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BIKE TECH

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DESIGN CRITERIA

The Aluminum Rim: Design and Function

Chris Juden

Editor's note: Chris Juden was, until recently, the Design Engineer for Mistral Rims, which is a division of TI Sturmey Archer Ltd. Mistral rims are fairly new in the marketplace and, unfortunately, are not readily available at the retail level in America.

Mr. Juden presents some illustrative data on the relative strength and rigidity of a handful of popular clincher rims. He subjects these rims to a radial load (in effect, squashing them) and measures deflection. But a good wheel rim must be resistant to lateral loads as well. He is preparing a test jig for lateral and torsional loading of rims and hopes to present comparative results in a future issue of Bike Tech.

Any choice to be made in the selection of high-pressure wheel rims used to be simply one of materials: steel or aluminum. Today, however, the various advantages of aluminum alloy as a structural material are widely appreciated, and a cyclist must choose among a proliferation of rim designs. Many cyclists select rims on the strength of anecdotal evidence which asserts that a certain brand is "strong" or "rigid," terms easily confused and rarely quantified. This article discusses the important and sometimes conflicting features common to all rims and considers the pros and cons of different rim designs.

Tires and Rims

A logical approach to wheel design is to start at the ground and work up. After considering the bicycle's frame size and riding conditions, such as terrain, speed, supported weight, and achievable tire pressure, the appropriate class and width of tire is chosen. This decision in turn dictates rim diameter and width. The diameter inside the tire bead must match the rim's bead seat diameter, but this is the only measurement which

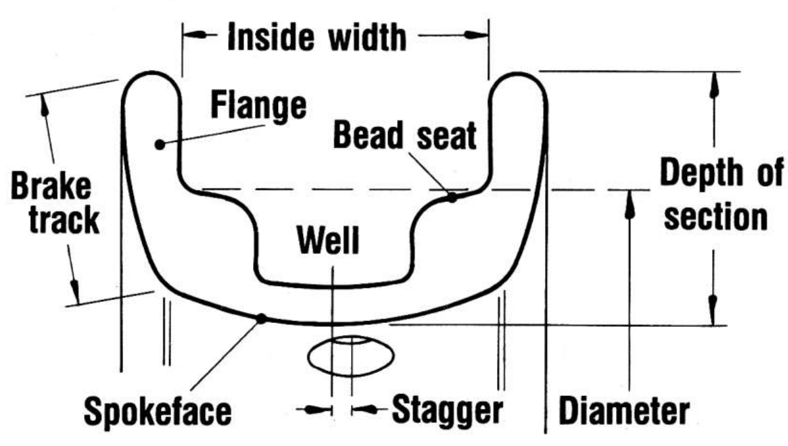

Figure 1: Rim Anatomy

Juden

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tire and rim have in common. Compatible widths of tire and rim must be matched through careful selection.

The European Tire and Rim Technical Organization (ETRTO) specifies the width and diameter of tires and rims by a standardized code. For instance, a tire coded 28-622 means it is 28 millimeters wide and has a bead diameter of 622 millimeters. Rims are designated similarly, but with one important difference: the first number is the measure of the rim's inside width. Suitable tire/rim compatability requires that the tire's width be somewhere between 1½ to 2 times the designated rim width. For example, a 28-622 tire is a good fit on a 16-622 rim.[1]

Tires are not made to the same tolerance as rims so it is possible to follow ETRTO recommendations and have problems mounting the tire to rim. Troubles can occur if the tire is too small—the tire bead may not seat correctly. Spoke tension can reduce a rim's diameter by up to 0.3 millimeters; mounting a slightly oversized tire may create a diameter mismatch large enough to cause the tire to blow off the rim under high pressure. Since tire manufacturing tolerances are wide, these mismatches can usually be solved by choosing another tire of the same type.

Rim Design Criteria

ETRTO makes recommendations for much of a rim's design—it specifies that the rim diameter be held to a tolerance of ±0.3 millimeters, for instance—but there is considerable latitude in executing these recommendations, as evidenced by the variety of cross-sectional shapes shown in Table 1. Figure 1 depicts a hypothetical cross section with design features shared by all rims.

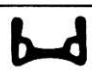
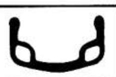
A high rim *flange* helps the tire settle onto the rim and not blow off when inflated. Too high a flange can make it difficult to get the tire bead over and seated on the *bead seat,* but a deep *well* facilitates tire installation by allowing the tire bead to drop into it while working the rest of the bead over the flange. The well also allows extra room for the inner tube to inflate. A typical well-depth dimension is flange height minus two millimeters. The profile of this part of the rim is important: the transition between the bead seat and the well should be smooth and gently radiused so that the inflated inner tube does not chafe against a sharp edge.

Room can get tight in shallow rims when the rim tape and spoke nipples are in place, so spoke nipples are sometimes recessed into the rim, either in sockets or dimples. Many tubular and narrow section clincher rims have sockets; it is common to dimple the wide, shallow rims used in BMX and off-road riding. It is important not to make the rim well too deep because the inner tube may have to stretch too far to fill the space, thus becoming weak and prone to puncture.

The *flange tip* is the point where the tire transmits applied loads to the rim. Here the tire is continually flexing, so a well-radiused tip, at least 1.5 millimeters where the tire touches, is vital to avoid chafing.

Folding tire rims, which have hooked

TABLE 1 Comparative Rim Data

Rim	Section	Inside Width (mm)	Weight of 700C	Strength M_S (Nm)	Rigidity EI_R (Nm^2)
Rigida 1320		13	434	43	92
Mistral 113		13	456	43	80
Mavic G40 (E2)		13	420	41	65
Weinmann A124		14	514	46	89
Mavic Mod. 3		15	503	55	85
Rigida 1622		16	527	62	98
Sup. Champ. Mod. 58		16	533	57	94
Weinmann A129		16	569	52	94
Mistral 217		17	498	55	89
Weinmann 256		17	531	41	64
Mavic Mod. 4		19	559	61	92
Mistral 120		20	579	63	113

Catherine L. Schwartz

[1] *If only it were that simple. Matching tires to rims can still be perplexing because, while most tires imported into America today have ETRTO dimensions, most rims do not. Also, many American suppliers and retailers list rim width by outside dimension, which is unfortunate because tires should be matched with a rim's inside width. For a comprehensive discussion of rim and tire compatibilities, see John S. Allen's series of articles on the February 1982, June 1982, and June 1983 issues of* Bike Tech.

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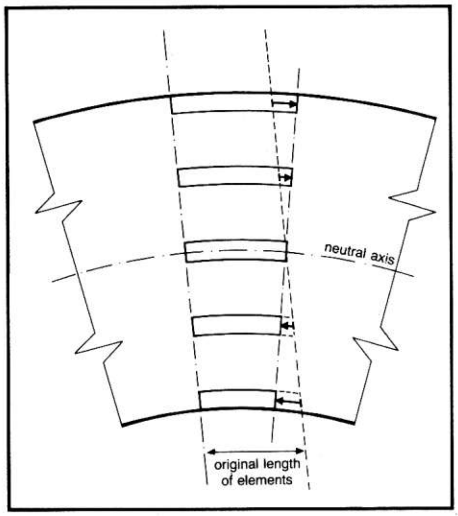
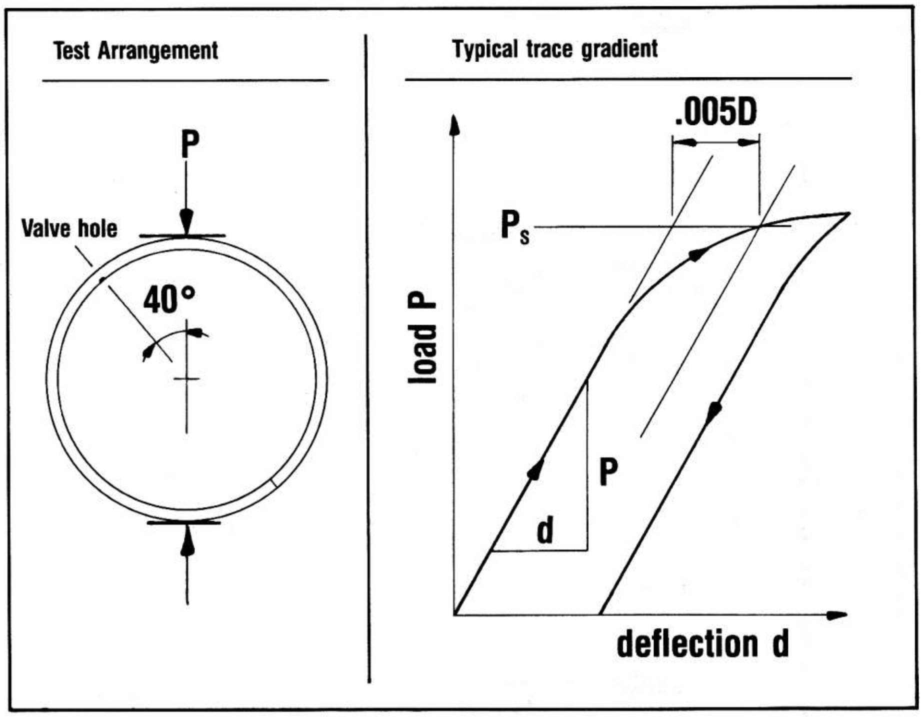


George Retseck

Figure 2: The neutral axis is a position of no deformation in a structure. Restoring forces within material are zero on the neutral axis, but increase in magnitude in direct proportion to distance away from axis. (See footnote 3.)



Chris Juden

Figure 3: Diametrical load application on test rim yields typical load/deflection trace.

flanges to retain the flexible fiber bead,are an exception. The hooks are always sharply radiused, so only tires specifically designed for these rims should be used on them. (See John S. Allen's article on this subject in June 1982 issue of *Bike Tech.*)

Brake tracks should be deep for an easy brake adjustment and not too thin, or the heat from braking can damage the inner tube. Parallel sides are safer than angled ones; they reduce the tendency of the brakes to grab if the wheel is damaged.

Spoke Attachment

A two-millimeter-thick *spokeface* can support spoke nipples without reinforcement, but eyelets are generally used to reduce friction. Tests show that more than twice the torque is needed to tighten spokes in aluminum rims compared to steel. Thinner rims should be reinforced, usually with eyelets or washers. Generally rims with wall thickness of one-millimeter or less are box sections or tubular sections with bell washers or double eyelets installed to share loads with the top surface.

Surprisingly, the traditional spokehole *stagger* or offset has little use, as tests of wheels built with "wrong way stagger" have shown. Indeed, auto wheels have been designed this way to resist side loads. If the spokeface is very curved or dimpled, it may be beneficial to orient the hole in the spoke direction, but in modern narrow rims any vestigial stagger is solely decorative.

Most aluminum rims are roll formed and their ends then connected with steel pins or plates forced into the hollows, making a strong, precise joint. A belief that these non-welded joints are prone to separate is unfounded, because a wheelful of well-tensioned spokes pulls the rim into compression with a force of up to one-half ton. Any problems with joint separation would be due to poor building or severe damage.

Mechanical Properties

Engineering analysis has shown that high, even spoke tension contributes most to the wheel's reliability. A well-built wheel is a strong wheel, capable of carrying high loads before losing spoke tension. Once spoke tension is lost, the wheel is in great danger of damage because the rim itself can offer little resistance to bending. But a rigid rim helps a wheel's strength by distributing the load over more spokes; with more spokes bearing the load, there is less chance that one spoke will become slack. Also, by resisting bending, a rim reduces spoke tension changes, which lowers the severity of fatigue cycling and hence reduces spoke breakage.

A rim's radial rigidity[2] is determined by the depth of the rim's section. The most rigid rims have a deep section, which means that most of the material is distributed at the top and bottom of the rim section, with little material near the neutral axis.[3] Sideways, or

[2] *Radial rigidity of a wheel rim is a measure of how much a rim deforms out of a circular shape when a given radial load is applied. This resistance to bending out-of-round is a function of the aluminum's modulus of elasticity (determined by the aluminum's atomic structure), the mass of aluminum in the rim, and how the aluminum is distributed in the rim's cross section. See also footnote 3.*

[3] *The neutral axis is a location within a structure where no deformation, or strain, of the material will occur when a load is applied. For a simple cross section with uniformly distributed mass, such as a cylindrical rod, the neutral axis runs through the middle of the rod.*

In more complex cross sections, the neutral axis may not be centrally located. In a wheel rim, the neutral axis lies in a plane that intersects the rim flanges just below the bead seats.

All the material in tension or compression counteracts the bending load with restoring forces. Since no strain occurs on the neutral axis, none of the material located there can help pull the structure back into its no-load shape. The size and effectiveness of these internal restoring forces depends on how the material is distributed off the neutral axis. The further away the material is from the neutral axis, the more effective it is in resisting bending. Therefore, to maximize a structure's rigidity while keeping the structure light, it's important to place as much of the structure's material as far away from the neutral axis as possible. This is why hollow tubing has a better rigidity-to-weight ratio than solid rods. For a more complete discussion of material rigidity, see Crispin Miller's article in the August 1982 issue of Bike Tech.

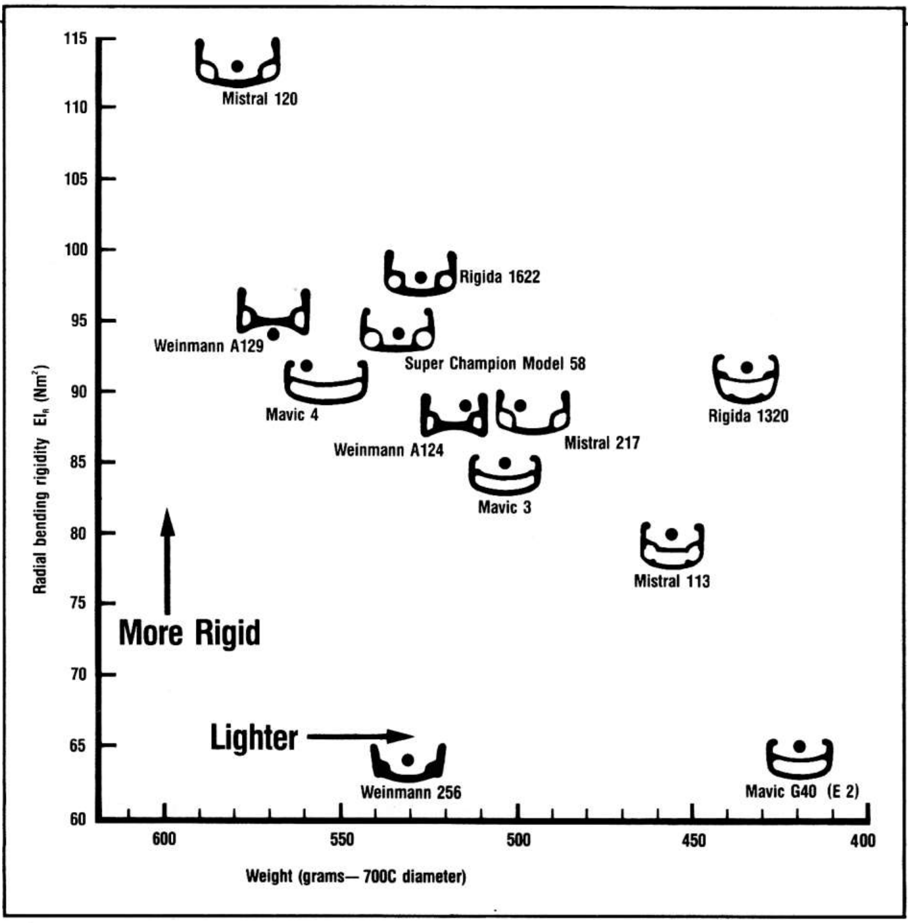


Figure 4: Rigidity vs. weight

lateral rigidity, is determined by the width of the rim. The majority of a wheel's lateral strength comes from the bracing angle and tension of the spokes, but a wide rim will be more rigid than a narrow rim and will, therefore, be more resistant to sideways deflections.

Design Advantages

Aluminum is the material of choice for wheel rims because of its good strength-to-weight ratio. An aluminum rim with all the qualities of a useful rim—high flanges, a deep well, wide brake tracks, a deep cross-section, and a thick spokeface—will be much lighter than a comparative steel rim. Lightening up a steel rim to match the weight of an aluminum rim would necessitate making its walls too thin to support the spoke's compressive forces and the heat and wear of braking.

Still stronger rims can be made from one of the heat treatable aluminum alloys. If done correctly, heat treating can increase the yield strength and the ductility of the aluminum, which makes the rim more resistant to bending and cracking.

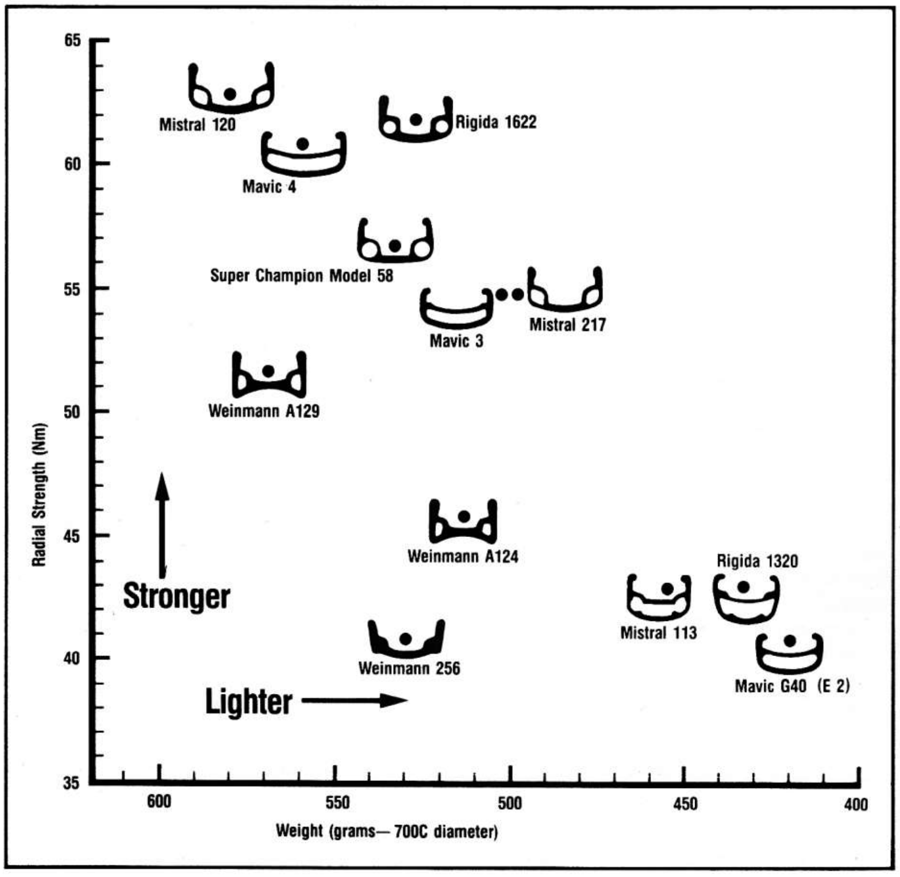
Aluminum is also fairly resistant to weathering. It will corrode if left unprotected, but the corrosion will not cause any structural damage, unlike the ruinous effects of rust on unprotected steel. The corrosion protection and finish of aluminum can be enhanced by the anodization process. This controlled corrosion of aluminum adds a protective layer onto the rim which can be dyed various colors. (Editor's note: Interestingly, a hard anodized layer increases the rim's modulus of elasticity, which makes the rim more rigid. See Mario Emiliani's sidebar "Anodized Rims are More Rigid," for details.)

The Tests

High-pressure rims are produced from extrusions, so their actual weight and rigidity will vary by as much as ten percent as the extrusion die wears. Testing large numbers of rims would have been prohibitively expensive so the values given are typical rather than averages.

The data were prepared from whole rim diametrical compression tests (squashing them!) on an Inston machine at Trent Polytechnic, Nottingham, under the supervision of Mr. W. F. C. Fisher. Figure 3 shows a typical load/deflection trace. Most of the rims tested were 700C; the weights of 27 × 1¼ samples were adjusted in proportion to diameter.

Figure 5: Strength vs. weight



George Retseck

A simple formula involving the rim diameter D relates radial rigidity EI_R to the trace gradient, P/d:

$$EI_R = D^3 \frac{P}{d} \frac{(\pi^2-8)}{32\pi}$$

where E is the modulus of elasticity, I_R is the rim's moment of inertia, D is the rim's ETRTO diameter, P is the load, and d is the amount of rim deflection measured under the load. To avoid the weakened area around the valve hole, the rims were positioned in the Inston machine so that their valve holes were located 40 degrees from the loading point, corresponding to a position of zero bending.

A measure of the rim's strength was obtained from the same trace by calculating the bending moment M_S at the load P_S which produces a 0.5 percent reduction in diameter of the whole rim, in excess of linear elastic deflection:

$$M_S = \frac{P_S\ D}{2\pi}$$

Table 1 tabulates the values for strength and rigidity of the test rims. Figures 4 and 5 graph these values compared to the weights of the rims.

The information contained in this article appeared in an abbreviated form in the British journal Cycle Trader *in the January 1983 issue.*

DESIGN CRITERIA

Anodized Rims are More Rigid

Mario Emiliani

Chris Juden's article explains how a rim's cross-section can affect its rigidity, but there is another factor to consider. Many of the clincher rims made today are available with hard anodized surface finishes. These rims are different from ordinary rims in that a thick layer of aluminum oxide covers all surfaces of the rim. Since the modulus of elasticity (or stiffness, as it is sometimes called) of this oxide is about five times greater than the aluminum to which it is attached, the overall stiffness of the rim is increased. The precise amount can be calculated as follows.

We'll assume the wall thickness of the rim is a constant 0.0394 inches (1 millimeter), and that the thickness of the oxide layer is 1.023×10^{-3} inches (0.026 millimeters). (These dimensions were taken from one of the anodized rims in my article on rims in the October 1983 issue of *Bike Tech.*) This situation is shown in Figure 1.

The equation to calculate the increased stiffness is:

$$\delta = \frac{PL}{AE}$$

where δ = elongation, P = load, L = length, A = cross-sectional area, and E = modulus of elasticity.

The cross-sectional area of the aluminum (cross-hatched) and oxide (shaded) is 0.0372 inches^2 and 2.12×10^{-3} inches^2, respectively. The modulus of elasticity of the aluminum and oxide are 10 million lb/in^2 and 50 million lb/in^2, respectively. Assuming a strip of aluminum 2 inches long and a load of 1000 pounds, the aluminum elongates

$$\delta_{Al} = \frac{P_{Al}\ L}{A_{Al}\ E_{Al}}$$

$$= \frac{(1000\text{ lb})\ (2\text{ inches})}{(0.0372\text{ in}^2)\ (10 \times 10^6\text{ lb/in}^2)}$$

$$= 5.37 \times 10^{-3}\text{ inches.}$$

The amount the oxide elongates must be equal to the amount the aluminum elongates because they are bonded together. Thus,

$$\delta_{oxide} = \delta_{Al} = 5.37 \times 10^{-3}\text{ inches.}$$

Solving for the load needed to produce the same amount of elongation in the oxide layer gives,

$$P_{oxide} = \frac{\delta_{oxide}\ A_{oxide}\ E_{oxide}}{L}$$

$$= \frac{(5.37 \times 10^{-3}\text{ in})(2.12 \times 10^{-3}\text{ in}^2)(50 \times 10^6\text{ lb/in}^2)}{2\text{ inches}}$$

or $P_{oxide} = 285$ lb.

The total load needed to produce 5.37×10^{-3} inches of elongation when the aluminum and oxide are bonded together is,

$$P_{Total} = P_{Al} + P_{oxide}$$

$$= 1000\text{ lb} + 285\text{ lb} = 1285\text{ lb.}$$

Solving for the modulus of elasticity needed to produce 5.37×10^{-3} inches of elongation when the aluminum and oxide are bonded together as a composite gives

$$\delta_{composite} = \frac{P_{Total}\ L}{A_{Total}\ E_{composite}}$$

where $A_{Total} = A_{Al} + A_{oxide} = 0.0393\text{ in}^2$, and

$\delta_{composite} = \delta_{Al} = \delta_{oxide} = 5.37 \times 10^{-3}$ inches.

or

$$E_{composite} = \frac{(1285\text{ lb})\ (2\text{ in})}{(0.0393\text{ in}^2)\ (5.37 \times 10^{-3}\text{ inches})}$$

$E_{composite} = 12.18$ million psi.

Thus the oxide layer increases the stiffness of the rim by over 21%. The rigidity of a rim is directly related to its cross-sectional shape (as you have seen), cross-sectional area, and modulus of elasticity. The equation governing this relationship is:

$$R = EI,$$

where R is the rigidity, E is the modulus of elasticity, and I is the moment of inertia, which incorporates both cross-sectional shape and area. So for the rim used in these calculations, its rigidity is 21 percent greater than it was if not hard anodized.

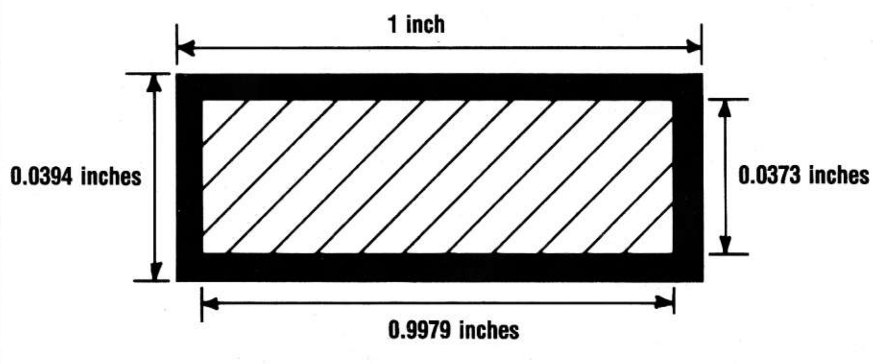


Figure 1: Cross section of a hard anodized piece of aluminum. Thickness of the oxide layer is exaggerated for clarity.

Relating Rim Rigidity and Strength

Doug Roosa with Dean Updike and Bob Flower

Dean Updike is a professor of mechanics at Lehigh University. Bob Flower is an engineering consultant to Rodale Press.

In the accompanying article, author Chris Juden shows that the relationship between a rim's weight and its measured radial rigidity and strength is usually predictable. But how important is this relationship? Does rigidity alone improve a rim?

Not surprisingly, these questions demand essay answers. It's a worthwhile exercise, though, because it induces us to calculate rim resiliency — the rim's ability to absorb loads from the rider and the road. This, in turn, allows us to see how "weight efficient" each rim's resiliency value is — to divide resiliency by weight and thereby calculate "specific resiliency." This exercise begins with a discussion of Juden's test data.

As shown in the graphs in Figures 4 and 5 of Juden's article, most of the tested rims fall neatly within diagonal bands that cross the figures from upper left to lower right. These patterns indicate a direct relationship between a rim's weight and its radial strength and rigidity.

There is one rim that ranks very differently in the two graphs: the Rigida 1320. Its rigidity-to-weight ratio is clearly superior to that of the other rims in the test, but its radial strength is only what is expected from a rim of its weight. Why does the Rigida stand apart in radial rigidity, but not in strength? Is there something unique about its design? What determines the strength and rigidity of the rest of the rims? To answer these questions, we studied the structural design of rims to sort out the differences between rigidity and strength. In the process, we discovered much about the rim as a structural member in a bicycle wheel. We also discovered that there is a great deal we don't know.

Rim Rigidity

The rigidity of a rim is a measure of how much the rim deflects per unit load within its elastic range. The less the rim deflects under a given load, the more rigid it is. As long as the rim is loaded within its elastic range, it will always spring back to its original shape when the load is released. Too high a load will compress a rim past its elastic range and permanent deformation will occur, i.e. the rim will not return to its original pre-load shape. The load at which permanent deformation occurs is a measure of the rim's strength.

A rim's rigidity depends on two variables: the modulus of elasticity (E) of the aluminum and the rim's moment of inertia (I). The modulus of elasticity is a property of the aluminum and is independent of any heat treatment or cold working done to the aluminum as it is formed into a rim. A hard anodized layer does increase the aluminum's modulus of elasticity,[1] but none of the rims in Chris Juden's test was hard anodized, so anodization is not a factor in the measured values of rigidity.

The other factor that determines rigidity — moment of inertia — depends entirely on rim geometry and is the determining factor in the ranking of the test rims in Figure 4 of Juden's article. Since rim rigidity is calculated by the product of the modulus of elasticity and the rim's moment of inertia, a large moment of inertia makes a rim rigid. Chris Juden points out that a rim with a deep section is a rigid rim because it has a large moment of inertia. Why is this so?

Strain

As explained in Juden's footnote about the neutral bending axis, the farther away a bit of rim material is from the neutral bending axis, the more effective it is in helping the structure to resist bending. This is so because material does not want to be strained from its rest position; since the amount of strain felt by fibers of material is proportional to their distance away from the bending axis, so is their resistance to being strained.

The sum of the contributions of all the fibers in a structure to resisting bending is mathematically expressed as the structure's moment of inertia. The more fibers there are, and the farther each fiber is from the neutral bending axis, the more rigid the structure becomes. (There is a limit to this, however. If material is spread too far and too thin in a structure, its walls and flanges will wrinkle or buckle when a load is applied. If this occurs, the structure will be unable to bear as high a load as it was designed for.) Looking at the cross-sectional shapes of the rims in Figure 4, we see why the rims are ranked as they are: the most rigid rims are heavy and have large cross-sectional areas, so they have their material well-placed off the neutral bending axis.

Strength of Rims

The ranking of the test rims in Figure 5 is similar to that in Figure 4, so there would seem to be some correlation between what makes rims rigid and what makes them strong. It is true: rim strength depends upon material used and upon cross-sectional geometry. But while the roots of strength and rigidity are the same, they are quite independent of each other.

Chris Juden tested the strength of each rim by first applying a force large enough to take up all the rim's elastic deflection and then applying an additional force that permanently bent them one-half percent (about 3.1 mm) of their diameter. The value M_s in his data was calculated from this load.

The material property that defines rim strength is the aluminum's yield strength. Unlike aluminum's modulus of elasticity, yield strength can vary widely from one type of aluminum to another. Yield strength varies with type of aluminum alloy, and can be increased by heat-treating and/or cold working the rim during its manufacture.[2]

It is possible to gauge yield strength with a hardness test of the rims. Unfortunately, Juden didn't conduct hardness tests, so the contribution of yield strength to the rim's radial strength cannot be judged. This important measure would separate the rims that are strong because of superior materials from the rims that are strong because of cross-sectional design.

Independent Quantities

With the similar factors of weight and cross-sectional geometry affecting the rigidity and strength of a wheel rim, how can these two quantities be independent of each other?

To illustrate this difference between rim rigidity and rim strength, let's consider two rims from Juden's test: the Mavic Model 4 and the Rigida 1320. Both these rims have equal values of rigidity — they will both deflect the same amount under equal loads — but the Mavic is roughly 50 percent stronger than the Rigida. Why?

There are obvious differences in their cross-sectional geometry: the Mavic is about as deep as the Rigida, but it is wider and heavier. These latter two factors should make the Mavic more rigid than the Rigida, but the Rigida's deep section, with its thin walls and thin central web, give it a cross-

[1] *See Mario Emiliani's sidebar in this issue on how hard anodizing increases aluminum's modulus of elasticity.*

[2] *For details on heat-treating and cold working aluminum rims, see Mario Emiliani's article, "Heat Treated Rims: Are They Worth the Money?" (Bike Tech, October 1983).*

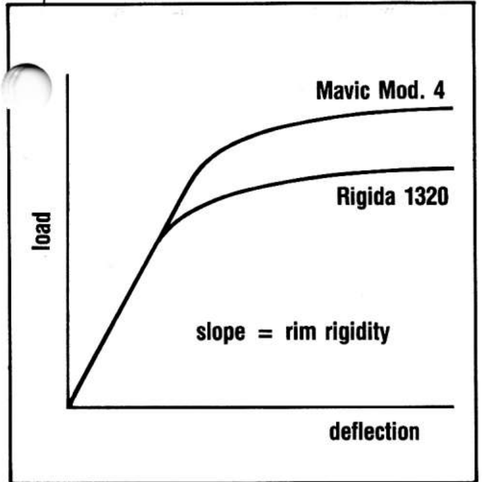


Figure 1: Superposition of load/deflection traces of two rims that have equal rigidity but different yield strengths.

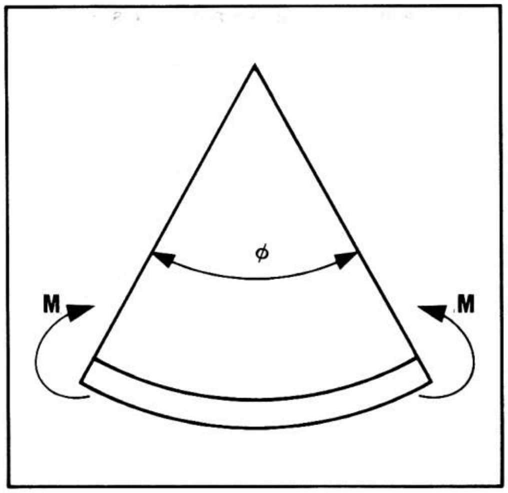


Figure 2: Curved beam loaded by a moment couple.

George Retseck

sectional design that achieves the same rigidity with less material. This "efficient" distribution of material in the Rigida has one big drawback: the Mavic can spring back into shape under loads that would cause permanent deformation in the Rigida.

Here's why: under equal test loads, the Rigida is nearer to its yield point than the Mavic because the Rigida has less material to bear the load, so each bit of material is under a higher level of stress. The Mavic has a greater load bearing capacity before some of its material is stressed to its yield point, so the Mavic can take a heavier load and will deflect farther before it finally yields. Figure 1 represents this situation by superimposing the load/deflection traces of the Rigida and the Mavic.

What's Important

So what is important for a wheel rim — strength, rigidity, or both? It is apparent from Figures 4 and 5 in Juden's article that both qualities are determined by rim weight, although deep-section rims like the Rigida 1320 have proportionately more rigidity than strength. Is one quality more important than the other? What optimum should a rim designer strive for?

Answers to these questions are suggested if we look at a rim from an abstract structural standpoint, i.e. considering it as a curved beam subjected to a moment couple as shown in Figure 2.

This moment versus the subsequent angle change per unit length of the beam plotted in Figure 3 shows a deflection curve with the same shape as the trace gradient plotted by Chris Juden's test apparatus. The initial slope of the curve in Figure 3 is the EI, or rigidity, of the beam; the point at which the deflection curve levels off is the strength value, M_s.

Interestingly, one quantity that can be evaluated from Figure 3 is the rim's ***resilience***. Rim resilience is defined as the ability of the rim to absorb energy from an impulse load without suffering any permanent deformation. The measure of resilience is the amount of work it takes to deflect the rim up to its yield point. Since the area under the curve in Figure 3 represents a measure of energy absorbed per unit length of the beam in Figure 2, a measure of resilience per unit circumference for a circular beam like a wheel rim can be found from the same area.

This is done in Figure 4 (it is assumed that the curve is straight up to the value M_s), with the accompanying equation,

$$\text{Resilience} = \frac{M_s^{\,2}}{2EI} \quad (1).$$

Note that the strength term in equation 1 is squared, but the rigidity term is only to the first power; the resiliency of a rim should depend more on strength than on rigidity. However, the rigidity term is in the denominator of the equation, so it is possible that a rim with a proportionally higher value of rigidity than strength may not be very resilient.

Let's check these assertions against the calculated values of rim resiliency listed in Table 1. Generally, the strong and rigid rims are clustered at the top of the resiliency column and the weaker, less rigid ones are at the bottom. Two rims that buck this trend provide evidence that there may be an optimum balance between strength and rigidity. The Mistral 120 is the strongest rim and is also the most rigid by a wide margin. The Rigida 1320 is near the bottom of the strength column, but is near the top in rigidity. The Mistral 120 rates lower in resiliency than its strength suggests; the Rigida really is penalized in resiliency because of its inordinately high rigidity value.

On the other hand, several rims, including the Mavic E2 and the Mavic Mod. 4, and the Weinmann 256 have measured strengths and rigidities that are proportionally closer and, as a result, fair better in resiliency. Rim resiliency does depend on rim strength, but rigidity can be a complicating factor.

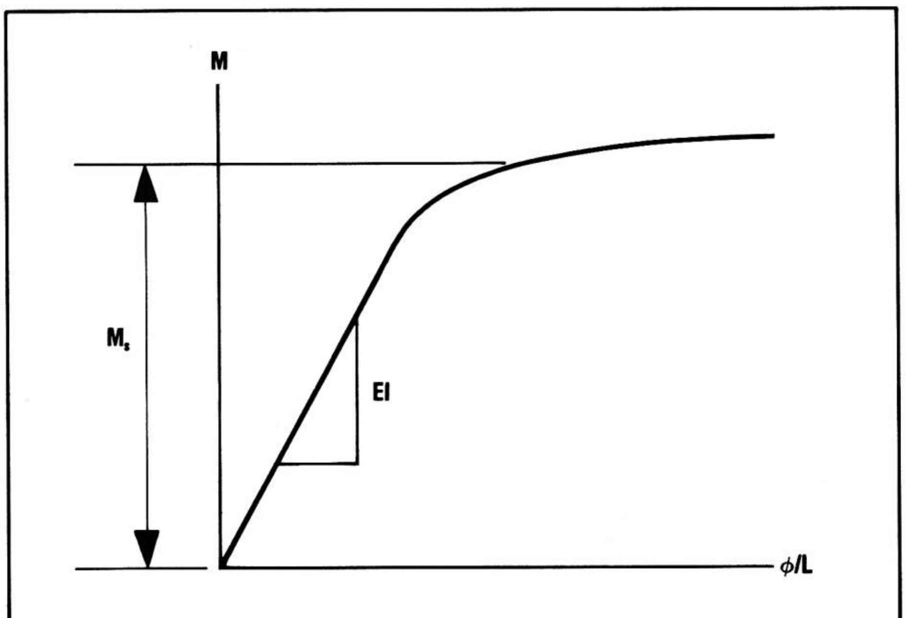


Figure 3: Bending Couple vs. angle change per unit length.

George Retseck

Rim	Rim Weight (grams)	Rim	Rigidity (Nm^2)	Rim	Strength (Nm)	Rim	Resilience ($\frac{Nm}{m}$)	Rim	Specific Resilience (Nm/kg)
Mistral 120	579	Mistral 120	113	Mistral 120	63	Mavic Mod. 4	40.5	Rigida 1622	74.4
Weinmann A129	569	Rigida 1622	98	Rigida 1622	62	Rigida 1622	39.2	Mavic Mod. 4	72.4
Mavic Mod. 4	559	Super Champ. 58	94	Mavic Mod. 4	61	Mavic Mod. 3	35.6	Mavic Mod. 3	70.7
Super Champ. 58	533	Weinmann A129	94	Super Champ. 58	57	Mistral 120	35.2	Mistral 217	68.2
Weinmann 256	531	Mavic Mod. 4	92	Mavic Mod. 3	55	Super Champ. 58	34.5	Super Champ. 58	64.8
Rigida 1622	527	Rigida 1320	92	Mistral 217	55	Mistral 217	34.0	Mavic E2	61.6
Weinmann A124	514	Weinmann A124	89	Weinmann A129	52	Weinmann A129	28.8	Mistral 120	60.7
Mavic Mod. 3	503	Mistral 217	89	Weinmann A124	46	Mavic E2	25.9	Mistral 113	50.7
Mistral 217	498	Mavic Mod. 3	85	Rigida 1320	43	Weinmann 256	24.7	Weinmann A129	50.6
Mistral 113	456	Mistral 113	80	Mistral 113	43	Weinmann A124	23.8	Weinmann 256	46.5
Rigida 1320	434	Mavic E2	65	Mavic E2	41	Mistral 113	23.1	Weinmann A124	46.3
Mavic E2	420	Weinmann 256	64	Weinmann 256	41	Rigida 1320	20.1	Rigida 1320	46.3

Table 1

Specific Resilience

Since the value of resilience can be made larger simply by adding more mass to the rim, the value of resilience per unit circumference does not identify a superior cross-sectional shape or rim material. What does identify a superior rim design is the resilience per unit weight, or *specific resilience.* This quantity is obtained by dividing the resilience per unit circumference by the weight per unit circumference. The equation for specific resilience is given by,

$$\text{Specific Resilience} = \frac{M_s^2}{2EIW} \quad (2).$$

Looking at the calculated values of specific resilience in Table 1, we see that most of the strong rims are again clustered at the top. The ranking of several rims bears comment: First, the relatively poor specific resiliencies of the three Weinmann rims points out problems with their cross-sectional designs. They are too heavy for the performance they give. Second, the Mistral 120 is even further down the specific resiliency column than it is in the resiliency column; its weight is the highest in the group of rims, which seems to be a penalty. Compare this rim to the Rigida 1622 and the Mavic Mod. 4: the Rigida and Mavic are virtually as strong as the Mistral but neither is as heavy, so their cross-sectional designs are superior because they can deliver more resilience with less weight.

Finally, the Mavic E2 is not strong but it is very light, so for its weight, it has great resilience.

It seems then, that some rim designs are better at absorbing energy from a ground load than others. There is no easily recognizable pattern in rim shape and size that allows us to predict how a rim will absorb ground loads, but the evidence suggests that there is an optimum relationship between a rim's strength and its rigidity. While it is arguable that strength is the most important quality of a rim, this article suggests that the durability of a wheel rim and the economy of its design may be determined better by measuring both its strength and its specific resiliency.

Questions Unanswered

When wheel rims are used for normal road riding and especially when used for heavily loaded touring, they should be designed for maximum strength and resiliency. But on the track or in smooth road racing conditions,

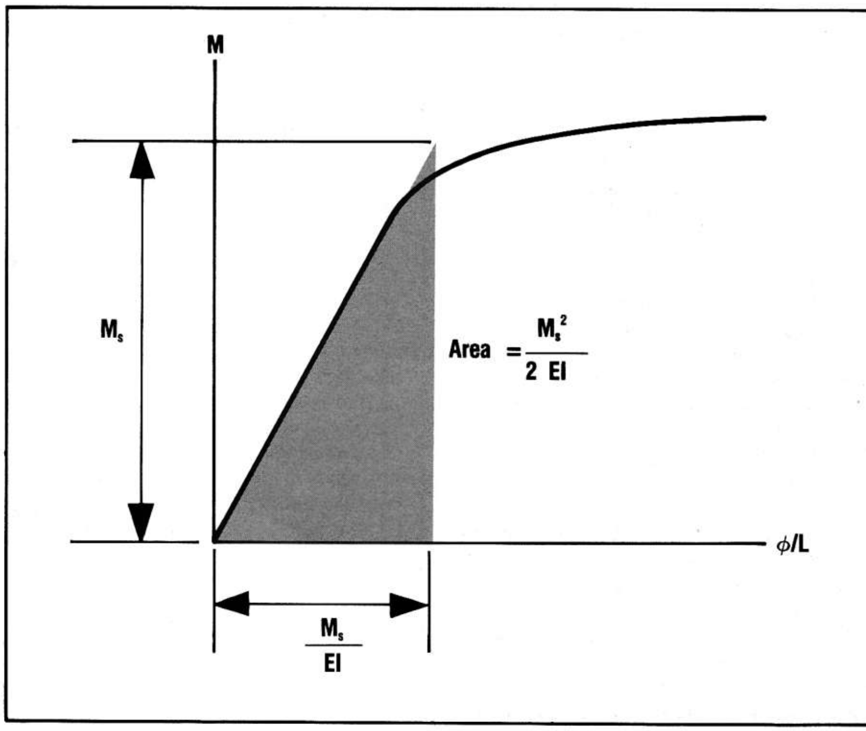


Figure 4: Shaded area is a measure of the energy per unit circumference absorbed by a rim under load. The energy absorbed is a measure of a rim's resilience.

rge Retseck

where the dynamic ground loads are relatively small, a light, rigid rim would be preferable. Light rims accelerate more quickly; when laced with fewer spokes, it is especially important for the rim to be rigid so that it distributes loads over enough spokes.

But how best to match the strength, resiliency, and rigidity of a rim to its intended use? To answer this question, we need a thorough structural analysis of the wheel as a whole, including the tire, spokes, and hub. Then we would be able to answer questions such as:

—How do the structural properties of a rim make it behave under load when laced to a hub and mounted with a tire?
—How are the static and dynamic loads distributed between the rim and spokes?
—What is the resiliency of the spoking?
—Is there an optimum resiliency match between rim and spokes?

These questions cannot be answered with the data given; nor can they be answered by analyzing the rim separately from the spoking. This is so because the spoked wheel is a statically indeterminate structure, i.e. the forces applied to each component in the wheel are influenced by the deflections in all the other components.

Analytical Model

Answers will emerge only with the development of an analytical model of the whole wheel assembly that can be subjected to the various forces encountered in operation on a bicycle. Jobst Brandt, author of *The Bicycle Wheel*, has made headway with this type of analysis, but more work needs to be done to determine the role of the rim in a spoked wheel.

An interesting analogy to a spoked wheel is the railroad track. The rail is analogous to the rim, while the ties and bed make up an elastic foundation analogous to a wheel's spoking. The railroad track model has been extensively analyzed in advanced structural engineering texts; a grasp of the engineering involved in designing railroad tracks represents the entry-level understanding necessary to analyze a spoked wheel.

A more promising approach might be to use the same techniques that civil engineers apply when calculating three-dimensional movement in steel-framed buildings. The analysis requires that the rim be subdivided into small "finite elements," and each element is treated as a segment of a circular arch on elastic supports. The solution to this sort of circular arch problem is well known for both static and dynamic loading conditions; many bridges are of this design. A number of inexpensive microcomputer programs are available for just this sort of structural analysis. These programs find solutions for each arch segment and then couple the solutions together, deriving the overall performance of the structure.

Frame Geometry for Rough Trail Riding

John Olsen

Today's commercially available all-terrain bikes (ATBs) are not really designed for hard trail use. Rather, this new breed of bike has a frame best suited for fairly smooth, uncluttered, not-too-steep fire trails and gravel roads, and its steering geometry is proportioned for the high-speed stability required for swift, downhill riding.

I hope to stir up some fresh thinking on all-terrain bikes by presenting the design and construction techniques that I've developed to deal with rough, uncleared mountain trails. Bikes for this type of riding must have generous ground clearance and steering geometry to give the rider precise control for navigating rugged terrain at slow speeds.

My suggestions for frame and steering geometry will be familiar to those readers who have participated in the fledgling sport of bicycle trials riding; bikes used in this sport have evolved into purely functional machines that perform admirably on treacherous terrain, but have markedly different designs from the all-terrain bikes on the market today.

Using specially built frames, and with lots of strength and skill training, riders can perform amazing feats of climbing and maneuvering in some of the toughest terrain imaginable. These bikes can climb hills that would leave a normal ATB at the bottom, searching for traction. They can clear tall obstacles (logs, rocks, abandoned cars) without grinding their chainwheels into aluminum powder. Their steering geometry is optimized for low speeds and quick maneuvering. Moreover, a bike that is well-suited to rough trail use is a natural for bike trials competition, and vice versa.

Chainstay Length

The most important design consideration for a bike intended to climb steep hills on loose surfaces is chainstay length. The formula here is simple: the shorter the stays, the better the bike's hill climbing ability. Long chainstays give poor traction on hills when the rider is standing, which he or she must do whenever the hill is anything but smooth and moderately sloped. This is not news to trials riders, whose purpose-built bikes have chainstays only 16.5 to 17.5 inches long, but consider what you get when you buy an off-the-shelf ATB: chainstays ranging from 18 to 19 inches! Nineteen-inch chainstays place the rear wheel too far back; climbing a slippery hill with such wheel placement is a trying experience because the wheel can't get sufficient traction.

Traction

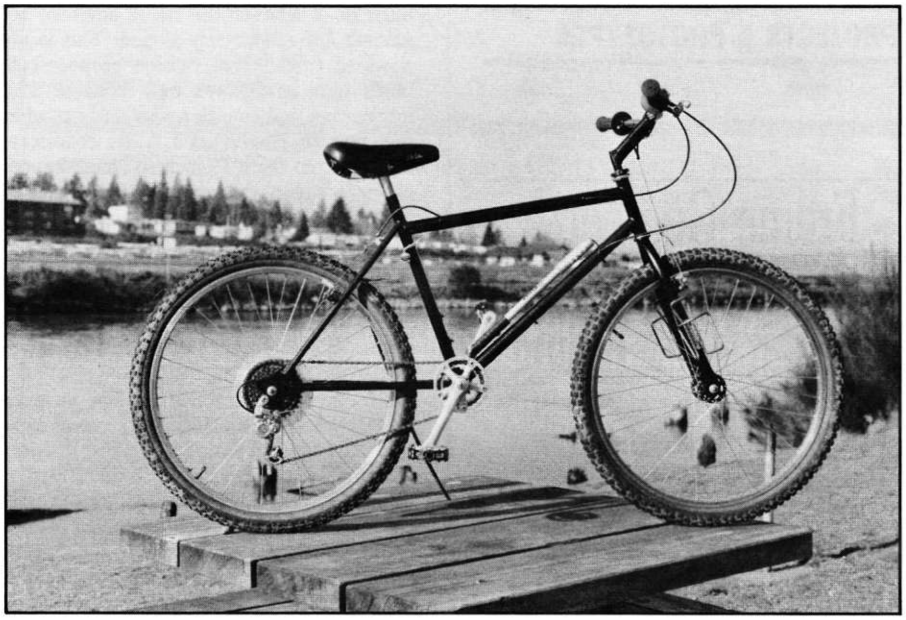
The physics of traction on hills is quite straightforward. Climbing a hill involves raising your body and your bike against gravity; this work requires tractive force. Tractive force on a dirt hill can be generated in several ways. For instance, hill-climbing motorcycles get tractive force primarily by digging into the soil, shearing gobs of it out with the tires, and then accelerating this mass of soil to high velocities. In pushing against the soil and propelling some of it backwards in a great plume, the forward force that drives the motorcycle is generated. So is a nasty trench.

A more subtle approach that is better suited to a low horsepower bicycle rider is to penetrate the soil surface with the knobs of the tires and push on the dirt between the knobs just to the point where the soil starts to shear. In a soil which is soft vertically but strong horizontally (such as pine needle reinforced forest humus, nicely packed and somewhat moist), incredible traction is available. Under these conditions, the limit to hill climbing is either the rider's strength or his inability to keep the front wheel on the ground.

Static Friction

Another traction mechanism which is familiar to all road riders is the static friction between the rear tire and the road. On a hard surface, the kind that shows no tracks, this mechanism dominates. The tractive force available here is roughly proportional to the normal force on the tire times the coefficient of friction between the tire's rubber compound and the road. The frictional coefficient varies widely depending on the gumminess of the tire compound and the nature of the surface with which it's in contact. Coefficients can vary from a numerical value of 0.01 for wet ice, up to a value greater than 1.00 for hard surfaces with microscopic bumps, which force the rubber of a gummy tire to shear and flow around the bumps at the point of slippage.

It's a law of introductory physics that static friction is independent of contact area, because the friction generated depends only on the total pressure of contact at the tire/ground interface. If the contact area is increased, the contact pressure per unit area



Lew Plummer

Form follows function on this rough-trail bike. Short chainstays give best traction for steep hills; high bottom bracket and minimal chainring optimize ground clearance.

is reduced by a proportional amount as long as the vertical force bearing on the tire remains constant. This keeps the overall contact pressure constant. But when micro- or macroscopic intrusions of the tire into the ground or ground into tire occur, this simple law does not hold fast.

Rough Surfaces

Micro- and macroscopic intrusions indicate the degree of roughness that all surfaces have. The more intrusions that the ground and/or tire must flow around, the greater the force has to be to make the two surfaces slip because work must be done to overcome the shearing and flowing between the two surfaces. How much intrusion there is between the tire and ground depends on the contact area between the two, which is a function of the construction and air pressure of the tire, and on the weight bearing on the tire.

So in the real world of tires and surfaces, letting some air out of a road tire effectively increases the tractive force between the tire and road because this allows more intrusions between the smooth, gummy tire and the relatively rough road. And, in the case of a knobby tire rolling over soft ground, the more macroscopic knobs that penetrate the dirt, the better the traction.

In sum, traction in the dirt is achieved by a combination of the tire knobs intruding in the dirt and pushing on the dirt up to the point of shear. Both factors are dependent on tire type and pressure, type of soil, and on the amount of weight that bears upon the rear wheel.

Shorten the Chainstays

How do you get more weight on the rear wheel? Easy: either move the rider's weight rearward or move the rear tire's contact patch forward. A rider's rearward weight shift is limited to the dimensional constraints of pedal and handlebar placement, so the preferred alternative is to shift the rear wheel up under the rider by shortening the chainstays. Figure 1 shows a seated rider and a standing rider climbing a hill on short- and long-stay bikes, respectively, illustrating the greater rearward weight transfer possible with short stays.

Seated climbing is limited because every time the rear wheel hits a bump it must lift the rider's mass (unsprung weight), and sometimes it would rather just stop turning. A seated position also precludes precise weight shifts to control fore-and-aft balance and absolutely prohibits more advanced unweighting techniques. (Unweighting techniques are purposeful shifts of rider and bike weight off either the front or rear wheel to change bike direction or to coax the rear wheel to ride up a slick surface like a rock, old car, or log.) Yet on long-stay bikes, often the only way to get enough traction is to sit, because standing takes too much weight off the rear wheel. Although seated climbing on a bike with short chainstays can be a problem (the large rearward weight shift can unweight the front fork, making balance and steering difficult), seated climbing isn't necessary. The short stays bring the wheel forward enough to work well with the rider standing on the pedals. Thus, on rough trails with steep, slippery hills, short chainstays are the obvious solution, since terrain of that sort must be negotiated standing up.

High Bottom Brackets

Another important design parameter is the height of the bottom bracket: it should be very high. I regularly build bikes with 14-inch-high bottom brackets. This dimension takes some getting used to, but on rough trails with large rocks and logs, its benefits are indisputable. Every inch of chainring clearance adds to your chance of successfully clearing these pesky obstacles. Aluminum chainwheels may survive contact with a log, but they don't fair well in collisions with rocks and concrete. Getting stuck in the boonies with a bent chain or peened-over chainwheel teeth is guaranteed to ruin your day.

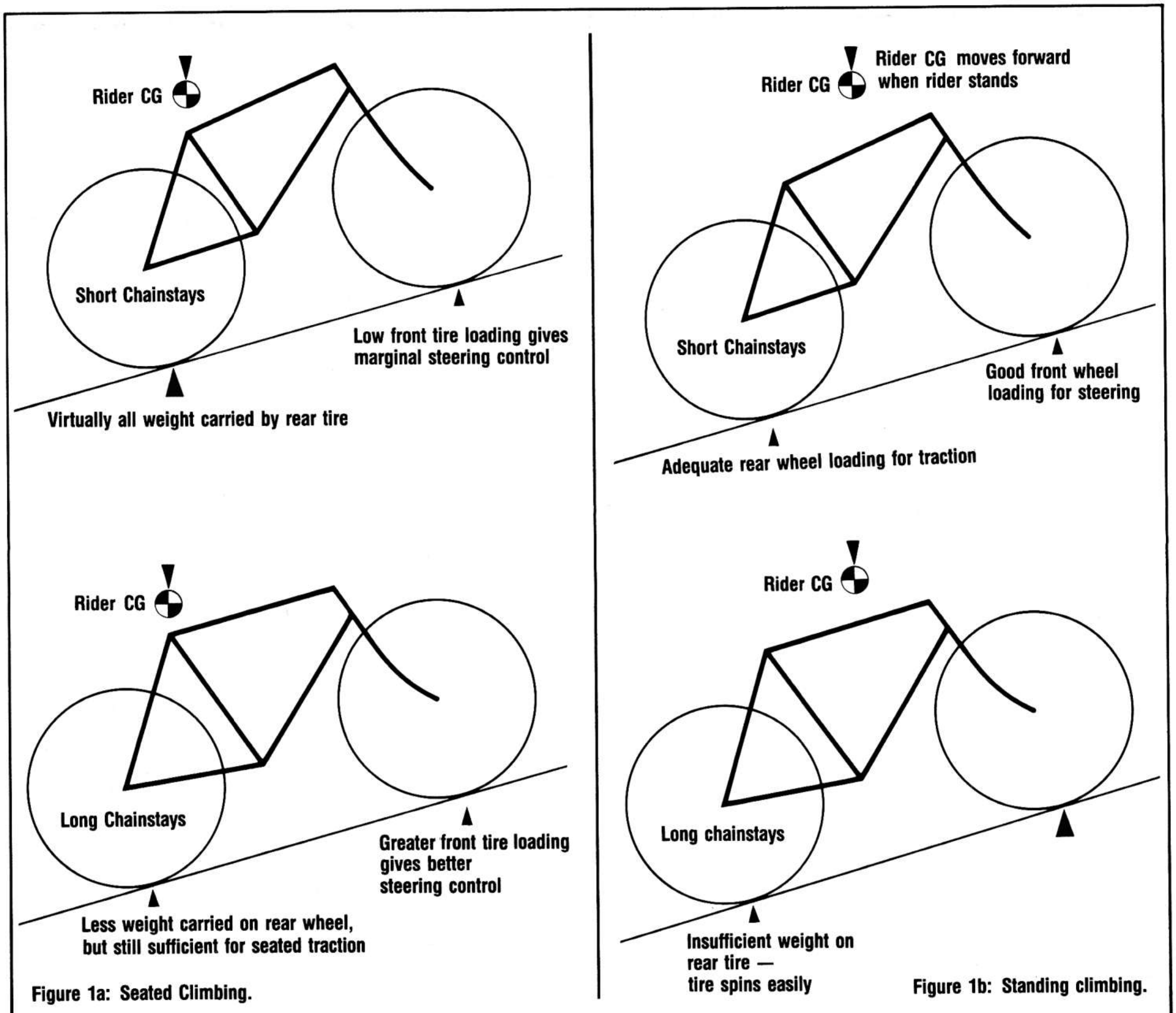
To prevent this sort of abuse, we keep our chainring small, between 26 and 28 teeth (normal gearing is only five speeds: one chainring up front with, typically, a 13-28 freewheel), and mount outboard of this inner ring a slightly larger chainwheel with its teeth ground off to act as a protector plate. This combination of high bottom bracket and ultra-small chainring is in marked contrast to the typical ATB with its 46-48 tooth large chainwheel installed in a bottom bracket 11 to 12 inches high.

Having a high bottom bracket creates another bonus—more traction. As the bottom bracket comes up, the standing rider is forced into a more bent-over position, moving his or her rear end farther back and taking the center of gravity back with it.

Lower the Top Tube

Another necessary modification from standard ATB design is the height of the top tube. On a difficult trail or trials section, a rider, no matter how good, will need to put a foot to ground, sometimes in a hurry. If the top tube is high, this necessary act can result in a painful encounter between rider and machine. I recommend a minimum of four inches of clearance between groin and top tube when straddling the bike. A low top tube, combined with a high bottom bracket, results in a short seat tube — on the order of 14 to 16 inches on a bike sized for a six-foot rider. Getting a good seated riding position then mandates having a seat post about 14 inches long.

Seat posts this long are not commercially available, so I make my own from one-inch thick-wall 6061 aluminum pipe (this pipe is actually 1.10 inches OD which can be turned down to 1.07 inches to match a 27.2 millimeter seat tube). Seat tube angle usually falls in the range of 70 to 73 degrees, which provides good seated riding position. I find that



George Retseck

Figure 1: Effects of rider's center of gravity (CG) on wheel loading for short-and long-chainstay bikes, when climbing seated (Figure 1a) and standing (Figure 1b). A favorable balance between rear wheel loading for traction and front wheel loading for steering control occurs when climbing standing on a bike with short rear chainstays.

the seat angle is not too critical because as your experience grows in this type of riding, you find that you spend little time in the saddle.

Head Tube Height

A rough trail bike frequently endures high impact loads through the fork, both vertically and horizontally. Because the fork is a lever, these loads are transfered up to the steering head bearings and frame joints. To minimize stress at these points, it is wise to have a tall head tube; the longer the head tube, the smaller the forces are at the bearings and joints that react to these loads. I suggest having a head tube no shorter than five and a half inches.

But given the low top tube, how do you get enough head tube length? Simple: slope the top tube upwards from the seat tube to the head tube. Horizontal top tubes are almost universal, but this sport demands that form follow function, and ample clearance for the rider combined with a long head tube requires an upward sloping top tube. A frame for a six-foot rider usually has a top tube that slopes up about ten degrees. Besides being functional, this angled tube lends a rakish look to the bike.

Steering Geometry

Up to this point, I have been dogmatic about the parameters for a true rough trail bike. Chainstay length, bottom bracket height, top tube angle — all these dimensions have been worked out from experience and common sense, and are not controversial among serious off-road riders. But personal preferences prevail on the topic of steering geometry; among riders, there is little agreement about which of the infinite combinations of workable front end geometry is best.

Usual talk about steering geometry orbits around head angle and trail, but I feel that, in the world of off-road riding, additional thought should be given to stem offset and handlebar width. Many treatises about steering geometry discuss the handling of a bicycle in the absence of the rider, since at the high speeds common for road bikes, the vehicle is stable, and the rider exerts minimum influence to maintain direction and attitude. But at low speeds, the stabilizing forces shrink and the ever-present destabilizing forces become dominant, so there comes a point where rider control becomes the dominant factor in maintaining balance. This threshold speed is where no-hands riding becomes difficult.

Rider Control

When a rider steers a bike, he or she exerts control by shifting his weight and adding corrective steering by turning the front wheel into the fall. In the act of steering into the fall, the front end geometry is very important because it determines the force and velocity with which the rider must push and pull to regain balance. For example, the head angle and trail determine the torque exerted by the tire and wheel on the steering axis; in off-road riding, this torque can vary in magnitude because the tire contact patch can easily be moved out from under the axle when the tire makes contact with rocks and when traversing large logs.

These tire-induced forces can become quite large, eager to wrest control from the rider, so it is important to consider the leverage effected by stem offset and handlebar width so that the rider can effectively counteract these unbalancing forces.

Pilot Induced Oscillations

This point in the evolution of ATB steering mechanisms has an interesting parallel in aircraft history. In the early days of aviation, aircraft stability was poorly understood (even though it is easier to understand than bicycle dynamics!), and sometimes, in the pursuit of higher performance, craft were built with controls that were so sensitive that the pilot couldn't fly them smoothly. The pilot would make control corrections, but rather than smoothing things out, the pilot's corrective measures would actually excite the instability — his corrections were made at the wrong time because his reflexes were too slow. Quite a few pilots and planes were lost because of these "pilot induced oscillations."

A similar thing can happen when a rider

Continued on page 14

PROJECTS & PROTOTYPES

Integrating the Rider

Block diagrams are wonderful things. They allow dynamists and control systems engineers to figure out and clearly explain the dynamics of very complicated physical and electronic systems. One such complicated dynamic system is a bicycle, especially one being ridden at low speeds on rough ground. I have attempted, in Figure 1, to develop a block diagram illustrating the dynamics involved in low-speed steering and balance of a bicycle.

To read this diagram, begin at the left-hand side and follow the arrows. To start, the human brain sends a signal to the arm muscles, telling them to turn the handlebars, because it has decided that the bicycle and rider is falling over or about to steer into a tree, or both. The steering muscles exert forces on the handlebars which the handlebars then convert into a torque working on the steering axis. This torque works against the inertia of the steering mass ($I_{steering}$), and produces an angular acceleration of this mass.

We integrate this acceleration and get angular velocity. This angular velocity causes sliding friction and viscous damping forces which resist the input torques, as you can see in the block diagram. We integrate again and get the instantaneous steering angle.

The tire, set at an angle relative to its velocity vector (approximately the steering angle shown, although I have left out some degrees of freedom such as lateral velocity and yaw acceleration, out of mercy), produces a restoring force dependent on tire construction and tire pressure. This force works on the contact patch lever arm (which is a function of trail, head angle, and roll angle) to produce a restoring torque, T_{tire}. Note that at any point in the steering process, it is the *net* torque, not the input torque, that determines the steering accelerations.

When you steer a bicycle, you cause it to roll. The shorter your wheelbase and the higher your velocity, the more roll you get per unit steer angle. This roll occurs about an axis joining the two tire contact patches, and is resisted by the inertia of your posterior (if it is on the saddle), and by the dynamic reactions of the arms and torso on the handlebars. Proceeding through the same type of integration as before, we get roll angle. This feeds back to influence the contact patch lever arm and to influence the brain through its roll sensors, the inner ears.

The brain has command of another balancing system: body English. By accelerating the masses of the various parts of your body, two things happen: First, you exert an equal and opposite force on the bicycle through the handlebars and, to a lesser degree, the seat and pedals. Second, you get your upper body to a new position relative to the bike frame (sometimes underneath it with your legs behind your head), which changes the static balance of the whole system. This all sums into the net roll torque and influences the steering angle necessary for a statically and dynamically balanced condition.

What does all this integration tell us? It surely emphasizes that human beings are amazing control systems and power units. It also shows some of the many complex interactions and feedback loops that exist in bicycle dynamics. Finally, it shows just how complicated even a very simplified dynamic model of a bicycle can be, and we haven't even *started* to talk about all the geometric and kinematic equations in blocks such as "contact patch lever arm" or "steering quickness factors."

For all you budding or fully bloomed bicycle dynamists out there, have a look at this block diagram and then try to add to it. Are there any errors? There's much to think about. This process probably won't result in a recipe for Optimum Steering Geometry for Any Circumstance, but it should help clarify your understanding of the interrelationship of factors involved in bicycle handling.

Remember, this problem is complex enough that it's unlikely that pure analysis will ever replace experimentation in the determination of good handling parameters. If you want to hire NASA, go ahead; as for me, I'll be in the shop building trials frames, guided by a pretty good seat-of-the-pants understanding of what factors do this and that to handling.

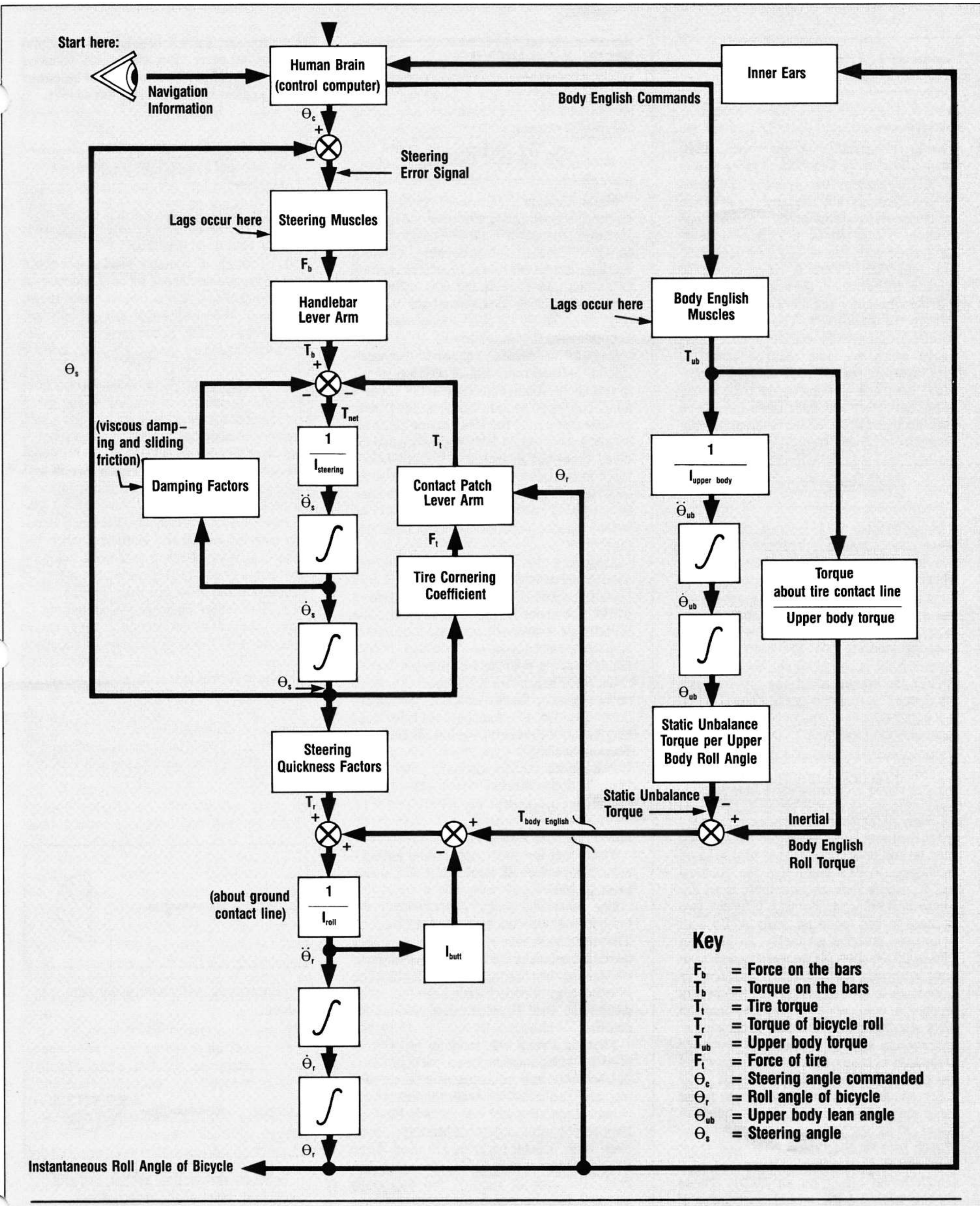
John Olsen

For readers interested in delving deeper into the mathematics of bicycle steering, I recommend these books:

American Society of Mechanical Engineers. *Mechanics and Sport.* ASME No. AMD, Vol. 4. New York: American Society of Mechanical Engineers, 1973.

Society of Automotive Engineers. *Motorcycle Dynamics and Rider Control.* ASE No. SP-428. Warrendale, PA: Society of Automotive Engineers, 1978.

____. *Road Vehicle Handling.* SAE No. MEP-174. Warrendale, PA: Society of Automotive Engineers.



George Retseck

Figure 1: Simplified bicycle steering and balancing control block diagram.

Frame Geometry

Continued from page 12

tries to ride standing on the typical ATB. These bikes' large fork rake reduces trail (a lot of trail stiffens the steering and helps damp oscillations) and the large offset of the Bullmoose-type stems gives the rider high leverage. These two factors create a steering system with low rigidity, low feedback, and hyper-sensitivity. A rider, trying to maintain his balance in the standing position, will inadvertently induce steering forces through the handlebars. These inadvertent steering commands excite a sinusoidal weave which the rider may be unable to stop; instead, these "pilot induced oscillations" keep him weaving up the trail. Fortunately, no riders and their bikes have been lost, but there is the embarassment of wobbling into rocks and trees.

Bump Steer

In addition to pilot induced oscillations, there arises another problem with large rake/low trail front ends. When the front wheel strikes an obstacle, a steering moment is created that attempts to wrest control from the rider. When the fork rake is large, the leading edge of the wheel is far from the steering axis; the farther the tire contact point is from the steering axis, the greater the torque about the steering axis which must be resisted by the rider. This effect is called bump steer, and decreasing trail increases the magnitude of bump steer.

Practical Compromise

Clearly, the rider must have enough leverage to deal with bump steer, and the steering must be stiff enough to prevent pilot induced oscillations. I have found that the practical way to satisfy both requirements is to decrease fork rake considerably, from the two to three inches found on many ATBs with high-speed steering geometry, to between 1.25 to 1.75 inches. By decreasing fork rake (thus increasing trail), the rider has to apply more force to start a turn, so the handlebars become a less sensitive place to lean on while standing. Also, the natural damping in the steering system grows more favorable as the trail increases because the front wheel has a greater self-centering tendency.

For adequate steering leverage to resist bump steer, I use rather wide handlebars (about 30 inches wide, as compared to the 27-inch bars on the typical ATB) and short stem offset (3-3½ inches compared to a 4-inch or so offset on an ATB). These choices minimize the lateral component of steering motion, and work well with my choice of top tube length.

IDEAS & OPINIONS

On Particle Blasting

Mario Emiliani's December 1983 article on particle blasting is a welcome one indeed. However, the editor's note on page nine is a bit out of context and premature. ("Great caution must be exercised when sandblasting paper-thin tubing. . . In the case of the Columbus fork blade sandblasted for 90 seconds . . . [there is] a nine percent reduction in both strength and rigidity.")

Readers may be led to conclude that sandblasting is dangerous, and all the facts aren't in yet! By the same logic used in the editor's note, you can conclude that brazing is dangerous: if you held the torch in one place for 90 seconds, it might burn right through the tube. True, but so what? You don't hold a torch in one place 90 seconds, nor a sandblasting nozzle either. Both procedures must be used with caution. In the hands of a competent person, both can be used to advantage.

Assuming the sandblasting nozzle was used 90 seconds all over a Columbus SL fork blade (90 seconds on each ⅛-inch square) it would take about 50 hours to sandblast one blade! Now it would be reduced in diameter and thickness as you've described. That's not realistic on your part or mine.

Let Mr. Emiliani finish his series of articles on sandblasting before damning the procedure! (Besides, I've found my old Navy chipping hammer too hard even on SP tubing!!)

Yours in cycling,
Bob Beecroft
Beecroft Cycle Works
Carlsbad, California

Mario Emiliani replies:

Thank you for your support and enthusiasm. I hope Part II won't be a disappointment to you!

The point you make about holding the torch in one place too long is indeed correct. That mistake is rarely made, however. But fewer framebuilders are competent in particle blasting than in torch brazing. By this line of reasoning, particle blasting can indeed be dangerous. Part II gives other reasons for concern.

There is a very wide range of procedures used by framebuilders when particle blasting, so there may be instances where a nine percent reduction in wall thickness will occur—if not after just one particle blasting, then maybe after repetitive blastings, especially when angular particles are used. Even if the thickness is reduced less than nine percent, the loss in rigidity and especially strength may be significant because design criteria for frames haven't been scientifically established.

As you say, particle blasting can be helpful if done properly. But there are nuances which I think framebuilders should be aware of so particle blasting will be even safer.

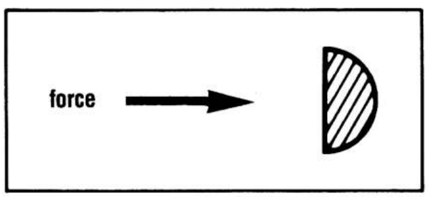
Ed Scott Responds

I'd like to offer some corrections and additions to my brake article, which appeared, heavily edited, in *Bike Tech.*

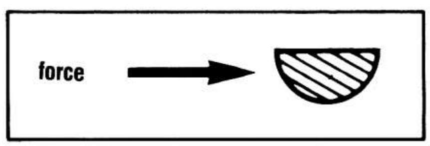
1. Though it appears that I advocate mixed types—centerpull on rear, sidepull on front—I don't. Cyclists wouldn't mix them, and I don't think either type is a good design. My point was that of the two designs, the centerpull is better used at the rear, sidepull at front.

2. To clarify section modulus (which governs the resistance to bending of any given cross section), I want to point out that a half-round is exactly half as stiff transversely (on the bike) as a full-round, but in the fore-and-aft direction it's only one-fourth as stiff as a full-round (our brake arms approximate a full-round section). Thus, conventional calipers are only marginally adequate on a standing bike but hopelessly inefficient when the bike is moving. Drilling lightening holes on the arm's centerline has very little effect on stiffness if the arms are thick enough.

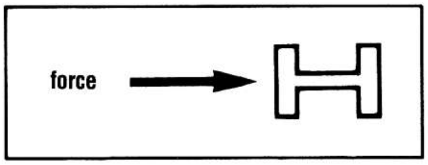
3. The editor changed my statement to read "the half-round section is very rigid in this direction" (across the bike, in the plane of cable-pull); but I wrote, "the half-round section is stiffest in this direction (though not really very stiff)." And elsewhere I wrote that "the half-round shape is about as inefficient as could have been devised for the upper arms." These facts can be confirmed by any engineer. See sketches which I've provided below.



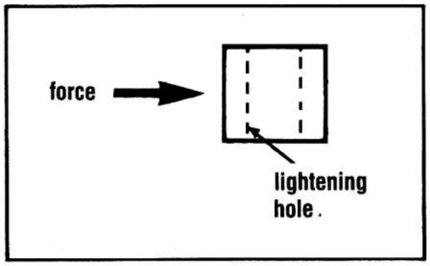
Hopelessly inefficient; wider than it is deep.



Twice as stiff as first sketch, but still inefficient. Most of the material is concentrated in center where it contributes very little to stiffness.



Very efficient. Weight and material are concentrated at tension and compression surfaces. But shape has no torsional stiffness; twists very easily; suitable only for upper brake arms.



Very efficient in resisting bending and twisting.

4. Shimano's 1/4-inch arm bearing bores are only .014 inch larger than 6 mm, not 0.14 inch. A typesetter's error.

5. Doug Roosa's statement that "No bike brakes work effectively in the rain," is directly contrary to hundreds of letters we've received saying that our brake shoes or pads enabled their existing brakes to stop well in the rain. That's what has kept us in business since 1976. Clean, rough-surfaced asphalt or concrete offers pretty fair traction when wet, so good brakes *are* usable in rain.

6. If Shimano officially believes that some sponge is desirable, why did they go to so much trouble to stiffen their Aero models?

7. On our new brake's shoe (called a "backing plate" in the article), the tubular portion is "integral," not "attached," and there are not "two conical washers," but "one spherical washer." Conical surfaces wouldn't allow any real adjustability except rotation, whereas spherical surfaces allow universal movement like one's ankle joint. The necessary second spherical surface is machined into the lower end of the caliper arm.

8. To avoid future disappointment: the comparative weight table is for front caliper assembly only, not for complete brakes. Campy, the standard to measure against, weighs 198 grams.

9. *Bike Tech* is correct in that we had this compound formulated "to help regular brakes provide good stopping power" (which they didn't have before). But consider this: If brake pads of this compound work well despite "weak arms and pivots," why should they be unsatisfactory with stiffer arms and pivots? Retarding force is governed by two things: pad pressure and coefficient of friction. With the same friction and pad pressure (even though you have to move the hand lever farther with weak arms), the retarding force (which bends the fork) will be exactly the same. So why should one judder and the other not?

10. On juddering, I've never been able to induce it on my bike—even with unbelievably severe testing—so I can't offer an explanation other than guesswork. Because weight is so important on good bikes, I wouldn't expect any manufacturer to use overly strong forks, so if our brake works so well on *some* bikes it must be satisfactory on *normal* bikes. Perhaps *Bike Tech's* test bike had too-light fork tubing, or the fork had been sandblasted too much and thereby thinned and weakened. Anyway, one juddering bike doesn't seem to indicate "pervasive problems." The only violent juddering I ever encountered was on a truck-like bike with hydraulic brakes having very weak arms of stamped sheet metal. I feel sure that that juddering was due to caliper arm flex, not fork flex. *Any* flex is bad.

11. Describing our brake parts, *Bike Tech* refers to a "large diameter pivot bolt." But this part is not a bolt; it's an L-shaped "post," slotted on one end to receive the head of the mounting bolt, and with internal threads at the other end to accept a retainer/adjuster bolt.

12. *Bike Tech* suggests a lower friction compound. This would simply require the cyclist to squeeze harder in order to stop as effectively, and that would create exactly the same force against the fork. So what would be gained? Worse, it might mean that they wouldn't be adequate in the rain.

It all comes down to this: brakes that will be fully adequate in the worst of conditions—steep hills, rain, steel rims, and a heavily-loaded bike—will be far more than adequate in normal conditions, and therefore the rider must learn to use them carefully, just as the first power brakes on cars required an educational period for drivers. For many years our instruction sheets for brake shoes have warned "brake with one finger to avoid over-breaking while getting used to." And it will be the same with our Superbrake.

Automotive experience teaches us that maximum rigidity of all brake parts is the goal. And certainly superior rigidity is the advantage that cantilevers have over center- and sidepulls, explaining riders' preference for them on tandems and mountain bikes.

13. Since this test, we've decided to stiffen further, particularly in the extended or long-reach position. And we've added roller spring pegs to reduce friction!

Anyone wanting the full, original text can send $2 to cover printing and postage, to Scott/Mathauser, Box 1333, Sun Valley, ID 83353.
Edward Scott

Stick-Slip

There's no way even an expert, if there are any in the bicycle brake field, could have looked at Ed Scott's brake ("On Scott's Brake," *Bike Tech,* December 1983) and known in advance that it had the problems that *Bike Tech* discovered. I have read enough articles and accounts of brake judder, squeal, and other forms of instability in automobiles, motorcycles, and aircraft to know that while it's obvious that stick-slip friction coupled with positive feedback from a natural frequency in the mechanism is the underlying cause, solving the problem is accomplished more by trial and error than by anything scientific.

There are many variables to play with. I would think that there is nothing fundamental about Ed Scott's brake that would prevent him from making some changes in stiffness and pad size to overcome the problem.

David Gordon Wilson
Cambridge, Massachusetts

Driven Oscillations

I think there is a better explanation than that in *Bike Tech's* analysis for the juddering phenomenon that occurred in *Bike Tech's* testing of Scott's brake.

Small variations in rim cross section width or local perturbations in surface flatness are inevitable in the best of extruded rims. My experience with cantilever brakes and rim design has confirmed that there can be problems in braking because of rim width variations.

Small rim width variations result in small changes in braking force for a constant lever position. The rider's reactions are not quick enough to accommodate these braking force fluctuations (constant lever position is more accurate and attainable than constant lever force for a human being). With the traditional caliper brake system, in which the actuating mechanism has a relatively small spring constant, these fluctuations are damped in the mushiness of the system. But in a brake system with a relatively high spring constant like Scott's brake, these force fluctuations are much more pronounced and can lead to system oscillation. Following this reasoning, we can describe the juddering as a damped driven oscillation, with the rim's perturbations being the driving frequency.

The lighter gauge fork deflects considerably farther than a more rigid fork and, therefore, makes the vibrations more noticeable. I have experienced this phenomenon on forks equipped with cantilever brakes.

Keith Bontrager
Bontrager Cycles
Santa Cruz, California

Testing Explained

I'd like to thank Mario Emiliani for his comments in the December 1983 *Bike Tech* regarding the article on frame strength that Jacquie Phelan and I did in the August 1983 *Bike Tech.*

In reply to your comment that "steel frames are strong enough," I recall several instances in which steel off-road frames bent at the head tube-down tube junction along with the fork. Accidents of this type are common for off-road bikes because they are pushed past their strength limit more often than road bikes. However, I know of two incidents in which the forks of heat-treated, oversize-tube aluminum bikes were bent while the frames were unaffected.

The main thing that we learned from our tests is how to substantially increase the strength of both steel and aluminum frames in the highly stressed head tube-down tube area with little increase in weight.

Your suggestion that the vise that supported the frames influenced the test forces may be true, but I am certain that its effect was negligible. We will check this factor when we run more tests.

You also suggested that we should have tested the frames dynamically rather than statically. I was originally planning to do the tests dynamically by dropping the test frames along a guide from a given height; the frames were to be loaded with increasing amounts of weight until failure was noted. However, static loading was chosen because it allowed us to observe the failure mechanism and also to measure the spring constants of the frames. I would like to do more tests using the dynamic method, and I plan to build more forward triangles for the purpose, if other manufacturers will contribute some as well.

I would, however, like to test wheels and forks independently of the frame so that we can separate the failure modes of each. We could then use this data to mate frames to forks that have a lower yield point than the frame.

Charlie Cunningham
Fairfax, California

In the June issue:

Headwinds:

Have you ever ridden your bicycle on a windy day and sworn that no matter what direction you head, you're fighting a head wind? Sometimes your perceptions are correct, as you'll learn in an upcoming *Bike Tech* article on how wind speed and direction affect a cyclist's speed.

Paint and Corrosion:

Imron® paint has earned a reputation as a tough durable paint that offers good corrosion protection. What is this stuff, and how does it protect your steel frame? In the first of a two-part article on painting with Imron®, *Bike Tech* presents a discussion on the chemistry of corrosion and how paints are formulated to combat it.

Chrome It!:

In the third installment of his series on surface finishes, Mario Emiliani discusses the process of chrome-plating.

In future issues:

Crankset Comparison: *Bike Tech* has initiated an in-house test on cranksets. We'll be measuring the bending and torsion in crankarms and crank spindles, and discussing the merits of various crankset designs. Watch for test results in the fall.

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.