If the chain was cleaned and lubricated regularly, it would probably work very well. The most suitable application for aluminum/steel chains would probably be pursuit bikes, where extreme light weight is a virtue, and road grit is not a problem.

Titanium, which is also strong and light (almost one-half the weight of steel) could also work well, especially in the sideplates. The main drawback to titanium is that it costs about 10 times more than steel, partly due to the special requirements for processing it. As with aluminum chains, the pins, bushings, and rollers would probably have to be made of steel. Unfortunately, this necessary use of steel parts in an aluminum or titanium chain puts a severe limit on the overall potential for weight savings.

Regina apparently discovered this when they made the "Titanio" titanium chain. This little gem, with a retail price of about $200 (before it disappeared from the market several years ago), had the same dimensions as the Regina Oro (Figure 3).

I recently examined a few links from a used Regina Titanio. The side plates are made of a heavily cold-rolled titanium alloy containing small amounts of aluminum and vanadium, probably less than 10% total. (Cold rolling, one of several methods used to strengthen metals, is accomplished by deforming the metal below about 1/3 its melting temperature.) The titanium sideplates do not have any special surface finish, and steel is used for the rollers, pins, and bushings. None of the components were excessively worn, but I don't know how severely it was used. I have been told that the Titanio chains wore out rapidly, but I'm more inclined to believe that their high price was the cause of their demise.

Reinforced Plastic Chains

An essential ingredient of Brian Allen's 22-mile flight across the English Channel in 1979 was a reinforced plastic chain. Allen's aircraft, the Gossamer Albatross, needed an 18-foot long chain to connect the pedals to the propeller. A steel chain was unthinkable because it would have weighed about 6 pounds—nearly 10% of the weight of the entire aircraft. The solution was a light polyurethane chain reinforced with 1/16 inch stainless steel cables. Eighteen feet of this chain weighed only 20 ounces.

This and other types of reinforced plastic chains have undeniable advantages. They are light, cheap (a few dollars per foot), have no moving parts, require no lubrication, and do not wear (if kept clean), stretch, backlash, make noise, or corrode. Even so, there are at least five reasons why reinforced plastic chains aren't yet on bicycles:

1. The Consumer Product Safety Commission requires that bicycle chains be able to support at least 1800 pounds of tension[3]. The best plastic chains with 1/16" stainless steel cables, can support a maximum of only about 400 pounds when sprinting or hill climbing.

2. Stainless steel cables in plastic chains are prone to fail prematurely by fatigue. The severe flexing, as the cables in a bicycle application passed over small diameter free-

[3] ***Code of Federal Regulations,*** *Commercial Practices, #16, published by United States Government Printing Office.*

wheel cogs and derailleur pulleys, would pose fatigue problems.

3. Dimensions of the reinforced plastic chains that are currently available are wholly incompatible with the sprockets used on bicycles. I don't expect the derailleur/crankset/freewheel manufacturers to re-tool just to use plastic chains.

4. The splice design currently used on plastic chains is neither narrow nor flexible enough to go through the twists and turns imposed by derailleur gearing.

5. While plastic chains won't rust, they could suffer other types of environmental degradation, including attack by sunlight, ozone, water, road oil, road salts, and temperature extremes.

Clearly, it's no simple task to develop a reinforced plastic bicycle chain that could be sold to the general public. Still, it's not impossible. As a starting point, the loads on chains must be better defined. Then, a new splicing method would have to be developed. Most important, new materials would be needed to meet the extreme requirements listed above. I expect that the reinforced composites used in the aerospace industry (Kevlar, graphite fiber, and silicones, for example) will be the way to go.

I am convinced that practical reinforced composite chains will be with us in the near future, and could even replace steel entirely. Light metal chains (titanium, aluminum) will most likely remain a novelty, like the Regina Titanio. And meanwhile, when your steel chain develops that distinctive rasping sound that says "clean me" . . . , grit your teeth and do it.

I'd like to thank the following for their assistance with this article: Chris Allen (SunTour); Cec Behringer (Behringer Company, Inc.); Bill Fiss (W.M. Berg Co., Inc.); Angel Rodrigues (R+E Cycles); Peter Weigle (J.P. Weigle Cycles); Shimano Sales Corp.

Mario Emiliani, a practicing material engineer in Providence, RI, has built a variety of bicycle frames over the past ten years. He has degrees in Mechanical and Chemical Engineering, and is now completing his Ph.D. in Materials Engineering at Brown University.

The Black Art of Chain Lubrication

Regardless of the alloy or surface plating that is used on a chain, friction between moving parts would ruin it in short order were it not for the *lubricant* on (we hope) all the surfaces.

Lubricants come in many varieties: solid (such as graphite), liquid (WD-40, LPS-1, and LPS-3), and liquids containing suspended solids (Teflon or molybdenum disulfide in TRI-FLOW, Super Lube, and Chain Life). Besides inhibiting wear, lubricants may protect against corrosion, form seals against the intrusion of contaminants, and dissipate heat. In addition, some lubricants penetrate into close-fitting surfaces better than others. Different areas of the bicycle operate under different conditions, and so the choice of lubricant varies with application.

The single most important property of a lubricant is its *viscosity*. This is a measure of its ability to resist flow when a pressure is applied; greater viscosity means that the lubricant is "thicker" and resists deformations better.

Placed between bearing surfaces, a lubricant forms a thin film which holds the surfaces a (small) distance apart. The layer of lubricant can carry large loads in compression, but can also be easily sheared by a relative sliding motion between the parts, thus minimizing friction. The more viscous the lubricant, the greater the compressive load it can sustain before "bottoming out" (when the metals parts come in contact), but the more friction it causes under sliding motion. The ideal then, is to choose a lubricant that is no more viscous than is needed to support the compressive load between adjacent moving parts.

By this criterion, many bicycle manufacturers could be guilty of lube overkill; their chains, when shipped from the factory, are coated with some of the highest-viscosity lubricants imaginable. The heavy lubricant is surely effective at preventing chain wear, but it is far from the minimum-friction solution. In addition, this may mislead some riders into thinking that their chain never needs cleaning and relubrication.

Those who *do* clean their chains are usually motivated into action by the sight of grimy sludge building up after a few hundred miles of riding. Some wait until rasping noises from the chain become unbearable. A small virtuous minority, including chain manufacturers, insist on cleaning the chain at *fixed intervals*. For instance, the small print on the Sedis package suggests a cleaning every 300 miles, but gives not a hint as to *how*. What, then, is the best way to clean and relube a chain?

Choosing Your Poison

Soaking the dirty chain in Kerosene (or parts-degreaser solvent) is common. If done improperly, however, this may be worse than no cleaning at all. Kerosene provides a satisfying cosmetic removal of visible road grit, but also strips the heavy factory grease from the chain, including that inside the pins and rollers, where the stresses are highest. When you re-lube the chain, the lubricant may not totally penetrate into these crevices. And even if the new lube makes it into every crack, residual solvent may thin it (reduce its viscosity) excessively. At every hand, you are faced with the potential of a new wear problem in just a few miles of riding.

What to do in this grim situation? If you are not concerned with grease accumulations on your chain, the just wipe it down with a clean rag and lubricate it after every couple of rides. After a season or so or riding, throw the chain away and buy a new one.

The other approach is to soak the chain first in kerosene, then in a more volatile solvent like naptha (white gas). The latter solvent will remove kerosene residue, and will quickly evaporate from even the tightest cracks, thanks to its volatility. At all costs, avoid setting yourself on fire, since naptha is highly flammable. You might want to repeat both soaking steps to ensure that all dirt and grease is removed. Then the chain can be relubricated as usual.

Here are some additional points to consider. In the no-soak wipe-down approach, relubrication may be ineffective because small passages are likely to be clogged with old grease and road grit. Your lubricant of choice, then, should be one with *low viscosity*, such as WD-40 or LPS-1. This will act as a solvent, soften the heavy grease deposits, and maybe even reach those close-fitting, high-stress areas.

In the Kero/naptha double-soak approach, you should use a moderate to high viscosity lubricant. Heavy gear oil (about SAE 80 viscosity) or paraffin are ideal, provided they are heated first to reduce the viscosity. (Caution and good ventilation are appropriate when working with hot oil.) An alternative is to use LPS-3 or TRI-FLOW, which both become quite viscous once their volatile constituents have evaporated. Using the high viscous oil, and making sure it reaches every surface, will give you the longest-lasting lube job possible.

Which approach is best? I used to be a fan of fixed-interval cleaning. For several years I cleaned my chain regularly in kerosene and naptha, and relubricated it with excessive amounts of LPS-3—even when it (probably) didn't need it. I now perform the ritual only if I get stuck riding in the rain, or ride on unpaved roads, or find a really objectionable amount of grime on the chain. Otherwise, I just wipe it down every couple of rides, and give it a light lube.

To those who've put off cleaning the chain for too long, remember: your chain is not the only potential victim of grime. Aluminum chainrings and freewheels, rear derailleur pulleys, and both derailleur cages are made of far softer materials than your chain. Wouldn't it be an outrage if these expensive components were destroyed by a dirty $10 chain!

—Mario Emiliani

COMPONENTS

Overheating Brakes

Some Common Beliefs Don't Hold Up

Allan Williams

In many parts of the country, including central California where I live, there are steep hills which descend 500 to 2000 feet in the course of a few miles. Brake overheating is a serious problem on these hills, particularly for heavy riders and in warm temperatures. I have made a few calculations to see if there is an optimum speed of descent which would minimize brake heating.

To my surprise, I found just the opposite: there is a "worst case" speed at which brake heating is *maximized*, and this turns out to be slightly less than half of terminal speed (i.e., the speed you would reach by coasting freely with no braking).

This result is certainly contrary to the intuitive notion that "braking harder makes the brakes hotter"; some cyclists take this notion for granted, but it's just not true. My results show that braking at a *moderate* speed produces the most heat.

Furthermore, the slope of the hill is a critical factor: doubling the slope *more than doubles* the amount of heat that the brakes must dissipate to hold a constant speed.

I have to wonder if manufacturers take overheating into account in the design of their brakes. It seems that brake performance tests focus only on short-time panic stopping ability. If bicycle brakes had a large thermal capacity, or could dissipate the heat more effectively, then melted brake pads and tire blowouts would not happen. But I've experienced these problems often enough to know that poor heat dissipation is a weak point inherent in the design of rim brakes.

In this article, I show how to calculate the amount of heat produced by brakes under various conditions of speed, slope, and rider weight. This is just the starting point in trying to correct the problem. Experiments are still needed to find out *where the heat goes.* But we have to start somewhere.

A Matter of Gravity

The force which propels a bike down a hill is determined entirely by the slope of the hill and the weight of the rider. Consider this example: a bike and rider together weighing 170 lb are coasting down a 15% slope (a hill where the road surface falls $1^1/_2$ feet for each ten feet of horizontal distance).

The gravitational force which propels this bike and rider down the hill is equal to the slope times the total weight; in this example, 15% x 170 lb = 25.5 lb. This propelling force remains constant regardless of the rider's speed (assuming the slope remains constant).

If the rider simply coasts without braking, his speed will increase until the forces of air drag and rolling resistance sum to equal the propelling force (25.5 lb). At this point, the rider is in "free fall" and has reached what's called *terminal speed*. For any given set of conditions (slope, weight of bike plus rider, and rider's air drag characteristics), the terminal speed is uniquely determined.

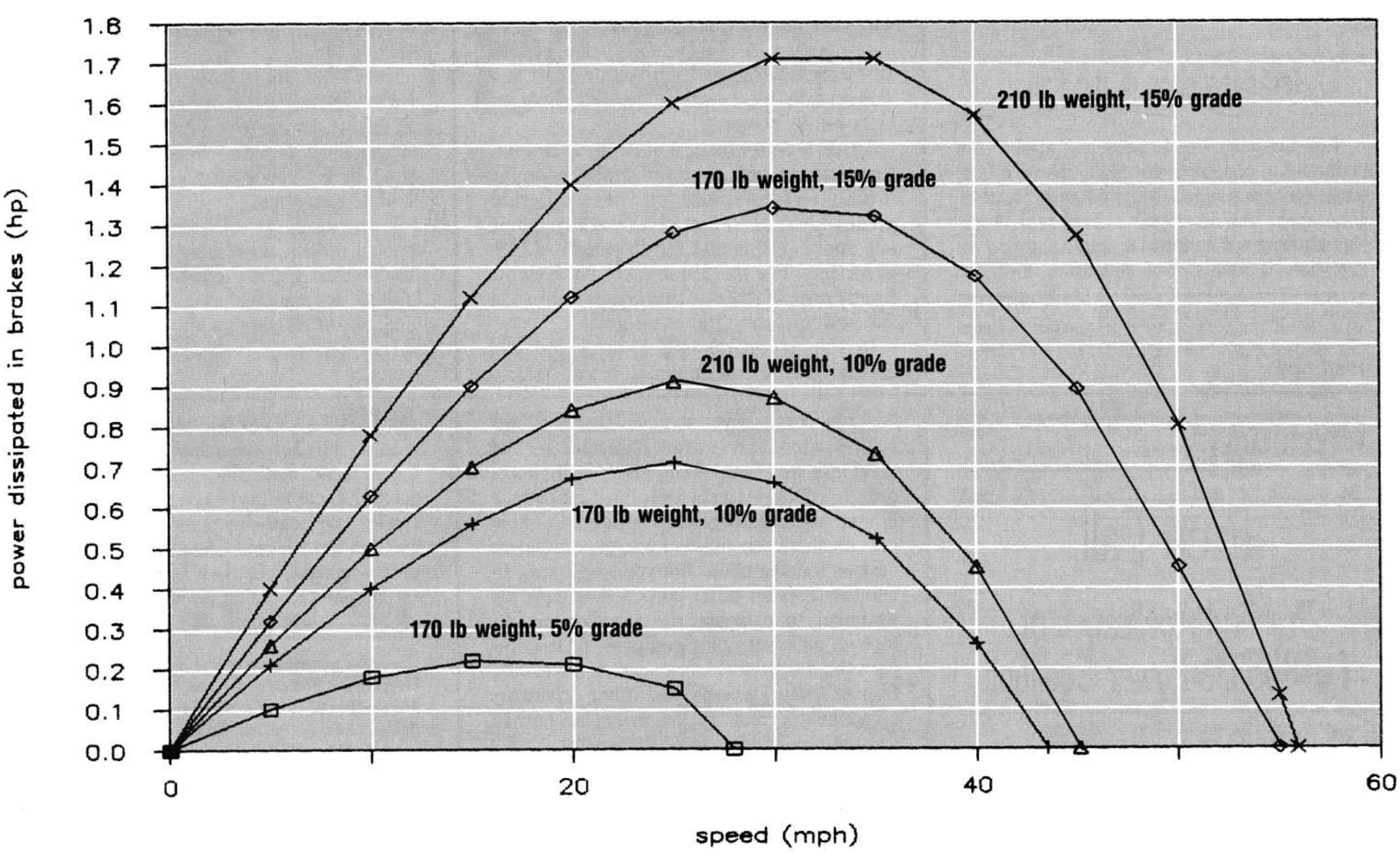
To calculate this terminal speed, I used simple formulas to express rolling resistance and air drag as functions of the rider's speed. A good approximation for rolling resistance force per pound of weight is given by (Ref. 1):

rolling resistance =

$$0.005 + 0.15/\text{tire inflation pressure (psi)} \quad \text{[Eq.1]}$$

[1] *F.R. Whitt, "A Note on the Estimation of the Energy Expenditure of Sporting Cyclists",* ***Ergonomics****, Vol. 14, 1971, pp. 419-424.*

Brake power as a function of speed maintained by rider on constant grades.



For the 170 lb bike and rider, with tires inflated to 100 psi, rolling resistance equals 1.1 lb. (In this formula, rolling resistance is independent of speed. Actually, rolling resistance increases slightly with speed - a factor to consider in conducting accurate tire tests, but something I neglect for the purposes here.)

Air resistance does vary with speed, according the aerodynamic formula (Ref. 2):

$$\text{air resistance} = 0.0023 \times \text{frontal area} \times \text{speed}^2 \quad \text{[Eq.2]}$$

If our sample bike/rider combination has a frontal area of 3.65 sq.ft., a typical value, then:

$$\text{air resistance} = 0.008395 \times \text{speed}^2 \quad \text{[Eq.3]}$$

Total resistance of the 170 lb coasting bike and rider, is the sum of rolling resistance plus air resistance:

$$\text{total resistance} = 1.1 + 0.008395 \times \text{speed}^2 \quad \text{[Eq.4]}$$

This equation may be rearranged to solve for speed, since the "total resistance" term is known:

$$\text{speed} = 10.91 \times (\text{Total resistance} - 1.1)^{1/2} \quad \text{[Eq.5]}$$

At terminal speed, "total resistance" equals propelling force (which is 25.5 lb for the sample 170 lb bike plus rider on the 15% grade). Plugging in this value to Eq. 5 shows that the rider will reach a snappy 53.9 mph terminal speed.

Incandescence of the Pad

Now suppose the brakes are applied to maintain a constant 45 mph. How much brake force is needed, and how much heat is generated? At 45 mph, rolling resistance plus air drag will sum to 18.1 lb, according to Equations 1 and 3. The propelling force is still 25.5 lb. So the stopping force, supplied by the brakes, must be 7.4 lb (25.5 - 18.1)

Brake power, the rate at which the brakes convert mechanical energy to heat, is computed as the stopping force multiplied by the speed of the bike:

$$\text{braking power} = \text{braking force} \times \text{speed} \quad \text{[Eq.6]}$$

In this instance, we have a braking force of 7.4 lb and a speed of 66 feet/sec (45 mph), giving a braking power of 488.4 ft-lb/sec. In other units, this equals 0.89 horsepower (1 hp = 550 ft-lb/sec) or 662 watts (1 watt = 1.3564 ft-lb/sec).

If the rider brakes more firmly to maintain 30 mph (44 ft/sec), then through similiar math, his total air drag plus rolling resistance is 8.7 lb and the braking force is 16.8 lb, with the result that braking power is 1.34 hp or 1003 watts. In other words, his brakes are putting out more heat than two 500-watt light bulbs, and no wonder they're hot!

Now, if he brakes even harder to maintain 20 mph (29.3 ft/sec), his air plus rolling resistance equal 4.5 lb, brake force is 21.0 lb, and brake power is 1.12 hp or 835 watts.

The important point is this: slowing down from 45 to 30 mph caused a big increase in brake heating (from 662 to 1003 watts), but slowing further to 20 mph caused a *decrease* in brake heat (to 835 watts).

Clearly, there is a maximum in heat production somewhere in the vicinity of 30 mph. The moral is: if your brakes are melting on a long grade (and you're already going too fast for comfort), then brake harder! It's true that your brakes will then have to convert a larger portion of energy to heat than before. However, this conversion will proceed at a *slower rate*; the result is, your brakes and rims will be cooler.

To get a better picture of all these factors, I generated a plot of power dissipated in the brakes *versus* speed for three different grades (5%, 10%, and 15%) and two different riders (170 lb and 210 lb weight of bike plus rider). For the 210 lb case, I assumed a frontal area of 4.2 sq ft (proportional to the 2/3 power of the ratio of weights).

In the accompanying figure, you can clearly see the maximum in brake heating which occurs at "moderate" speeds. Zero brake heating occurs at a minimum speed (zero mph, i.e., stopped) and a maxium speed (i.e., the terminal speed, with no brakes applied). Note also that doubling the slope, say from 5% to 10%, more than doubles the power dissipated in the brakes.

To Pump or To Jump

We all supposedly "know" that it is better to pump the brakes on a steep hill than to hold them on constantly. But why? Can the brake-heating analysis given here explain it? In fact, the equations above say that pumping makes *no difference* in the amount of heat dissipated in the brakes. This amount of heat is determined *entirely* by the rider's weight, the slope, and the average speed of descent. Whether this average results from a fluctuating speed (as in pumping the brakes), or a constant speed (as in riding the brakes) makes no difference in the average amount of brake heat generated.

Why, then, do many riders (myself included) think that pumping the brakes is better? The answer has much to do with details of the *cooling* process at the brake shoes, I believe. That is, even though the brakes generate the same total amount of heat energy, whether they're pumped or not, that heat may be *dissipated* better when the brakes are pumped. I could imagine that pumping the brakes will periodically expose the (hot) friction surfaces to a cooling air stream. But holding the brakes on constantly will not allow the cooling air to pass over the pads at all.

But to find out how the cooling process at the brake pads really works, a good empirical field test is needed. For instance, if most of the heat energy is conducted into the rims, then "cooling fins" for brake blocks would be pointless.

In any case, the analysis here tells us the amount of heat *input* which the brakes must handle. And we now understand better why braking to maintain moderate speed on a long, steep hill gets us into trouble, particularly if the rider is heavy and the day is warm.

[2] *F.R. Whitt and D.G. Wilson,* ***Bicycling Science*** *(Second edition), Cambridge, MA: The MIT Press, 1982, p. 92.*

PHYSIOLOGY

Free Fall

Practical Application of The Bicycle Power Equation

Robert L. Boysen

If you have access to a few unobstructed hills, you can do a variety of simple tests, basically coast-downs and uphill sprints, that will reveal some important characteristics of your bike and your riding style. I originally developed these tests in connection with a fitness training program: I wanted to know how much muscle power I was generating on various training rides. But you might want to use the tests for other purposes as well: for example, to compare the aerodynamic effects of different riding postures, or to compare the mechanical efficiencies of novel bike transmissions, wheels, and other drivetrain components. Here, I'll simply explain how to run the tests and analyze the results.

To keep procedures as manageable as possible, you need to make some simplifying assumptions. The full-blown bicycle power equation[1] shows that at least *twelve* independent variables must be measured if the goal is to account for every last watt of power in the system. Such fine detail is needed, of course, in certain types of research. For example, the coast-down methods developed by Glen Brown[2] and Chester Kyle[3] are both very accurate, but they require specialized equipment such as an on-board accelerome-

[1] *The complete power equation for the bicycle is given on page 157 of* Bicycling Science, *by F. R. Whitt and D. G. Wilson, (MIT Press, 1982, second edition). Practical applications of it are mentioned in "The True Hour Record Holder . . . Is Bracke!," by Claude Genzling,* Bike Tech, *Vol. 3 No. 4, August 1984, pp 1-5.*

[2] *"Testing for Aerodynamic Drag: A New Method," by Crispin Mount Miller,* Bike Tech, *Vol. 1 No. 4, December 1982, pp. 1-3.*

[3] *"Rolling Resistance: A Bicycle Tire Test Reveals the Big Secret," by Chester R. Kyle,* Bicycling, *May 1985, pp. 140-152.*

ter or a computer. As a recreational rider without such equipment, I am more interested in how my routine measurements of overall elapsed time and distance might yield, under careful analysis, insight into the sources and uses of the rider's muscle power.

Sinks and Sources

In most common cycling conditions, the greatest proportion of power by far is consumed by **wind resistance**. In equation form, we can say $P_{wind} = K \times V^3$, meaning that power consumed by wind resistance is proportional to the rider's velocity cubed. The proportionality constant K expresses the overall aerodynamic properties of the bike and rider taken together as a system.[4] Because of its importance, the constant K must be known or measured for any meaningful analysis to proceed.

In fact, this is the purpose of the coast-down tests described below. By measuring the speeds reached during a "free-fall" of known elevation, you can easily determine the value of K that pertains to your own case. To minimize random fluctuations, I usually work with velocities averaged over a distance of at least one mile. For this purpose, distance is determined by a cyclometer on the bike, and elapsed time is measured by a stop watch.

Power consumed in **climbing hills** is the second most important factor to consider. This quantity is equal to the weight being raised (rider plus bike plus equipment) times the rate of ascent: $P_{ascent} = W \times A$. Weight W is easy to measure on a common household scale. Rate of ascent A is found by knowing the starting and ending elevations for each leg of the course, and the elapsed

[4]*Editor's note: Boysen's constant K is seen to be the product of frontal area, a (dimensionless) drag coefficient, and air density, per comparison with sources given in footnote 1. The product of just the frontal area and the drag coefficient is termed "effective frontal area."*

Figure 1: Free fall data from three test runs.

Route	Grade (%)	(E) Change in Elevation (ft)	(L) Distance (miles)	(T) Time (min)	(D = E/T) Rate of Descent (ft/min)	(V = L/T) Avg. Speed (mph)	Constant $K = W \times D/V^3$
1. Cokesbury Rd.	-5.0	340	1.3	3.1	110	25.2	1.48
2. Guinea Hollow Rd.	-3.4	250	1.4	3.9	64	21.5	1.38
3. Water St.	-2.3	180	1.5	5.5	33	16.4	1.61

Total weight (rider and bicycle): W = 215 lb. **Average K = 1.49**

Figure 2: Plot of free fall data from Figure 1

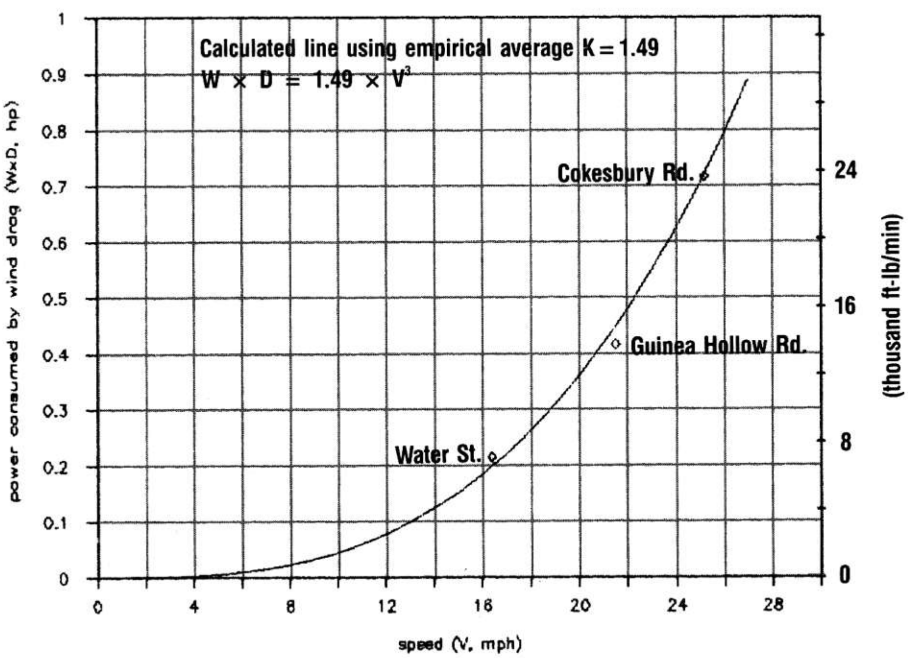


Figure 3: Uphill Sprint Data (Total weight W = 215 lb.) **Conversion factor: (ft-lb/min)/33,000 = (hp)**

Route	Grade (%)	Change in Elevation (ft)	Distance (miles)	Time (min)	A Ascent Rate (ft./min)	V Speed (mph)	W × A Ascent Power (ft-lb/min)	$1.49 \times V^3$ Wind Power (ft-lb/min)	Pedaling Power $W \times A + 1.49 \times V^3$ (ft-lb/min)	(hp)
Philhower Rd.	6.92	420	1.15	9.00	46.67	7.7	10,033	671	10,704	0.32
Guinea Hollow	3.38	250	1.40	7.25	34.48	11.6	7,414	2317	9,731	0.29

Figure 4: Longer Trip Data (Total weight W = 215 lb.) **Conversion factor: (ft-lb/min)/33,000 = (hp)**

Route	Change in Elevation (ft)	Distance (miles)	Time (min)	A or D Rate (+ or -) (ft/min)	V Speed (mph)	A or D Power (+ or -) (ft-lb/min)	$1.49 \times V^3$ Wind Power (ft-lb/min)	Pedaling Power $W \times A + 1.49 \times V^3$ (ft-lb/min)	(hp)
Califon to Bound Brook	-750	25	80	-9.375	18.75	-2,015	9,822	7,806	0.24
Bound Brook to Califon	+750	25	100	+7.500	15.00	+1,613	5,029	6,692	0.20
Califon to Bridgewater	-700	16	50	-14.000	19.20	-3,010	10,546	7,536	0.23

time required to cover the course. (See Table 2 for a sample calculation.) I use USGS topographic maps to determine elevations.

Other **dissipative forces** also consume power: tire rolling resistance, drivetrain friction, and energy lost through flexing of various parts of the bike (frame, crankset, etc.) may all be lumped together as "dissipation." I will leave these forces out of the calculations because, under typical road-riding conditions, they consume much less power than either wind resistance or ascent of hills.

The major *sources* of mechanical power in cycling are **pedaling** and **descending hills**. The power gained in a descent is exactly the same as that used in an ascent; thus, $P_{descent} = W \times D$, where D is the rate of descent. The power generated by pedaling, P_{pedal}, is the quantity we are trying to determine.

When the amount of power added to the bike/rider system equals the amount of power consumed, then the bike will move at a constant speed, neither accelerating nor decelerating. This is expressed in the law of conservation of energy:

$$P_{pedal} + P_{descent} = P_{wind} + P_{ascent},$$

where the sources on the left side are balanced by the sinks on the right. Solving for P_{pedal} gives:

$$P_{pedal} = K \times V^3 + W \times A - W \times D \quad [1]$$

We can now set up the coast-down tests.

The Wind Resistance Constant

Each combination of rider and bicycle has its own constant of wind resistance because each presents a different size and shape to the wind. To find the constant of proportionality (K) for your own specific case, you will need time and distance measurements from several coast-down runs in free-fall conditions. When you are in free-fall, Equation [1] becomes very simple. In free-fall, you are not pedaling, so $P_{pedal} = 0$. Also, you are not ascending a hill, so $A = 0$. This reduces equation [1] to:

$$0 = K \times V^3 - W \times D,$$

which is easily solved:

$$K = W \times D / V^3 \quad [2]$$

Some care is needed to collect reliable data. Here are the points I consider important:

—The hills you choose should be 1 to 5 miles long and as straight as possible. Be certain that the course requires no braking or pedaling anywhere along the route. Grades in the range of 1% to 6% should work well. Make some dry runs to become familiar with traffic hazards that could develop during a test.

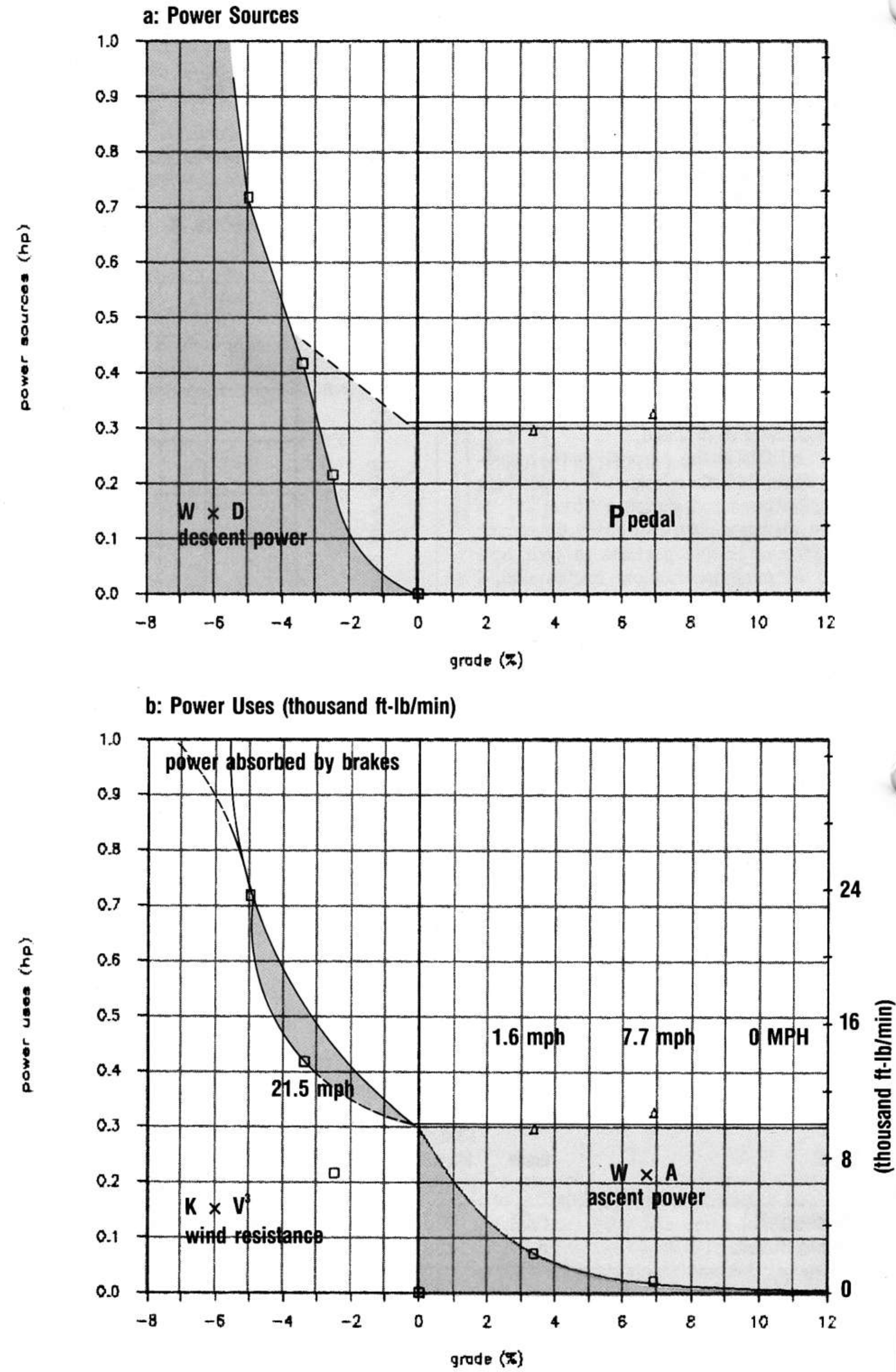
—The test hills should have as *constant* a slope as possible, to minimize acceleration/deceleration during the runs. You can check this on the topographic maps by looking for *equal* spacing between the elevation contour lines over the entire route.

—At least two, and preferably three to five, different hills should be used for collecting data, and the results averaged as discussed below. Several trial runs on each hill are also desirable.

—Hold a constant riding posture during each trial.

—Start each run at about the same speed as the average speed you will attain during the run. Go through the starting point at that speed and then stop pedaling. This minimizes acceleration during the run, which the equations given here neglect.

Figure 5: Sources and Uses of Power in Uphill Sprints and Free Fall Tests



—Choose as smooth a road as possible to minimize rolling friction.

—Be sure the wind is either very light or across your direction of travel. Since wind resistance is a major consumer of power, significant head- or tailwinds will substantially affect your results.

Figure 1 summarizes the data I gathered on three different free-fall courses in Hunterdon County, New Jersey, and shows how the analysis is carried out. The actual measurements are listed first: change in elevation (E), distance covered (L), and elapsed time (T). The three calculated values of K are nearly equal; a good sign. I obtained the final result, K = 1.49, by averaging these three values together.[5,6]

Figure 2 shows the theoretical curve relating velocity to power consumed by wind resistance, based on my empirical value of K. The three data points fall very close to the curve. You can test the accuracy of your data similarly.

Pedaling Power

Knowing your personal wind speed constant, you can determine the power you apply to the pedals in other riding conditions. Here again, measurements of only time, distance, and starting/ending elevations are needed. To illustrate how, Figures 3 and 4 list data that I have collected on my own uphill sprints and longer distance trips. On a five- to ten-minute sprint, my output is about 1/3 hp, while in longer distance runs, my output is about 1/4 hp. That these results are fairly constant over several trial runs, with my subjective level of effort about the same in each, suggests that the method of analysis is acceptably accurate for training purposes.

Figures 5a and 5b combine all of the sprint and free-fall data into one graph to compare the sources and uses of power in various up- and down-grade conditions. Note that at greater than about nine percent up-slope, the lack of low enough gears on my bicycle make it almost impossible to continue riding. Thus, there is a drastic drop-off in power source and use. At down-grades of more than about six percent, my speed exceeds 40 mph and I worry more about crashing than about collecting data, and start consuming some of the available power in my brakes.

[5] *Editor's note: Because the value of K depends on the* cube *of V, the estimate of K is very sensitive to errors in measuring V. Thus the arithmetic mean given in Table 1 may not be appropriate for averaging the estimates of K. The least squares criterion for estimation is satisfied by the geometric mean (the nth root of the product of n data points). For the data of Table 1, the arithmetic mean and the geometric mean produce the same estimate of K; this may be a lucky consequence of the fact that the velocity covers a fairly narrow range (less than 2 to 1). If a wider range of velocity were analyzed, say 5 to 1, then the geometric mean would be called for.*

[6] *Editor's note: Boysen's data from Table 1 (K=1.49) yields a value of 3.09 ft^2 for effective frontal area; see footnote 4. This value is roughly 25% smaller than the values measured by Genzling (3.875 ft^2, footnote 1) and by Brown (3.74 to 4.24 ft, footnote 2), all of which apply to a conventional bike plus rider.*

IDEAS & OPINIONS

Bike Headlights Revisited

To the Editor:

The recent articles in *Bike Tech* (Winter 1985) and *Bicycling* magazine (July 1985) on bicycle lights will assist me and other makers of bicycle lights to improve our products. Your measurements appear reasonably accurate, but there are some minor errors that should be corrected:

—Your comparison with car headlights may be misleading. The *Bike Tech* article (page 7) says that the wattage rating of the 50-watt GE #7610 bulb which I use in my headlights equals that of "a small car headlight." True, 50 watts compares favorably with the 37.5 to 75.0 watt lamps used in all motor vehicles, large or small. But the *candlepower rating* for the #7610 is considerably *lower* than motor vehicle headlights.

—The *Bike Tech* article does not list the fact that I offer systems using *ni-cad* batteries as well as lead-acid cells.

—Batteries are not necessarily heavy, and do not need to be taken off the bicycle for recharging, contrary to the statement in *Bike Tech* (page 8). My 1.2 amp-hour ni-cad battery weighs little more than a generator. And I have not removed the battery from my own bike headlight in more than six months, even though I use it daily.

I started manufacturing bicycle headlights because I found, during the winter of 1973-74, that lights sold in bicycle stores did not enable me to see the roadway ahead, nor could I see a pedestrian 20 feet in front of me. The lights also performed poorly in terms of other people seeing me. My approach has always been to use the best lighting technology available in terms of rechargeable batteries, headlamps and taillights.

One problem is that there are no government-sponsored standards for bicycle headlights in the United States. Two states (Pennsylvania and D.C.) have laws authorizing such standards, but they have never been developed. An old standard of the BMA (Bicycle Manufacturers Association) did specify that a bicycle headlight should illuminate a substantial object 50 feet ahead, and suggested that the object be a common brick.

Edward F. Kearney,
Bicycle Lighting Systems,
Falls Church, VA

Dave Sellers replies: All headlights mentioned in the Bike Tech *report which were* factory-supplied *with rechargeable batteries* do *include provision for recharging without removing the batteries from the bike. These systems include an electrical connector somewhere in the wiring, to which the battery charger is temporarily connected. You then must park your bike close to an AC power outlet, so the charger can be plugged in. On the other hand,* any *headlight (or taillight) which accepts standard-size batteries (i.e., D-cells or C-cells) will work with rechargeables (usually ni-cads) of the proper size. In these cases, there is no on-board provision for recharging, and the batteries must be removed for a fill-up.*

Whose Gauge do You Believe?

To the Editor:

The virtues of low rolling resistance have been extolled recently in *Bike Tech* and *Bicycling* articles. Tire manufacturers (Avocet, Specialized, Michelin...) are advertising tires with new materials, and the rolling resistance of some clinchers may be as good as the best sew-ups.

But without an accurate tire pressure gauge, there is no way to really benefit from these new designs. Underinflated tires substantially increase rolling resistance. And overinflated ones increase the chance of a flat.

The gauge on my tire pump reads 92 psi, and my other two gauges read 82 and 75 PSI respectively. I could purchase an industrial gauge with certified accuracy for about $50, and connect it into the pump's hose for correct readings. But this still won't help me when I need to reinflate a tire on the road.

Can anyone provide information on the accuracy of commonly available pressure gauges? What is the best gauge for on-road use?

Michael S. Lasky
Brooklyn, NY

Purloined Letters

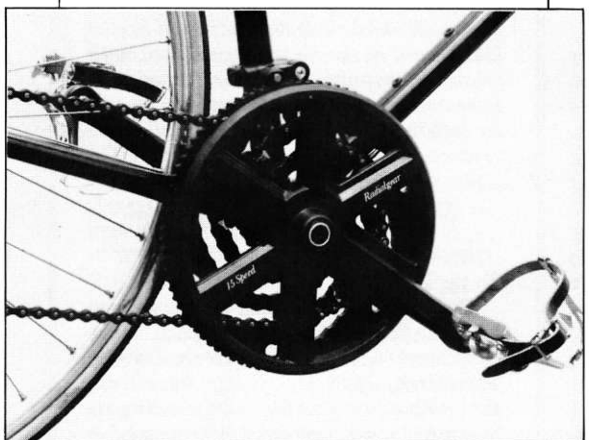
To the Editor,

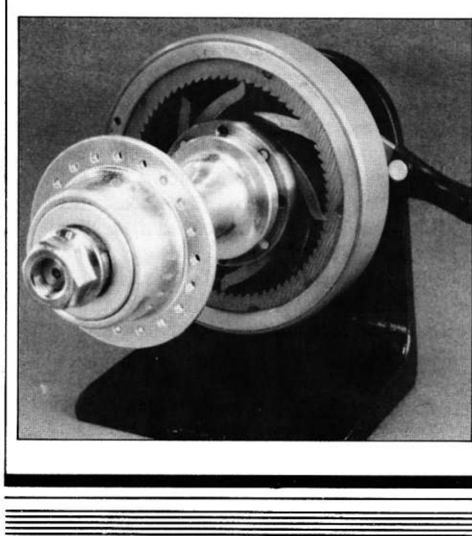
I was surprised at the response to the article on my bicycle frame drafting computer program "BIKEDRAW" in the Fall 1985 *Bike Tech*. I received over 60 letters asking for copies of the program, and I have answered most of these.

But since I have moved to Texas recently, my home was burglarized, and a few *unanswered* letters were stolen! I seriously doubt that the individuals who robbed me will reply to these letters...

To those who wrote and received no reply, I will gladly send a copy of my program, if they will *re-write* to me at the new address:
Mike Cambron
Mike Cambron Cycles
1903 Place Rebecca Lane #9
Houston, TX 77090

newsline





"RADIALGEAR" 15-SPEED TRANSMISSION NOW IN PRODUCTION ON HUFFY BIKES: The Radialgear transmission, invented by engineer Royce Husted, is one of the few non-derailleur drives to be adopted by a high-volume bike manufacturer. Huffy Corporation recently purchased marketing rights for one year to the Radialgear design, after conducting three years of technical evaluations and six months of market tests.

The Radialgear system has only 11 separate parts, compared to more than 100 in conventional derailleur systems, and it requires no lubrication other than an occasional water-wash with the garden hose. The system is so simple that, in the Huffy manual, an 8-page section on derailleur maintainence was eliminated by the 2-page section on Radialgear.

◀ Mechanically, Radialgear is a refined version of an old idea: the front sprocket is comprised of a number of planetary gear segments (six, in this case), each of which moves radially inward or outward to change the gear ratio (see accompanying photos). Each gear segment, or sprocket, slides in a spiral-shaped groove in the drive plate. Fifteen detents molded into the drive plate provide fixed stopping points for the sliding sprockets. To shift, the rider presses a thumb-lever on the handlebars, which frees the sprockets to slide in their grooves, and then simply pedals forward (to upshift) or backward (to downshift).

The essential new ingredient which makes this design workable is a high-modulus thermoplastic, DuPont "Rynite." This 55% glass-filled polyester material is used in all major components except the sprocket carriers, which are glass-filled "Zytel" nylon. The only metal parts are the sprocket teeth (hardened steel) and an aluminum insert where the drive plate mates with the crank axle.

The main drive unit weighs about the same as a good quality aluminum alloy chainwheel/spider/crankarm assembly. But inventor Husted says that a major weight reduction is possible, because the rear derailleur and freewheel cluster can be eliminated. (A BMX-style spring-loaded chain tensioner is needed, though.) Radialgear covers a range of 24T to 54T at the chainwheel; this, combined with a 14T single-sprocket rear axle, gives a range of about 46 to 104 gear-inches, adequate for many riders. City bikers and ATB'ers could add a two-speed rear hub for greater range.

◀ How much weight is saved? Husted told us that a Miyata racing bike shed about 8 ounces after conversion to Radialgear, and the Huffy "Easy-Shifter" bike weighs 2 pounds less than if steel drivetrain components had been used.

Does Radialgear represent a head-on challenge to conventional derailleur systems? Certainly, but it may take a while to catch on. If the system proves its worth in the Huffy low-market application, get ready to say goodby to your trusty old pantograph. For more information, contact Saroy Engineering, PO Box 615, Lisle, IL 60532 (312-971-8888).

BRIDGESTONE UNVEILS STEPLESS REAR TRANSMISSION: A prototype ratchet-drive transmission, built directly into a sealed rear hub, was displayed by Bridgestone Cycles at the Long Beach (CA) Bike Show in January. The unit (see drawings and photo at left) works as follows: power is transmitted from the chain to the outermost "ratchet drive ring." Two sets of four pawls which engage on this ring then transmit the motion to a "pawl ring" which is fixed to the rear axle. Variations in speed are achieved by an eccentric mechanism which varies the offset of the pawl ring with respect to the drive ring. The lowest gear ratio possible with the unit, 1 to 1, occurs when the center of the pawl ring coincides with that of the drive ring; see "Low Speed" illustration. Higher gears are achieved by increasing the eccentricity (i.e., moving the centers of the two rings further apart); see "High Speed" illustration.

Bridgestone's stepless front transmission, announced in October 1984 (see *Bike Tech*, April 1985, p. 16), also uses a ratchet-and-pawl eccentric mechanism. Bridgestone says the rear transmission will be available in spring 1986, as a component on their new model MB-3 bicycle. For further information, contact Bridgestone Cycle USA, Richard Nazario (Sales), 15061 Wicks Blvd., San Leandro, CA 94577 (800-847-5913). ▼