Materials • Mechanics • Physiology • Engineering • Aerodynamics

BIKE TECH

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MATERIALS

Can Surface Finish Affect the Strength of Your Frame? Particle Blasting, Part II

Mario Emiliani

Part I detailed the factors influencing the rate at which metal is removed from frame tubes by particle blasting. Among the most important parameters are particle size, shape, and velocity. Experiments were performed to illustrate the dependence of material removal upon the particle type. The results showed that angular particles, such as sand, removed metal 2.3 times faster than similar-sized glass spheres, and that the wall thickness of thin tubes can be reduced significantly in the time it takes to particle blast frames.

Additionally, we saw that particle blasting can put microscopic pits and cracks into the metal's surface. These surface irregularities are a potential source for stress raisers that can endanger the structural integrity of the tubing.

If an energetic engineer wired a bicycle with strain gauges and analyzed the stresses encountered while cycling, he or she would quickly find that the stresses are cyclical. For example, each revolution of the cranks places an alternating stress on the tubes connected to the bottom bracket. Other types of cyclic loading are produced by bumps, potholes and even just getting on and off the bike.

The magnitude of these stresses can vary considerably. For example, an uphill sprint

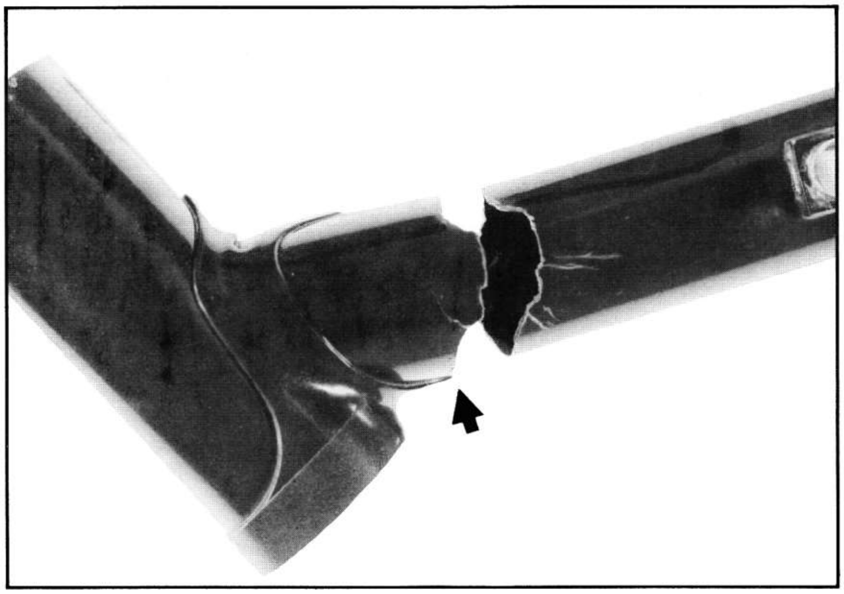

Figure 1: This fractured frame tube was weakened and may have failed from sand blasting.

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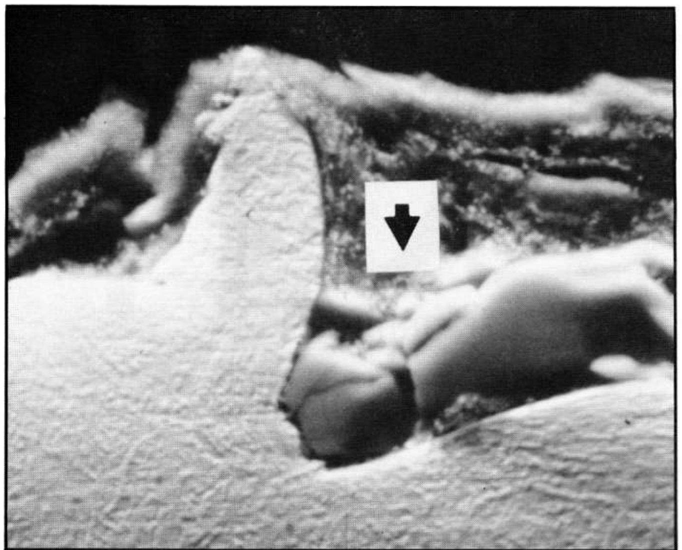

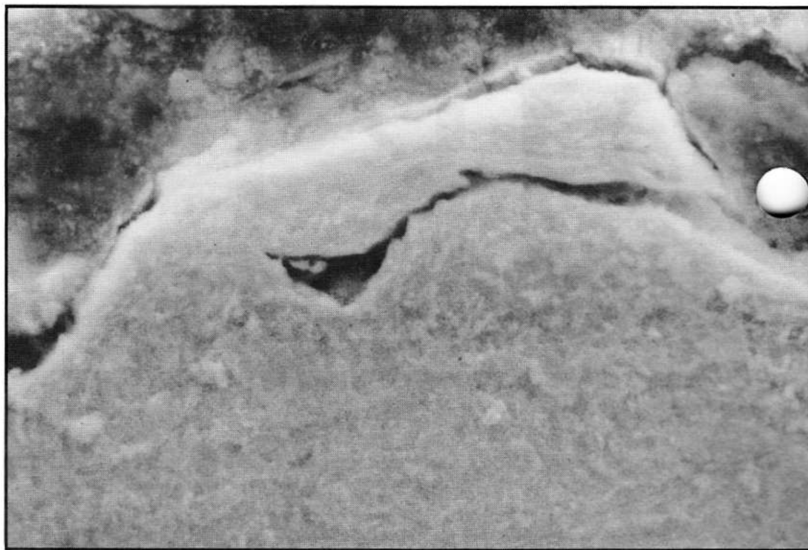

Mario Emiliani

7 microns —— Figure 2a

Figure 2b 7 microns ——

Figure 2: Surface irregularities and embedded particles are telltale signs of particle blasting. Figure 2a shows a raised lip and an embedded sand particle. Figure 2b reveals a piece of Reynolds 531 tubing on the verge of detachment.

will put stresses into a frame far above those incurred by pedaling at a steady cadence on level ground (input torque in all-out sprinting can go as high as 150 ft-lb). Road-induced stresses can range from low magnitude thumping caused by expansion joints, to a one-time, frame-jarring stress caused by a pothole. So a typical ride will expose the frame to many different types of pedaling and road stresses that vary in quantity and magnitude.

Pedaling simultaneously produces tensile, compressive, bending, shear, and torsional (or twisting) stresses on the down tube, seat tube, and chain stays. These stresses alternate on different parts of the tubes as the cranks rotate through 360°. Road shocks will usually produce bending, compressive, and tensile stresses, mainly in the front fork, the head tube/down tube and head tube/top tube junctions, and the rear stays. When more than one type of stress acts simultaneously upon a component, the effect is called combined loading.

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Tensile Stress

One of the most important types of stress to consider in materials science is tensile stress. Tensile stress is a pulling stress; strings break under tensile stress when the pulling force exceeds the strength of the molecular bonds. All materials can resist being pulled apart to some degree; how much force is required is a measure of the material's yield strength. Tensile stresses can exist by themselves, or as components of other types of stresses. For example, a component of tensile stress can be found in bending, shear, and torsion.

When any metal is subjected to cyclic stresses, it is possible that the metal will weaken, distort, or crack; in general, it can fail. This type of failure is called fatigue failure.[1] Fatigue failure will occur at a stress level below that needed to cause failure by the application of a single load (like in a tensile test). Since the stress applied to a metal that has failed by fatigue appears low, it's usually assumed that the metal's yield strength was not exceeded. This is not correct; at some point in the metal's microstructure, the yield strength was exceeded because there was a local concentration of stress sufficient to pull apart the metal's molecular bonds.

Stress concentrations are small areas on the surface or within the metal where the stress of an applied load is concentrated. This local increase in stress can be many times greater than the stress in adjacent areas and can often grow in magnitude to well beyond the yield strength of the metal. Under this condition, the concentrated stress will seek relief by breaking the metal's molecular bonds: a crack will form. If repeated tensile stresses are put into the area, the crack will continue to grow as more molecular bonds are pulled apart each cycle.

Stress Raisers

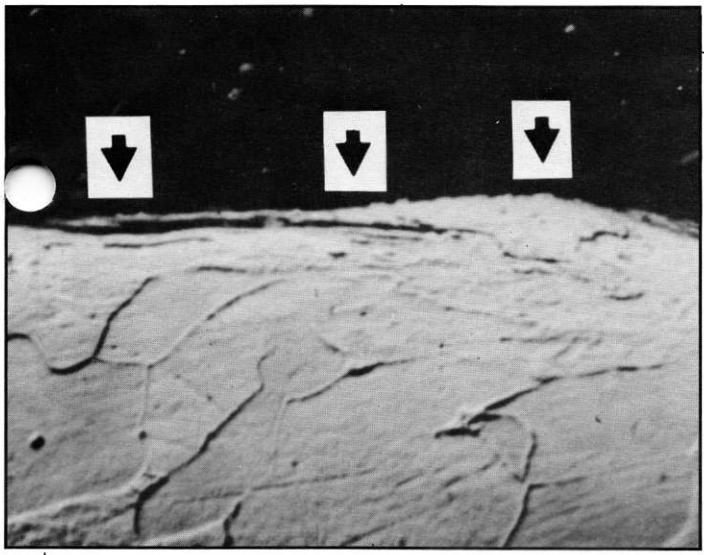
Areas that are likely to harbor stress concentrations, or stress raisers, are holes, grooves, scratches, errant file marks, and foreign substances within the metal, like oxide inclusions.[2] In general, stress raisers appear any place where there's a discontinuity, or sudden change, in either the molecular structure or the cross section of the metal. These types of stress concentrations can be found in any metal component, but on a bicycle frame, there are several particular points where they're likely to be. These include the points on lugs, fork blade and chain stay reinforcements, and some styles of fork crowns, in addition to any sharp-angled cutouts these components may have. And, as we saw in Part I of this article, the pits and cracks placed in the frame's surface from particle blasting can act as stress raisers.

Fatigue Resistance

The magnitude of stress that is concentrated at one point is determined by the size,

1. For a comprehensive discussion, see "What is Fatigue," by Richard Brown, Bike Tech, *October 1982.*

2 Oxide inclusions are non-metallic impurities trapped within metals upon solidification.



7 microns Figure 2c

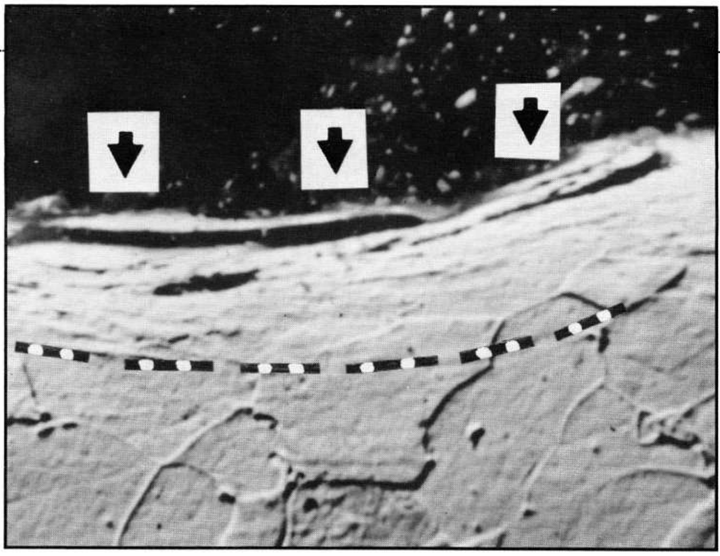


Figure 2d 7 microns

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The thin flakes of metal and plastic deformation beneath the surface shown in Figures 2c and 2d are the result of glass bead blasting.

or radius, of the discontinuity. The smaller the radius, the greater the stress concentration. Sharp pits and cracks create the worst type of stress raiser because the radius of the crack tip is so small. Nearly every other type of defect is less severe, but they can still cause trouble, especially if the component is loaded beyond its intended use.

It is wise, then, to design and manufacture a component with a minimum amount of natural stress raisers if maximum fatigue resistance is desired.[3] With our knowledge of the perils of particle blasting, it would seem foolish to jeopardize the fatigue resistance of a component by subjecting it to the pitting action of fast-moving particles of sand or glass. But, interesting enough, some engineers believe that particle blasting can actually increase the fatigue resistance of metal by work hardening the surface of the metal (see the accompanying article, "Peening").

Surface Tension

When molten metals solidify, the atoms settle into distinct arrangements. Occasionally there are defects in the packing sequence which causes an uneven distribution of forces between atoms. But if we assume that all atoms are packed ideally so they are positioned symmetrically with respect to their nearest neighbors, then the forces acting upon atoms inside a metal will be the same from all directions. But atoms on the surface of metals aren't being pulled equally from all sides; they feel a net pull inward from the atoms below. The result is that the surface is placed in a state of tension. Since the surface of metals is normally in tension, it's no surprise that fatigue cracks tend to initiate there. Cracks can also form within metals, but this is less common.

Particle Blasted Frames

The series of Figures 2 and 3 are photomicrographs of various portions of expensive racing and touring frames that have been particle blasted. All photos are cross-sectional views of the tubing surface. Figures 2a and 2b show portions of an investment-cast lug and a Reynolds 531 tube, respectively. Notice the highly irregular surfaces. This is characteristic of metals which have been particle blasted with angular particles. Figure 2a shows a lip of steel displaced by an angular particle. The particle fractured upon impact and became embedded in the lug (arrowed). Figure 2b shows another lip of steel that is near the point of detachment.

Figures 2c and 2d show the eroded surfaces of a stamped lug. The smooth surface indicates this frame was particle blasted with small spheres. Both figures show thin flakes of metal that are at the point of detachment (arrowed). In addition, notice the small voids beneath the thin flakes in Figure 2d. Between the irregular surface and the dotted line in Figure 2d is a deformed region of metal that looks compressed. This region is marked by lines of plastic deformation, called flow lines. The depth of these lines indicates the depth of work hardening that the metal received from particle blasting. In the pictured sample, the work hardened region is about ten microns deep.

More Cracks

Figures 3a, 3b, and 3c show more cracks produced by particle blasting. Figure 3a shows an investment cast lug which has previously been particle blasted with angular particles. Note the embedded particle fragment and non-metallic inclusion to the immediate right and left of the large arrow, respectively. There is also a large crack at the base of the lip (small arrows). (Figure 3b is a higher magnification photo of this crack.) Figure 3c shows a crack in a Reynolds 531 tube; to the left of the crack is an embedded angular particle (arrowed). Note the flow lines around the crack.

Embedded particles, flow lines, thin flakes, subsurface voids, raised lips, and surface roughness are all characteristic features produced by particle blasting. The unwanted by-product of these characteristics is, of course, the microscopic regions of high tensile stress: stress raisers.

Frame Failure

In fatigue failure analysis, the role of stress raisers is central; but, in spite of the telltale characteristics imparted to a metal's surface by particle blasting, particle blasting is rarely considered as a possible cause of frame failure. I believe, however, that many frame failures can be traced back to excessive or improper particle blasting.

A well-known American frame builder I know recently had a custom touring frame fail. The frame was about two years old, and was made of Columbus SL tubing. The frame was used by a commuter and had about 10,000 miles on it. The actual riding conditions at the time of failure (i.e. rider weight, road conditions, etc.) are not known, but the bicycle wasn't in an accident and it took two years to fail, so it's likely that fatigue was the cause of failure.

The framebuilder suspected the tubing manufacturer was responsible because the failure was very close to the Columbus dove identification stamp on the tube (this was be-

[3]*See "Stress Raisers in Bicycles," in the October 1983* Bike Tech.

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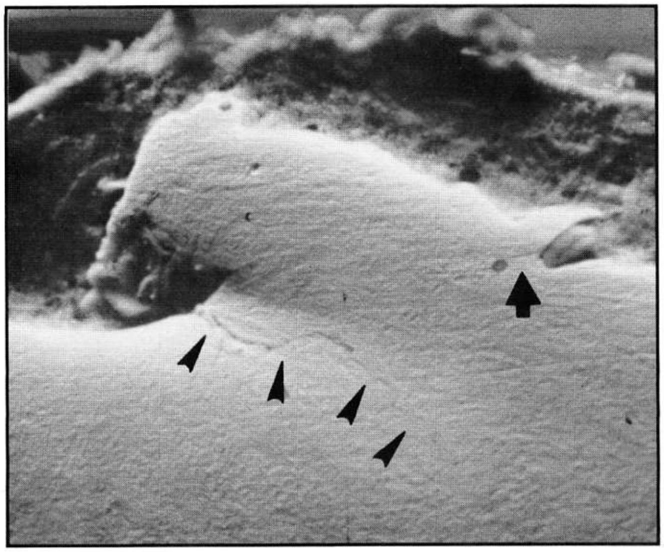

10 microns —— Figure 3a

Figure 3b 7 microns ——

Figure 3: Surface cracks and embedded particles plague a particle blasted frame. Note the crack (arrowed) forming in Figure 3a. Figure 3b gives a closer look.

fore the tubes were marked by the less destructive methods now employed. See Part I of this series in the December 1983 *Bike Tech* for more details on tube marking.). He sent the failed frame to Columbus S.r.l. for failure analysis. Columbus in turn sent the frame to the University of Milano, Department of Solid Mechanics. A short while later the framebuilder received a report from the university detailing their analysis of the cause of failure. The framebuilder then sent the report to me to see what I thought of it. Figures 1 and 4 were taken from the report.

Faulty Pickling?

Figure 1 shows the failed portion of the frame. The point of failure at the tip of the lower down tube/head tube lug (arrowed), is known to be highly stressed during cycling. It's not uncommon for frames to fail at this location.[4] Figure 4 is a cross section showing the outer surface of the down tube near the failure. Cross sections taken from other areas revealed the same type of surface features.

It's clear from Figure 4 that this frame was heavily particle blasted with large angular particles. Note the embedded particles (arrows), flow lines, and surface roughness. The report concluded that the frame failed as a result of the stress concentrations produced by these pits near the highly stressed lower lug point.

Interestingly, though, the investigators concluded that the pits were caused by "... a faulty pickling process made before varnishing the frame." "Pickling" means that the frame was placed in a corrosive liquid to clean it prior to painting. But pickling cannot deform metal, create flow lines, and embed abrasive particles such as are clearly observable in Figure 4. And, since either cleaning method works well, why would a professional painter take the time and expense to do both?

Uncertainties Remain

While both the investigators and myself acknowledge that the pits in the tubing very likely instigated frame failure, we don't agree on their origin. Nor can it be said that they were the only cause of failure. There are too many unknowns involved, including the history of stresses in the frame from the rider's weight, his baggage, and the innumerable road shocks encountered during two years of steady riding. The report from Italy did not include a stress analysis nor did it indicate if the investigators had checked for any other fatigue cracks, measured the thickness of the tubing around the break, or investigated the brazing at the joint.

Curiously, though, photos that accompanied the report showed that there were several oxide inclusions in the area of the break; one photo revealed an oxide inclusion in the fracture zone. The report judged that these inclusions were normal and did not contribute to the failure.

The failed frame is no longer available for investigation so the real cause of failure will never be known. But the evidence strongly suggests that the stress raisers put into the tubing surface by particle blasting helped to initiate the cycle of fatigue failure.

Precautionary Measures

The frame failure in this story was dramatic, whatever the cause. The evidence in this two-part story suggests that more attention must be paid to the deleterious effects of particle blasting in future frame failure investigations. But of all the frames made, only a small fraction fail in normal use. This indicates that intelligent frame design and correct selection of tubing gauges gives most frames a large safety factor and, therefore, a healthy tolerance for the abuses of particle blasting.

But a frame purposely built at the limits of safe structure—one built with ultra-thin Reynolds 753 or Columbus Record tubing, for example—must be blasted with utmost care, or else cleaned by another method. Other methods include pickling, chemical stripping of old paint, wire brushing, and sanding. The first two can be economical if a large number of frames are involved, but there are problems in flushing the acids out from the tubes. The latter two are tedious and not well suited to clean hard-to-reach places.

So, the method of choice for an overwhelming number of builders and painters is particle blasting. This being the case, it's important that the safest methods for particle blasting be outlined. Here are my suggestions:

Angular particles are the worst to use because they remove metal with nearly every impact and leave sharp pits on the tube's surface. And the larger the particle, the worse the damage. Spherical particles are

[4] *Personal communications with Fabrizio Giussani, metallurgist, Columbus S.r.l.*

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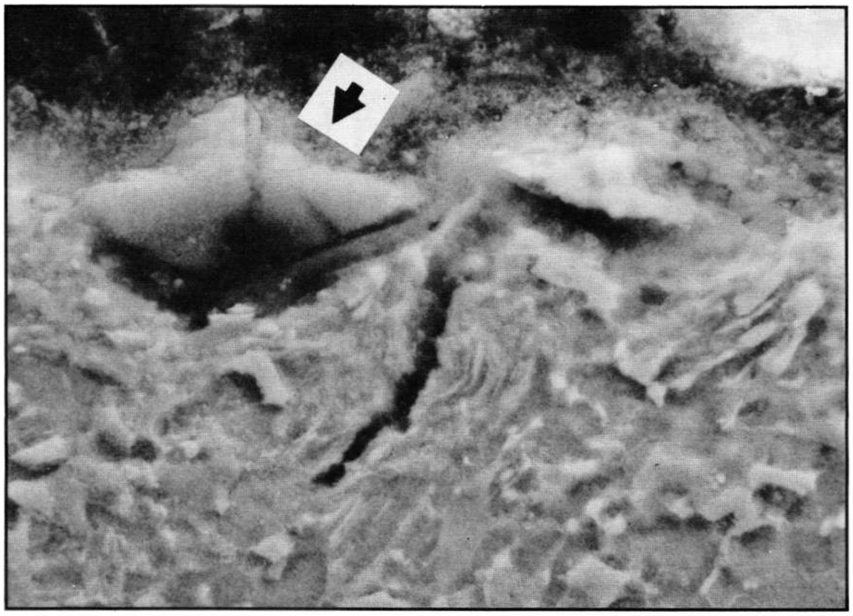


7 microns ——— **Figure 3c**

Both a crack and flow lines (see text) are evident in Figure 3c.

24 microns ———

Figure 4: Deep pits like these create stress raisers that can cause fatigue failure of steel tubing.

less destructive, but are also less able to remove brazing flux, old paint, etc.; this is especially true for the smaller sized particles.

So we need to strike a compromise. If angular particles are used, they should be small—no larger than about 100 microns (140 grit). If spherical particles are used, they should be between 70-210 microns (75-160 grit) in diameter. In addition, the gas pressure (or particle velocity) should be set as low as possible to do an effective job. Above all, if a frame must be particle blasted, it should be done for the shortest amount of time.

Part III of this series will appear in the June issue.

MATERIALS

Peening

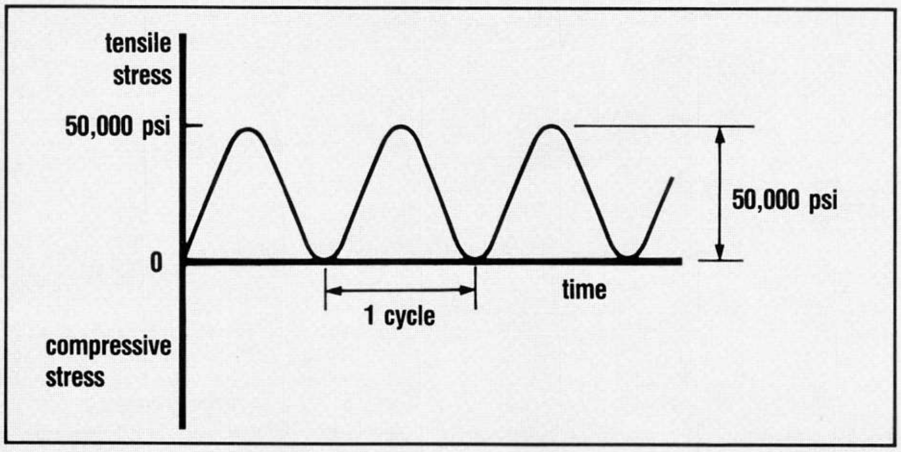
One way of improving a metal's resistance to fatigue is by altering the surface so that it is in compression instead of tension. In the old days, steels were very crude and contained many oxide inclusions. This limited the service life of cyclically stressed components. Then blacksmiths figured out that they could improve the fatigue strength of steels by hammering the surface. What they did was cold work (i.e. permanently deform) the surface by repeatedly striking it with a ball peen hammer. This placed what is called a residual compressive stress on the surface. This practice is known as peening.

Peening by hand is very labor intensive, so other means were developed to work harden the surface. Shot blasting is one such method. Hardened steel balls are propelled to high velocity using compressed air and then aimed at the surface of the metal like a thousand little hammers. Glass bead blasting, as the name implies, utilizes spherical glass beads to do the same job.

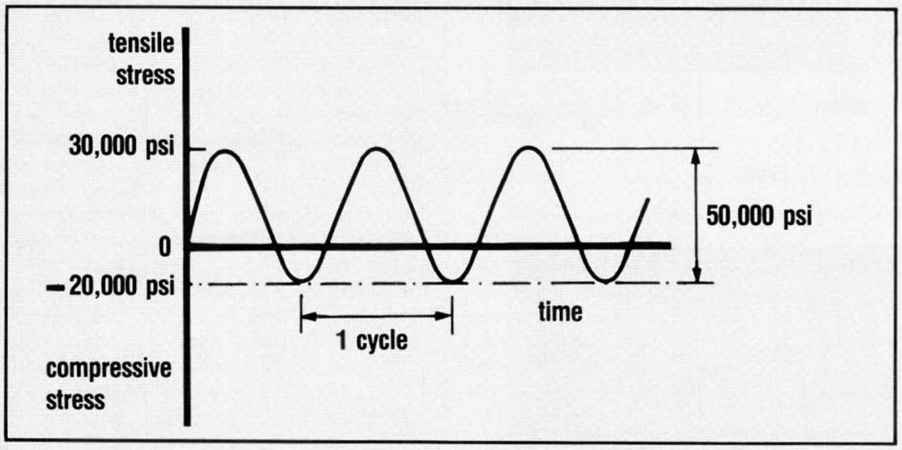
Figure 1a and 1b illustrate how peening improves fatigue resistance. Let's assume an unpeened piece of steel undergoes a simple cyclic loading sequence as shown in Figure 1a, with a maximum tensile stress of 50,000 psi and a minimum stress of zero psi. This equates to an average tensile stress of 25,000 psi. A peened specimen of the same type of steel undergoes the same cyclic loading sequence as shown in Figure 1b. However, notice the dotted horizontal line indicating zero stress. This shows that the surface of the peened specimen has a residual compressive stress. We'll assume the magnitude of the compressive stress is 20,000 psi. With this amount of compressive stress, the peened specimen can support a tensile stress of 20,000 psi and have zero net stress on its surface. Thus the net maximum tensile stress on the peened surface is 30,000 psi (i.e. 50,000 psi minus 20,000 psi), and the average tensile stress is only 15,000 psi.

It's clear that the specimen without a residual compressive stress is subjected to a greater maximum tensile stress. Also, a peened surface will be more resistant to cracking under cyclical stress and the component will have the capacity to operate under higher stresses and not fail by fatigue.

It's important to realize that a residual compressive stress can only be obtained by using spherical particles. Part 1 of "Particle Blasting" showed that one impact compressed the metal, but that after several coincident impacts, metal began to flake off. So the surface can be work hardened by glass beading, but there is only a brief "window"



Unpeened sample **Figure 1a**



Peened sample **Figure 1b**

Figure 1: Cyclical loading of unpeened (Figure 1a) and peened (Figure 1b) steel samples. Unpeened sample has a maximum surface tensile stress of 50,000 psi; peened sample has a surface compressive stress and "feels" a surface tensile stress of only 30,000 psi.

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between work hardening and metal removal. Angular particles, on the other hand, remove metal with nearly every impact, so it is impossible to form a surface compressive stress with them.

But questions about glass beading remain. If peening imparts a residual compressive stress to the surface, then there must be a corresponding residual tensile stress somewhere within the metal. According to metallurgical theory, the residual tensile stress lies below the surface layer in compression. But if the compressive layer is not uniform, then there might be areas of tensile stress on or near the surface which can provide avenues for cracks to propagate. And if any cracks do form on the surface, is the surrounding compressive stress high enough to prevent the concentrated tensile stress from enlarging the crack or not?

These questions are not easy to answer. Successful work hardening by glass beading will occur only under carefully controlled conditions. Even then, a conscious effort may do more harm than good and, ironically, a simple clean-up job involving a quick pass over the frame with a blast of glass beads may leave a well-compressed surface.

Peening has additional limitations. It has little effect on high-strength alloys because they don't work harden as much as softer alloys. Metal will be removed before an adequate residual compressive layer can be developed. Peening also has minimal effect when the operating stresses are near the yield strength of the metal. Because of these limitations, and because of the advent of stronger alloys and improved design, production, and finishing techniques, peening metal for fatigue resistance is not used much today.

Mario Emiliani

SHOP TALK

Chain Behavior in Front Derailleurs

Crispin Miller

At first glance, the front derailleur seems like the simplest control mechanism on a bicycle—just a pair of plates to shove the chain back and forth between a set of chainwheels. But given its task and location—operating on the taut, power transmitting portion of the chain with minimal clearances between the crank and frame—it really can't be much more sophisticated than it is. Whereas the rear derailleur can control the chain in an S-curve over rollers, the front can never grip the chain, yet manages to work well, if it is properly adjusted.

In the last ten years, the front derailleur's shifting ability has improved, but because the mechanism is so minimal, the chain is free enough when being thrown from one chainwheel to the other that it can behave in ways that aren't always obvious. If you watch the chain carefully, and think about it, this behavior can suggest design features to shop for in a new derailleur and adjustments you can make on your existing one that can make a big difference in shifting performance.

(In this article I'll assume that you already know how to do the basic adjustments like setting the stop screws and adjusting the cable. For help with these adjustments, see "Front Derailleur Adjustment" in the Repair Stand column in the February 1984 issue of *Bicycling.)*

Three Problems

The challenging part of a front derailleur's job is to get the chain from a small chainwheel to a larger one. (Unless you have basic adjustment problems or improper chainwheel spacing, going the other way is easy.) Shifting up can encounter three types of problems:

—You grind along, halfway shifted, the chain unwilling to climb up onto the teeth of the larger chainwheel.

—The chain climbs up but unships.

—The chain jams between the upper chainwheel's teeth and the inner cage plate of the derailleur, carving metal off both components as you continue to pedal and fumble with the shift lever.

I'll discuss the last problem first because it involves a design feature that you can select in a new derailleur but can't change in one you already own.

Ramp Turned Sideways

The chain jams because one of its links gets trapped between the inner cage plate and the larger chainwheel, a consequence of the cage forcing the chain sideways too far, too quickly, before the chain can climb up onto the chainwheel. But pushing against a taut chain for a quick shift is the proper action of a front derailleur, so how are we to prevent the jamming problem?

The answer is that there are two ways that the cage can deflect the chain, and one works better than the other. Both ways have to do with how the cage is oriented in relation to the chainwheels. The first way is for the inner cage plate to be parallel to the chainwheels, so that as the cage moves, it nudges the length of chain within its plates towards the large chainwheel (see Figure 1a).

If the cage plate is parallel to the chainwheel, its side force on the chain can be increased only by the rider's active operation of the gearshift lever. If the cage sits still, a given link can travel through the cage without encountering any change in sideways clearance or force; if it doesn't climb onto the larger chainwheel, it can exit the front of the cage. In this case, it's unlikely that the cage will exert a damaging force on either the chain or chainwheel.

Oblique

But if the inner cage plate is not parallel to the chainwheel, but is positioned so that its nose is closer to the chainwheel than its tail, then as the cage moves into contact with the chain, it forces the chain to run in a diagonal path (see Figure 1b). This oblique diversion of the chain can wedge the chain into the chainwheel and, if it doesn't climb up, it will wedge between the cage plate and chainwheel.

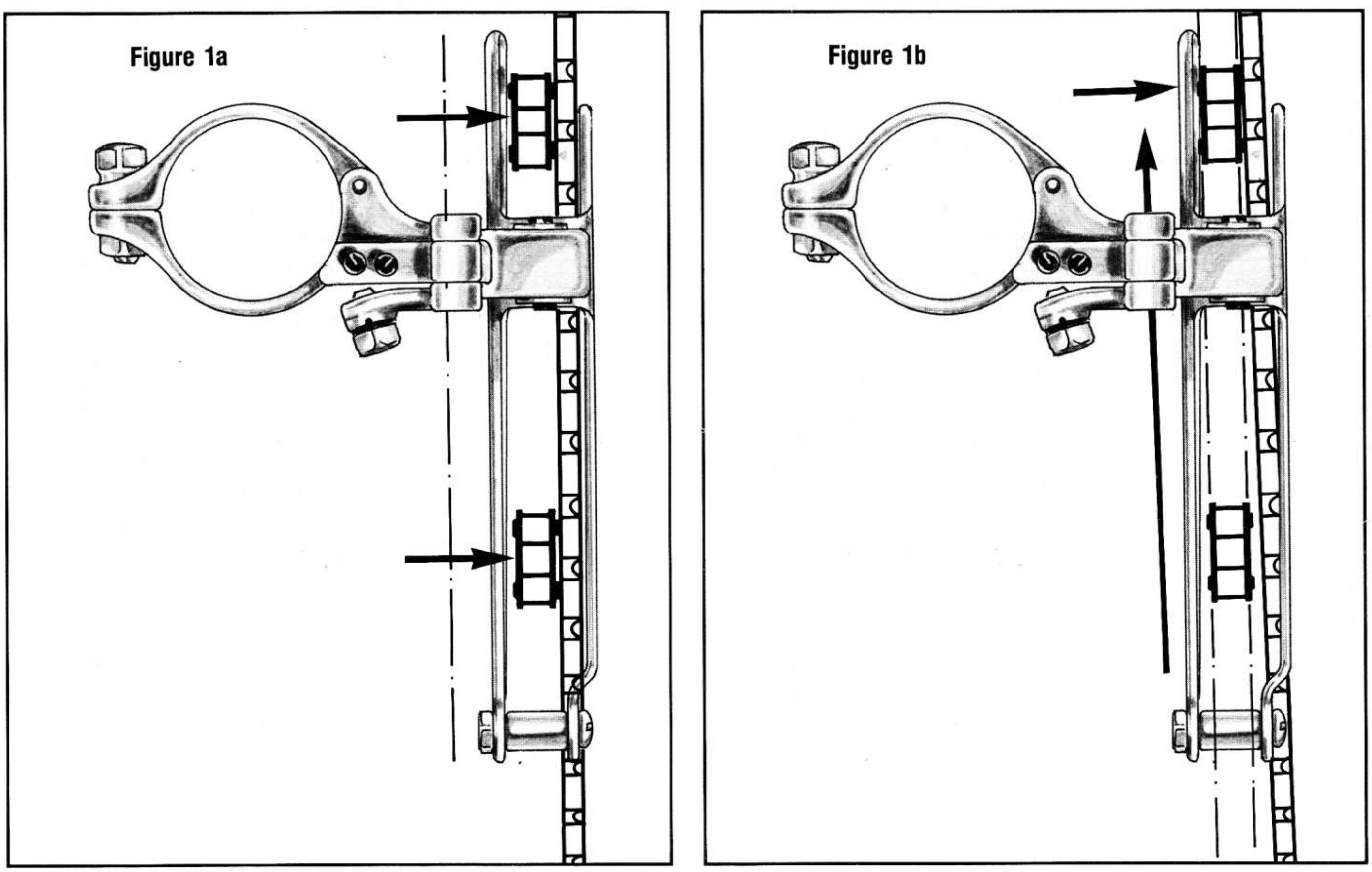
Fortunately, even with the inner cage plate oblique, the cage will usually deflect enough at its support not to trap the chain up at the nose. But if the chain starts to wedge farther back in the cage, it's likely to cause trouble. This problem is prevalent on bicycles with wide-range front gearing because the chain is so low on the small chainwheel that it passes through the back end of the cage. This means that any obliqueness in the cage adds up to a lot of sideways wedging by the time the chain travels to the front of the cage. To compound the problem, the chain's initial contact with the cage is so far from the supporting linkage that it's easy for the side force of the chain to flex the back of the cage and skew it even more.

Minimizing Wedging Angle

A derailleur for granny gearing, then, ought to have a cage with a rigid rear section. (Frank Berto includes this characteristic in his ratings of front derailleurs in the March 1980 issue of *Bicycling*.) A helpful adjustment to minimize this wedging angle is to mount the derailleur with its tail pointing away from the bicycle as far as the outer plate/crank arm clearance will allow.

So far I've described the jamming problem as if the chain were only caught between the cage on the left and the chainwheel on the right. But with a triple chainwheel, the chain can also get in a vertical snag between the chainwheel below and the cage plate above. This problem is attributable to the shape of

Figure 1: Two ways to make a chain move sideways. These top views of the front derailleur show the inner cage plate parallel (Figure 1a) and oblique (Figure 1b) to the chainwheels. Parallel plate moves chain by cage motion; angled plate moves chain by ramp action.



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the inner derailleur cage plate. Many derailleurs' inner plates have a lower edge that is not concentric with the chainwheels. This means that the vertical clearance between the plate and the teeth of the smaller chainwheels decreases towards the front of the cage (see Figure 2a). If your bicycle has half-step-plus-granny gearing, this excessive clearance at the tail of the derailleur is enough to cause vertical wedging.

The best solution for this wide-range gearing problem is to buy a derailleur designed for the job. A few manufacturers have offered a solution: derailleurs are available with an inner cage plate that more closely follows the contour of small chainwheels. Examples of this type are the SunTour AG Tech and the Shimano Deore XT. This type of cage shape is easily recognizable because the lower edge dips down and then levels out towards the fixing bolt at the rear (see Figure 2b).

Overboard

The other two problems—a grinding chain and a chain that shifts but then unships—are more responsive to adjustments, but they still involve subtle aspects of chain behavior. They really are part of the same problem: how to get the chain up onto a large chainwheel without it being thrown overboard.

Push and Catch

When the inner plate pushes the chain into the larger chainwheel, the chain has to veer sideways. A chain is not very flexible in the lateral direction; once it's pointed sideways it wants to keep going. The chain often goes a bit beyond the teeth of the chainwheel, but, with luck, it gets caught by the outer plate before it unships. Once it curves back to straight ahead, it drops onto the chainwheel's teeth and grabs hold. The important dimension of the derailleur is that its outer plate be close enough to this action to keep the chain from going overboard.

This behavior of the chain means that you need the "pushing" plate to come close to the large chainwheel when executing a shift, but the "catching" plate can't move too far away. The spacing between the two cage plates is a delicate compromise. On the one hand, the plates must be far enough apart to allow clearance for the various alignments of the chain and chainwheels. But they also have to be close enough to keep what little control these plates can exert on the chain to execute a shift.

(One elementary point about this trade-off is that it's very important that the derailleur cage be mounted as low as chainwheel clearance allows. This assures that the derailleur isn't always trying to shift with its tail. Besides making shifting vague, an improperly mounted derailleur invites the jamming problems described earlier.)

Wide and Narrow

The optimum design for a front derailleur is out of necessity a compromise between the wide and narrow demands. But a simple modification to the derailleur cage may alleviate the mediocre shifting inherent in this compromise.

When a chain is in gear, it's nestled down onto the chainwheel teeth with its rollers in the notches between them. In this position, the chain needs a lot of clearance. But when a chain undergoes a shift, it will be dancing around on the tops of the teeth, about a quarter-inch higher. Here is where close control of the chain is needed so, ideally, the cage should be narrow. If a derailleur's cage were wide on the bottom but narrow at the top, then you could have both the clearance and control for good shifting.

I'm not aware of any derailleurs with cages that come this way, but if you are not adverse to a bit of metal work, you can easily bend your present derailleur to conform to this idea. Try twisting the nose of each plate in a little bit, so that their bottoms are still full width but their tops are pinched in about a $^{1}/_{16}$ of an inch each side. The cage's supporting linkage may not be too strong, so it's important to use two pairs of pliers, one to do the bending and the other to hold the plate.

I've found that this modification can make a mediocre shifting derailleur work rather well, especially one employed in a wide range gearing setup.

Figure 2: Different shapes of derailleur for different jobs. Figure 2a depicts traditional derailleur for narrow range gearing; Figure 2b shows new-style derailleur with modified inner cage plate. The constant radius of the inner cage plate reduces chain jamming and improves the shifting of wide-range front gearing.

Figure 2a

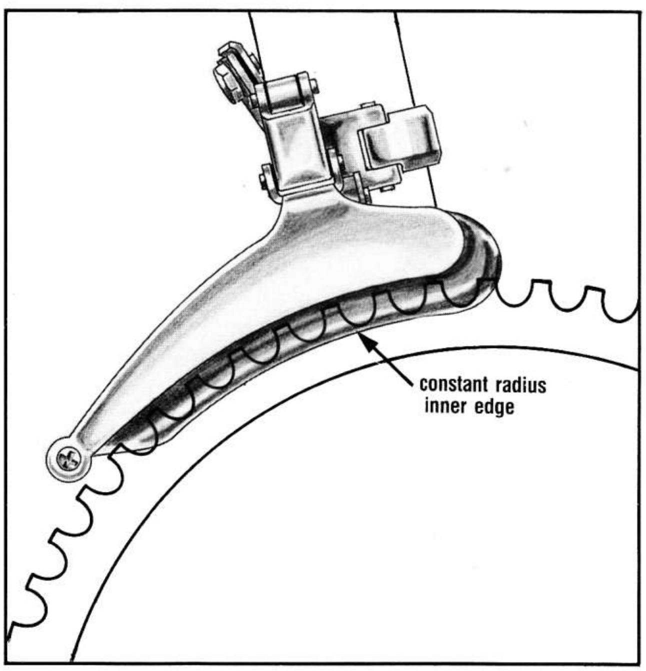
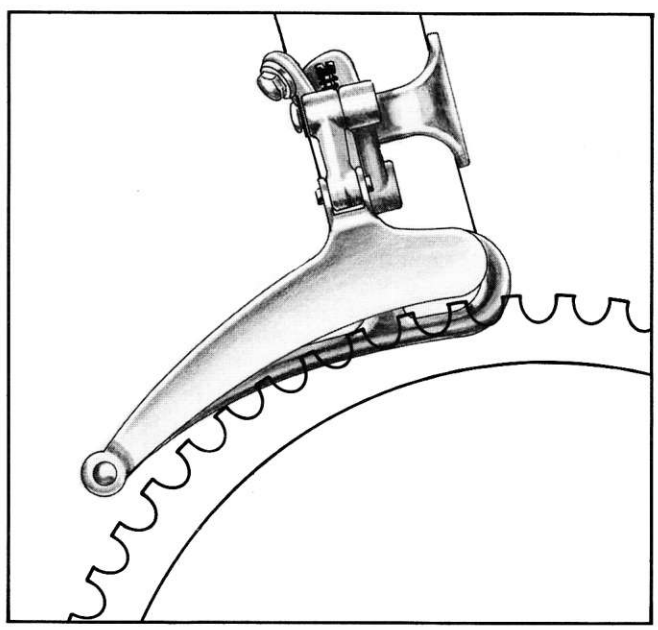


Figure 2b



George Retseck

SPECIAL HPV SECTION

New Technology from Indianapolis

Tom Healy

Despite the absence of several of the most successful performers in past years — notably the Vector tricycles, the Phoenix, the Other Woman and the Quantum Cruiser — nine vehicles topped 50 mph and three world's records were set in the 1983 International Human Powered Vehicle Association (IHPVA) Speed Championships, held in Indianapolis in October.

The most important technical highlights were enticing:

—High-technology composite fairings began to elbow aside heavy fiberglass fairings.

—More vehicles combined elements of day-to-day practicality with high speed potential.

—A new one of these more practical vehicles, which is similar to one routinely used by its owner for daily commuting, became the fastest two-wheeler in history.

—The 4,000 meter pursuit, which takes a national-class rider 4:41 on a conventional bike, became a sub-four-minute event.

Makeshift Race Sites

Perhaps more importantly, though, the event was put on a firm foundation that should help strengthen it — and speed development of alternative bike designs — in the coming years. The IHPVA race had been without a permanent home since after the 1980 event, when its customary home, the legendarily fast Ontario Motor Speedway, fell victim to southern California's suburban sprawl. So IHPVA gypsied between makeshift race sites in 1981 and 1982 before being welcomed to Indy for its ninth annual event.

The Indianapolis Motor Speedway, the most well-known of the four race courses used during the three-day event, has a rich tradition of technical development through racing. Originally built by former bicycle racing entrepreneurs as a proving ground for the then-fledging auto industry, the Indy track has been a proving ground for innovations ranging from rearview mirrors to improved tire and brake compounds to lightweight structural materials and new aerodynamic shapes.

Some 62 entrants participated in nine separate speed contests and one practical vehicle judging. There were two 200-meter sprints, one with unlimited run-up and one with 600 meters of run-up, both held at the

Dan Bonwell

***Dragonfly* ready to roll.**

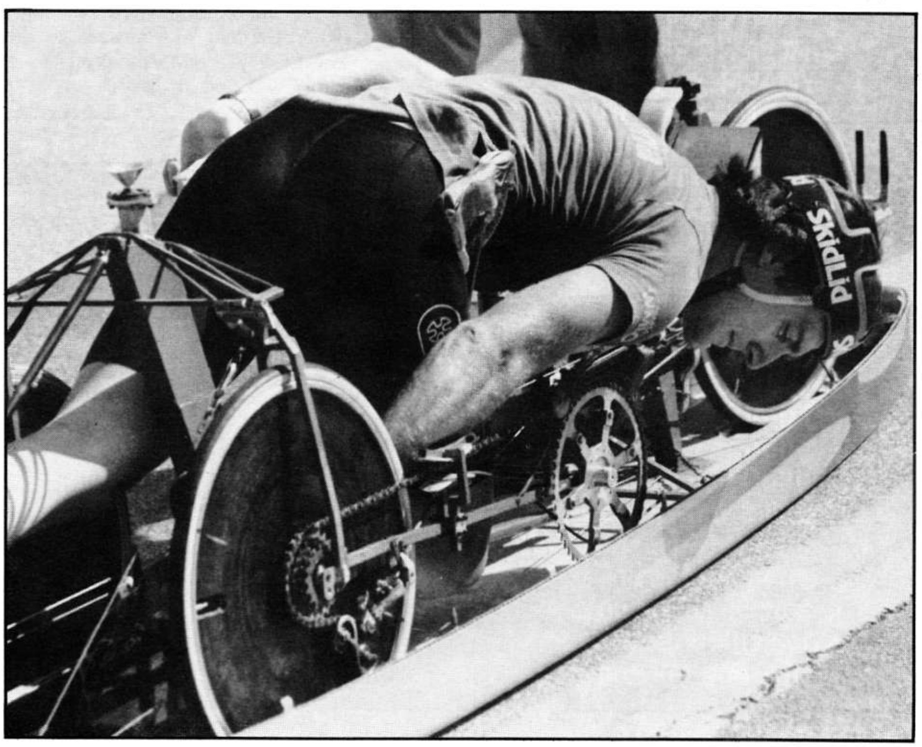
speedway. The new Major Taylor Velodrome was the site for the 4,000-meter pursuit.

Indianapolis Raceway Park hosted the quarter-mile drags, a 20-kilometer LeMans start and 30-kilometer paced start road races; the twisting, hilly two-mile circuit at Eagle Creek Park hosted the eight-kilometer LeMans start and 32-kilometer paced start road races, and a 10-kilometer road race as part of the practical vehicle competition.

With a 10-year history and solid footing, the IHPVA is now in a position to significantly influence the future direction and design of bicycles and practical commuting vehicles. Although the majority of the developmental work has been done within the confines of the racetrack, recent activities have spilled over into the more familiar world of cycling.

IHPVA stalwarts Chester Kyle, Paul McCready, Allan Abbott, and Jack Lambie have been lending their talents to the 1984 U.S. Olympic Cycling Team's efforts through the Elite Athlete Program of the U. S. Cycling Federation (USCF), redesigning and refining the aerodynamics of the conventional bicycle. Many of their ideas were first tested in the competition of the IHPVA races.

One measure of the IHPVA's influence came this year on the 50th anniversary of the Union Cycliste International (UCI) ban on recognizing streamlined bicycle records. Now, a half-century later, the UCI's domestic arm, the USCF, is giving serious consid-



Dan Bonwell

Richard Byrne readies himself for a run in Steve Ball's *Dragonfly.*

eration to allowing an "open" class in its national championships.

Kevlar, 38 Pounds

Among the most notable entries was a brand-new and very fast lightweight. At 38 pounds, Tim Brummer's Lightning X2 may end the era of the heavy fiberglass Vector-type vehicles. Noteworthy because it resembles Brummer's day-to-day bike, the Lightning X2 is a semi-short wheelbase (44-inch) bike with an 18-pound high-technology fairing, composed of Nomex honeycomb in between slices of Kevlar. The fairing is hinged at the front for easy ingress and egress, and push-out flaps underneath allow the rider to catch his balance when coming to a stop.

And Carl Sundquist, Indiana's kilometer and match sprint champion, rode the Lightning X2 to the "world's fastest bicycle" record with a 54.78 mph effort in the 200-meter sprint — only two days after seeing the bike for the first time.

Sundquist undoubtedly would have set more records, but he had to miss many of the events to be at his job. He couldn't even make his third run at the 55-mph barrier for that reason; he had ten minutes to get to work when he jumped out of the bike. Despite these successes, Brummer isn't satisfied: he feels he can shave off more weight, improve the fairing, and make the bike still faster.

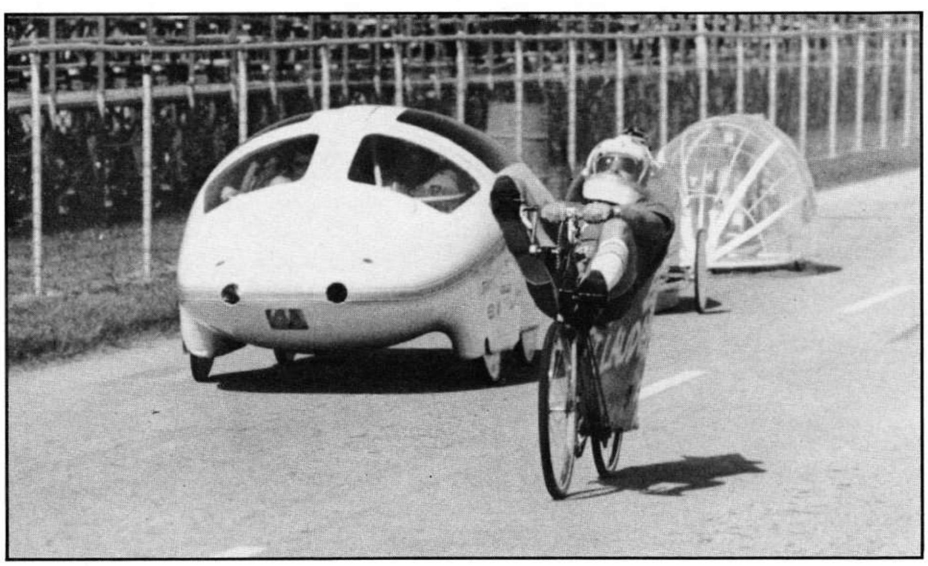
But the Lightning X2 was not the dominant machine. Excellent aerodynamics and maneuverability allowed the two Easy Racers to overcome their heavy fairings (each fairing weighs 55 pounds) to win four road races and the practical vehicle contest, take second in a fifth road race and in the flying start 200 (in 53.2 mph, faster than last year's winning time), and, with help from 1976 Olympic cyclist Fred Markham's horsepower, clock 3:54.95 for the 4,000-meter pursuit.

Dan Bonwell

Murray Wilmerding pilots a freshly repaired *Moby Infinity* around the Major Taylor Velodrome.

The Easy Racers differed from the similarly successful 1982 versions only in gearing; under the fairing, they're the same bike that designer Gardner Martin sells to the public. For next year, Martin promises a lighter replacement for his fiberglass fairing.

A two-wheeled hand-powered version of a conventional track bike, designed by Al House as a senior mechanical engineering project at the University of Connecticut, won the 200-meter event "hands down," as House said, in a world-record 26.59 mph. The hand cranks work in unison in an up-and-down motion. House says this gives more power for sprints, but at the expense of endurance.



Dan Bonwell

Bob Demarco is chased by *Pegasus,* a partially hidden *Aerocoupe,* and *Freewheeler* during road races at Indianapolis Raceway Park.

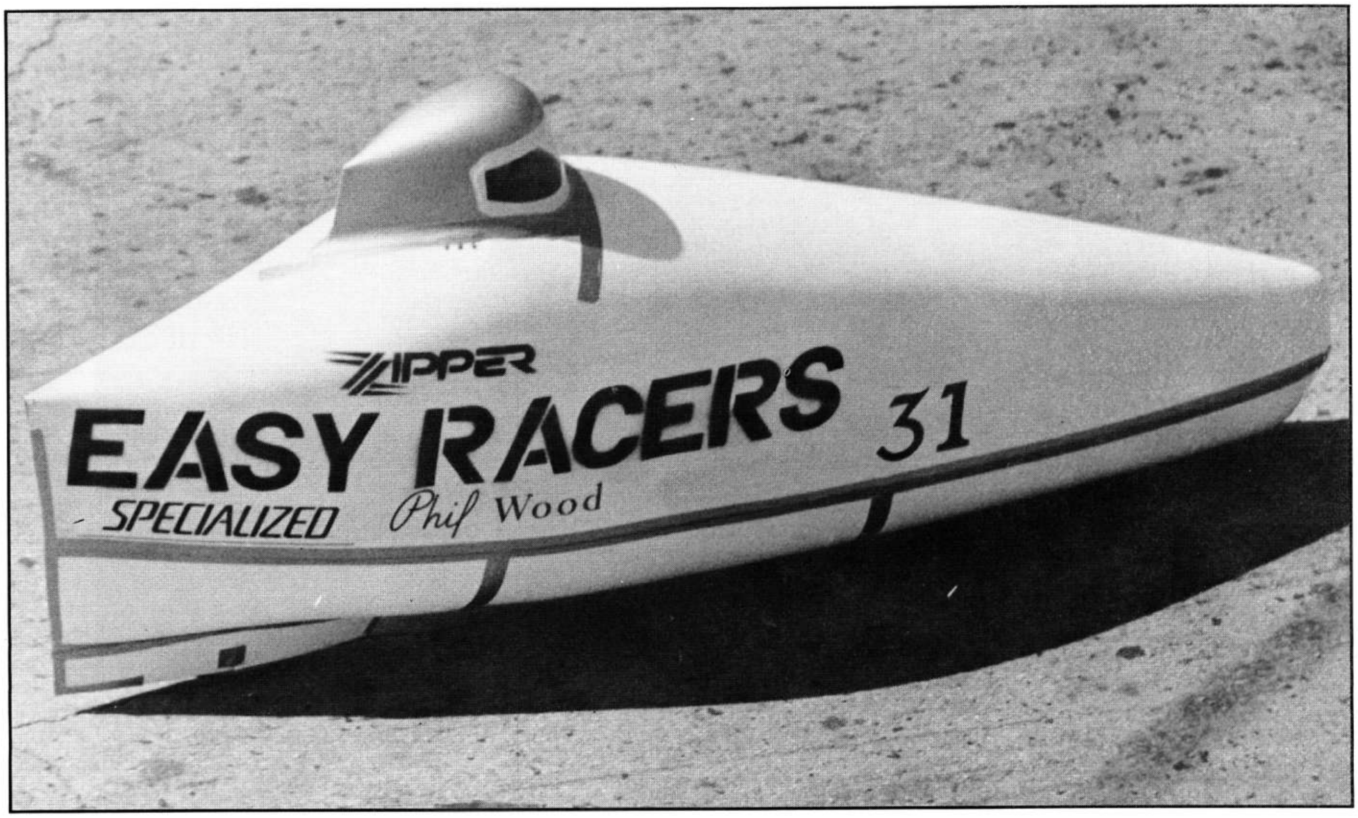
Aerocoupe

Mark Murphy's Aerocoupe tricycle sported a new full fairing of foamcore board, which Murphy praised for its easy working characteristics and its light weight. The Franklin, Indiana native, who now resides in San Luis Obispo, California, celebrated his return to his home state with his fastest time ever — 37.7 mph, more than four mph faster than his previous best.

Murphy said the drag coefficient of his machine is equal to the air resistance of the flat side of a letter envelope, even though the two front wheels are outside the fairing. An unfaired version of this commercially-available trike won notice from the judges in the practical vehicle competition as well.

By all accounts, the most striking debut at HPV Indy 83 was the University of Cincinnati's four-rider Pegasus, a product of two years' research and development by mechanical engineering students under the watchful eye of faculty advisor Dean Shupe.

Pegasus, too, points to a new direction —



Dan Bonwell

The most consistent vehicle this year was Gardner Martin's *Easy Racer* powered by Fred Markham.

a melding of HPV lightweight design and automotive technology. Featuring a body styled after Italian auto designer Pinin Farina's models, an 18 'speed' drivetrain with 3 overdrives, hydraulic brakes, independent suspension, quartz lighting system, and weighing in at 300 pounds, Pegasus cost somewhere around $75,000 in materials and donated student time, and was not designed for top speed so much as for highway use.

Kelly Londry, student design team leader, said the approach Pegasus took differs radically from the MIT and Northeastern entries. "They aim for a smaller frontal area in an attempt to reduce drag, but we feel that surface area and body shape are more important." Riders sit back-to-back and side-by-side in semi-reclining seats taken from an Infinity recumbent.

Londry said he was pleased with the vehicle's performance during the event. "Not once did we have to take the shell apart and it proved very reliable." He said plans are in the works for a cross-country run sometime this year.

Questioned on the practicality of the design, Londry remarked, "It depends on how you want to define practicality — We think we're practical in the sense that we're developing a technology that can be applied to low horsepower-type vehicles with electrical or gas engines in the future — we just happen to be human-powered right now."

White Lightning

Multiple rider categories were also led by veteran machines. A perennial favorite and unchanged from previous years, Tim Brummer, Don Guichard and Chris Dreike's White Lightning was the only vehicle to break 55 mph, hitting 55.92 mph at IMS. In addition to competing, the venerable tandem tricycle was the centerpiece of a Human-Powered Vehicle exhibit in the local children's museum prior to the event. After the weekend of racing, the machine was returned for another week of display at the museum.

Northeastern University's four-rider Tensor machine, undeterred by last year's drivetrain and steering troubles, returned to the competition with a new look. The 40-foot long, 235-pound chassis sported holes in the side for greater rider access and visibility, and featured an acrylic nosecone to further increase visibility. No longer held three feet aloft off the ground, Tensor wound up with a ground clearance of four inches. Wheel positions were reversed (two in rear, one in front) for better handling and a larger turning radius (Tensor negotiated the downtown streets amazingly well during the HPV parade and stopped more than its share of pedestrians.) The wheel diameters were reduced from 27 to 20 inches to cut down frontal area and the front rider was given control of both steering and braking.

Tensor used one drivechain throughout the entire length of the machine, with six gearing options on a standard derailleur. A new aluminum frame was constructed using approximately two-inch square tubing, welded in modular units. As a result of these modifications, Tensor was the only other multiple rider vehicle to top 50 mph, with 50.04 mph.

Such modifications take more than just time, they take cash — $35,000 in cash and material support were needed to construct the entry for the eighth IHPSC. An additional $3,500 was spent this year.

HPV Indy '83 could spell the death knell for MIT's five-rider New Wave machine, which was plagued by drivetrain failures and fell short of its 1982 top speed of 48.9 mph. The hand cranks were a continual problem and it never went through the traps with all five riders pedaling. Morose MIT students were making half-hearted sales pitches to get plane fare home, but had no takers.

Steve Ball, a mechanical engineer from San Diego, has been working with his linear drive tricycle, Dragonfly, for more than five years. "I just guessed I could build something efficient that way," he says. His guess paid off. With Richard Bryne pedaling furiously, the rakish-looking machine reached the top speed for a single rider vehicle —

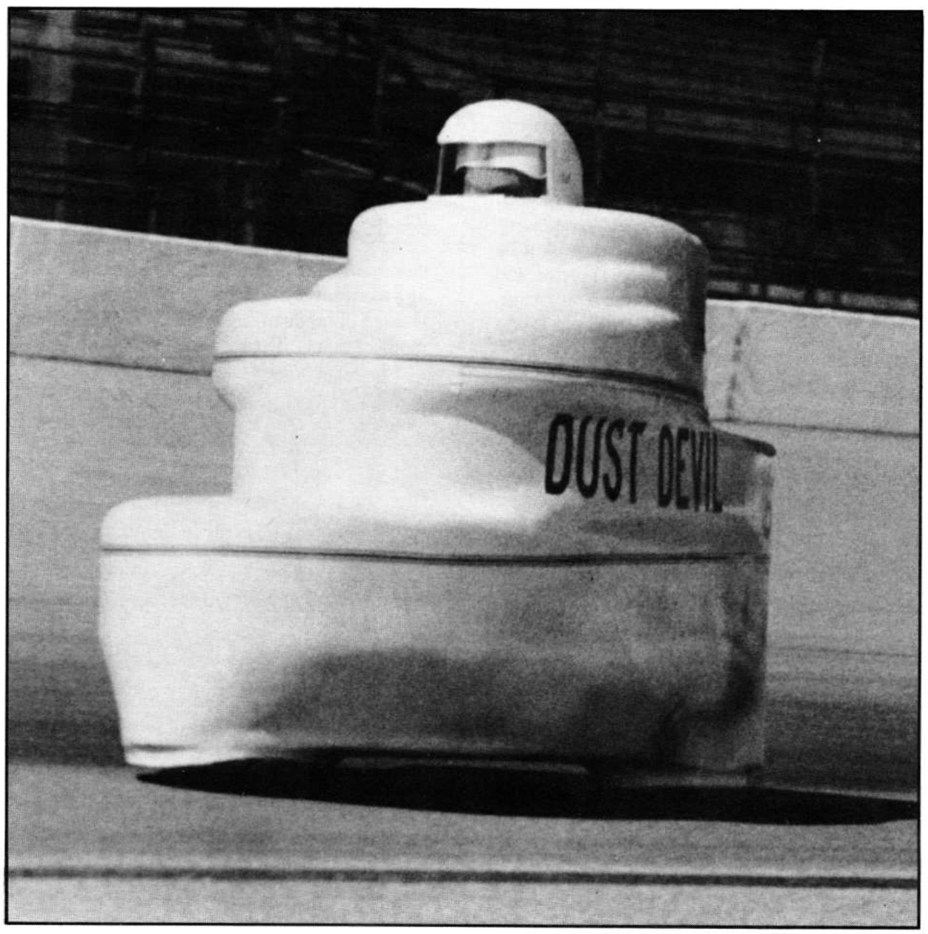
54.92 mph (the best of three rides, all of which topped 54 mph). By comparison, Dragonfly's top speed last year was 48.77 mph. The only major change from last year's machine was the use of sew-up tires instead of solid tires.

Though the Dragonfly's limited steering and visibility (the rider views the course through a periscope) and its 1/4-inch ground clearance made the vehicle only competitive in the drags and sprints, Ball received the $200 Nanos Design Award for engineering excellence. Ball, who has submitted papers to the IHPVA Scientific Symposium in the past, said, "I didn't have any data that said, 'Go linear,' but now I do."

Infinity recumbents, a homegrown Indiana product, also had a good showing in their first crack at the championships. The aluminum frame recumbent with remote cable-linkage steering competed with three different fiberglass fairings and was the third fastest single-rider two-wheeled vehicle at 52.46 mph. Dubbed Moby Infinity, a fully-faired model took first place in the 200-meter sprints with 600-meter run-up at IMS — a miracle in itself, since the machine was badly damaged the previous afternoon in a crash during the final road race at the Raceway Park. A quick trip to Infinity's Mooresville shop, and some harried repairs on the fairing and mounts pulled the pieces back together, resulting in one of the best first-time efforts ever for a competitor in the championships.

Glen Cole and Nick Macias' Dust Devil took some kidding from competitors who likened the bulbous fairing to a toiletbowl. The Tucson, Arizona-based designers surrounded a stock RANS recumbent bike (manufactured in Hayes, Kansas) with a four-ply, fiberglass fairing that Cole claims minimizes surface area and skin friction. "We made measurements of the limiting dimensions of the rider and machine, and at each level designed a streamlined shape around it, while minimizing the fineness ratio," Cole said. Dust Devil was fourth fastest qualifier at the Velodrome and posted a 43.5 mph performance at the Indianapolis Motor Speedway.

Other notable single rider entrants included Eric Edwards' Pegasus machine. The former team manger for Vector designed the rear-steering trike with a full fiberglass fairing and an elliptical pedal stroke. Unfortunately, Edwards did not choose to enter any of the road races so there's no way to report on its maneuverability.



Dan Bonwell

Glen Cole and Nick Macias' *Dust Devil* attacks the Indy 500 Speedway.

SPECIAL HPV SECTION

Judging the Practical Vehicles

Tom Healy

One of the aims of the IHPVA is to hold design contests highlighting utilitarian vehicles. But the ninth annual speed championships marked only the second time that a formal Practical Vehicle Competition was ever held. Competition rules in this category were modified as a result of last year's results in which two of the top-ranked machines were tricycles unsafe for street use with autos present.

It was decided to set up separate categories for two-wheelers and multi-wheeled machines. Objective tests included a six-mile hilly road race at Eagle Creek to simulate an average commute, and a parking lot-skills test of handling, maneuverability and braking. The judging panel included Dr. Allan Abbott, who co-ordinated last year's event; Karen Missavage, a bicycle educator and urban transportation consultant and David Gordon Wilson, MIT professor and co-author of *Bicycling Science*. They rated each entrant subjectively according to such criteria as weather protection, speed, safety, maintenance, luggage capacity, handling, construction fit and finish, comfort and aesthetics.

"Our problem was to define what 'practical' is," said race director David Pearson, adding that this year was a learning year in that respect. "But most importantly, we wanted to show that these vehicles are being built and being made available to the general public. Rather than pick an overall winner, we wanted to rate entrants."

But when inventor/philanthropist Fred Lang of Landenberg, Pennsylvania, offered $500 as prize money for the event, picking the "winners" fell to the judging panel.

In the two-wheeled division, Gardner Martin's Easy Racer recumbent bike was rated highest for the second year running. The judges commented, "Easy to handle and shift, highly refined and functional." A lycra cape which stretched over the rider for foul weather protection also won praise.

The DeFelice recumbent, a new mass-produced machine from New Palestine, Indiana, took second. The judges found the rod-steering, handling and balance excellent, though one added, "It would be nice to match it side-by-side with the Avatar." (Note: Wilson disqualified himself from entering an Avatar in the competition.)

Dan Bonwell

Peeling back the fairing of the University of Cincinnati's *Pegasus* reveals a square-four powerplant.

The third prize winner was Jim Bradford's EVOS, a product of a $10,000 Department of Energy grant, which featured a nicely integrated fairing that doubles as protection against the elements. The judging panel found the luggage capacity, visibility and weather protection good, and summed up, "This could serve as a useful vehicle." Bradford obviously thinks so because he is preparing to make his aluminum-frame recumbent commercially available.

Since the judging panel felt there were no multi-wheeled vehicles suitable for use in traffic, they made no awards. But they felt one entrant, Mark Murphy's Aerocoupe, was practical for fun use. The panel liked its solid cornering ability and excellent brakes. Two "Best of Show" awards were presented to two other multi-wheeled entrants in recognition of their efforts. New England Handcycle's hand-cranked trike won kudos as "an excellent design and a needed product." The University of Cincinnati's four-rider Pegasus won special note as "an excellent design. Lots of bugs to work out, but lots of ones already done."

The only two-wheeler receiving "Best of Show" notice was the OPUS II tandem built by Counterpoint Conveyance in Seattle. This machine seats the stoker in a recumbent seat in front. "Very practical design for novice stokers and easy to handle for novice captains," wrote the panel. They also made note of its easy shifting fore and aft, and "the surprisingly secure feeling in the front seat." Some concern was voiced over heavy loads on the front wheel on rough surfaces.

While not without faults, the Practical Vehicle Competition at the Ninth Annual Human Powered Speed Championships did succeed in heightening awareness in the area of HPV design for everyday use. Based on what the organizers learned this year, changes in the competition are inevitable. Testing for braking ability has to be modified and some provision must be made to test luggage capacity and nighttime visibility.

Anyone interested in contributing to the establishment of rules and guidelines for judging HPVs on the basis of practicality should contact the IHPVA.

DuPont Offers Prize for HPVS

The International Human Powered Vehicle Association and the DuPont Corporation have announced a prize of $15,000 for the first single-rider human-powered vehicle to reach or exceed 65 miles per hour on level ground. Called the DuPont Prize for Human Powered Speed, the award is offered for the period of four years, beginning January 1, 1984 and ending December 31, 1987. If no one has won the prize by the end of the four years, the prize will go to the owner of the vehicle that has come closest to 65 mph.

The current record for a single rider HPV was set by Dave Grylls in a Vector tricycle on October 27, 1980, during the filming of a segment of the television show, "That's Incredible." The vehicle was designed and built by Al Voight, Doug Unkrey, John Speicher, and Don Fernandes of California.

The challenge of the DuPont Prize is to design a vehicle that is aerodynamically efficient, as light as possible, and that allows firm directional control while permitting maximum power output by the rider (perhaps using both arm and leg power).

Computer modeling has shown that the theoretical upper speed limit for a single-rider vehicle is somewhere between 65 to 70 mph. The purpose of the prize is to bring the technology as close to that limit as possible.

Rules for the prize are essentially the same as for speed attempts regularly sanctioned by the IHPVA. Vehicles must run on a surface level to within .667%, with wind not exceeding 1.67 meters per second in any direction. Power must come only from the single rider, with no energy storage of any kind allowed.

More information, complete rules and entry applications may be obtained from the IHPVA, P.O. Box 2068, Seal Beach, CA 90740.

Directions for HPV Drag Reduction

Glen Brown

The next advances in HPV aerodynamics will not be made with better and smoother body shapes. The most that a good body shape can do is to promote attached flow and current designs achieve this goal reasonably well. Furthermore, efforts to reduce drag by reducing skin friction will yield little improvement.

The goal of achieving substantial laminar flow over the surface of an HPV is both of little payoff and is probably not attainable. It's of little payoff because less than half of the total drag of an HPV comes from skin friction. An extensive laminar boundary layer is probably unattainable because the vibrational input from the wheels running on the road surface is equivalent to the roughness of the body. A similar effect has been noted in wind tunnels when vibration from the tunnel motor finds its way to the model under test. Vibration causes both early boundary layer transition from laminar to turbulent and early separation in areas with steep pressure gradients. For these two reasons it is not important to have a perfectly smooth surface finish. Cusped (concave) aft body sections should also be avoided because of the steep pressure gradients that form around them.

If attached flow is maintained, the sources of drag that are more significant than skin friction are ground effect, interference drag, and internal flow. All three of these are interrelated.

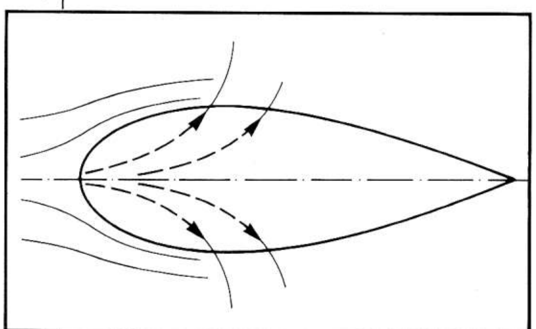


Figure 1: Induced underbody crossflow.

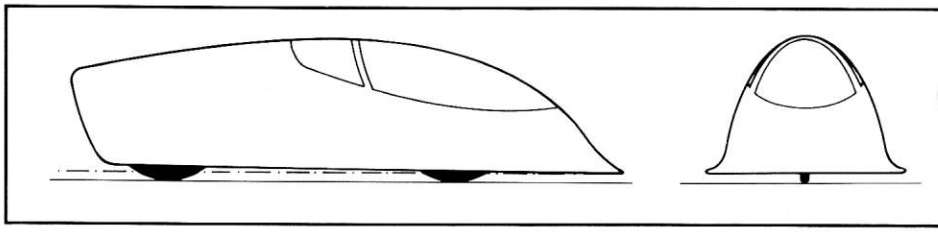


Figure 2: Angled bottom plate compensates for boundary layer growth.

Ground Effect

A body that has low drag in free air will have a much higher drag when close to the ground. This *ground effect* is similar to interference drag in that the body's proximity to the ground changes the pressure distribution on the surface of the body, leading to premature separation. An HPV runs so close to the ground that strong cross flows are induced under the body. Cross flow coming from under the body at a large angle to the freestream direction can easily trigger separation on an afterbody. (See Figure 1.)

Ground effect can be minimized by using a higher fineness ratio (ratio of a body's length to its width) than is otherwise indicated for minimum drag-free air shapes. High fineness bodies will have lower pressure variations on their surfaces, reducing the driving pressure that causes underbody cross flow.

Interference

When two or more simple shapes are joined, the resulting aerodynamic drag is usually greater than the sum of the drags of the individual shapes. This excess drag is known as *interference drag*. Wheels are a major source of interference drag for an HPV. Extra vehicle drag is induced by the exposed portions of the wheels and is additive to the direct drag of the wheels.

Internal Flow

Internal flow causes substantial drag because the momentum of the air entering the body is almost totally lost. Major infiltration occurs around the wheel openings of HPVs. The importance of minimizing internal flow is amply illustrated by competition prepared sailplanes. Even without special preparation, a sailplane will have internal flow far below a vehicle with wheel openings. Yet with meticulous preparation — sealing canopies, gear doors and wing roots — improvements on the order of ten percent are possible. Imagine the improvements possible in reducing the truly gross levels of internal flow found in HPV's.

Design

I'd like to share some ideas on how to reduce these three sources of drag, and hope that HPV constructors will address the aerodynamic problems caused by the wheels and by ground effect early in their design phase. Design solutions for reducing these sources of drag are quite different for two- and three-wheeled vehicles.

Tricycles

The tricycle needs to be wide and close to

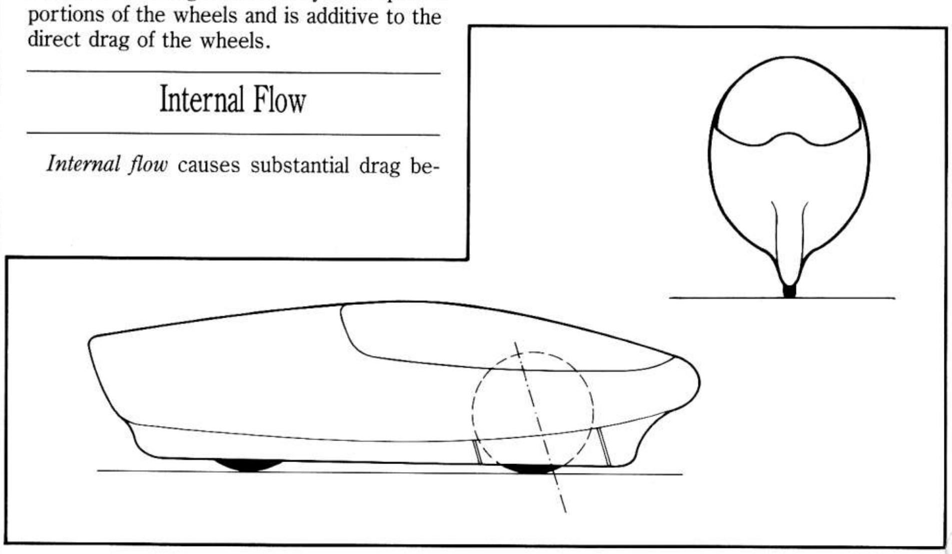


Figure 3: Elevated two-wheeled HPV with wheel fairings.

George Retseck

the ground for good handling. The method for reducing ground effect for a tricycle is to merge it with the ground in a way that will reduce underbody cross flow. While underflow bodies are currently the method of choice due to the success of the Vectors, even lower drag can be achieved by minimizing and controlling underbody flow.

Underbody flow is induced by the pressure distribution near the ground at the sides and bottom of the body. Typical pressure distribution for a streamlined shape consists of a high pressure region in the vicinity of the nose, followed closely by a strong low pressure region on the forward quarters. The proximity of these high and low pressure regions drives the flow under the body at the nose and then out at the sides, creating a strong crossflow component. This cross flow can be greatly reduced if a flat plate is attached to the underside of the body. This plate must extend out far enough to the front and sides so that the adverse pressure influences at the edges of the body are diminished.

Two design features of this installation are important. First, the plate should be installed so that it slopes slightly upwards from front to rear, matching the swelling of the boundary layer underneath the vehicle (much as the walls of the test section of a wind tunnel flare slightly in the streamwise direction). (See Figure 2.) This results in a constant pressure equal to freestream static over the entire bottom of the vehicle. Otherwise, the static pressure under the vehicle will drop towards the rear as the boundary layer grows and the flow accelerates.

Secondly, the ground plate should have a generous fillet at the body junction to reduce interference effects. This is similar to the wing/body junction of an aircraft, although not quite as important as the HPV body is not a lifting surface. (See Figure 2.)

Two Wheels

The aerodynamic situation is quite different for a two-wheeled vehicle. Since a two-wheeler needs a certain height for good handling, its body can be raised high enough to minimize the ground effect. If the bottom could be raised to the height of the wheel hubs, and the bottom half of the wheels enclosed in thin fairings (see Figure 3) the result would be a vehicle with very low drag. Steering and other practical requirements make such a design challenging, but by no means beyond the talents of today's HPV designers and builders.

Whether or not these speculations prove to be specifically correct, let the message be clear: progress will come from attention to the issues of ground effect, interference, and internal flows. Cookbook laminar flow shapes are not in themselves sufficient to achieve low drag on a land vehicle.

IDEAS & OPINIONS

Kudos From Pipkin

My compliments to Crispin Mount Miller for his article on steering stability in the October 1983 issue of *Bike Tech.* He did an excellent job in explaining a rather complex topic. His inclusion of a fourth steering torque, that due to centrifugal force acting on the fork/wheel center of mass, is a valuable addition to the theory.

It is interesting to combine the four torque equations into the following single expression for total steering axis torque T_{sa}:

$$T_{sa} = (R\ t \sin H + W\ f)\left(L + \alpha \cos H - \frac{v^2}{g\ r_c}\right) \qquad (1)$$

where I have substituted the radius of curvature of the bike's path (r_c) in place of ($b / \alpha \sin H$). A positive value for torque in the above equation denotes a turning moment into the direction of lean.

For small angles, and neglecting the additional lean required to generate the gyroscopic precessional moment,

$$L \approx \tan L = \frac{v^2}{g\ r_c} \qquad (2)$$

(See, for example, Sharp, *Bicycles & Tricycles,* Figure 193 on page 203, and also Section 168, pages 207-208).

Thus the expression for total steering axis torque reduces to

$$T_{sa} = (R\ t \sin H + W\ f)\ (\alpha \cos H), \qquad (3)$$

a non-zero, positive quantity at all angles where the lean of the bicycle is in equilibrium with the centrifugal force.

Unless the steering axis torque given by equation (3) is counterbalanced by some means, the steering fork on a riderless bicycle or on a bicycle ridden without hands along a smooth curve would, under the action of this torque, continuously rotate through a progressively greater steering angle, thereby causing the bike to spiral inward and ultimately crash. Because such behavior does not occur, there must exist an opposing reaction equal in magnitude to the steering axis torque which resists the effect of the latter. I suggest that this counterbalancing mechanism is provided by the gyroscopic reaction of the front wheel, without which the self stability of bicycles would be impossible.

The importance of gyroscopic reaction is confirmed by Jones' experiments with a bicycle having a counterrotating front wheel, which he called the URB I ("Unridable Bicycle I"). He writes: "Then I tried to run URB I without a rider, and its behavior was quite unambiguous. With the extra wheel spinning against the road wheels, it collapsed as ineptly as my nongyroscopic hoop; with it spinning the same way it showed a dramatic slow-speed stability." Jones continues: "URB I is not an easy bicycle to ride 'hands-off' even with the front wheel static. In the disrotatory mode, *it was almost impossible and invited continual disaster* [italic mine] but it could, just, be done." I imagine Jones accomplished this feat by a frequent and sudden shifting of his weight from side to side while riding through a series of short arcs of alternating curvature. I very much doubt if he were able to ride without hands in a smooth curve of constant radius, as can be done on a bicycle without the counterrotating wheel. It appears that Jones' test was more a measure of his own agility than of the inherent self stability of the bicycle.

The magnitude of the steering axis torque can be found from equation 3 which, using Miller's estimates of 110 and 18 inch-pounds for Ru and Wf respectively, yields a torque of 7 inch-pounds at a steering angle of ten degrees. That is, if the gyroscopic reaction were absent, a rider would have to exert an outward torque of this magnitude to maintain a constant steering angle. Gyroscopic reaction, however, reduces the amount of effort required by the rider to steer a steady curve.

I hold the opinion that gyroscopic reaction is essential for riderless and no-hands stability. It plays a lesser, but not negligible, role in ordinary hands-on cycling.

On another subject, I would like to make the observation that large-angle expressions for the moment arms of the lateral forces R_c and W_c can be immediately derived by noting that the ratio of the moment arms for vertical and lateral forces equals $\tan \Theta$, where Θ denotes the angle between the wheel plane and ground.

That is, if a_1, a_2, a_3, and a_4 represent the moment arms about the steering axis for torques M_r, M_w, M_{cr}, and M_{cw} respectively, then

$$a_3 = a_1 \tan \Theta \qquad (4a)$$

and

$$a_4 = a_2 \tan \Theta. \qquad (4b)$$

Upon substituting these become

$$a_3 = r\ (\cos \alpha \cos L \cos H - \sin \alpha \sin L) - y \sin \Theta \qquad (5a)$$

and

$$a_4 = f \sin \Theta. \qquad (5b)$$

Consequently, expressions valid at all angles for M_{cr} and M_{cw} are:

$$M_{cr} = \left(R \frac{v^2}{g\ r_c}\right)\ [r\ (\cos \alpha \cos L \cos H - \sin \alpha \sin L) - y \sin \Theta] \quad (6a)$$

and

$$M_{cw} = \left(W \frac{v^2}{g\ r_c}\right)\ [f \sin \Theta] \qquad (6b)$$

where r_c, the radius of curvature of the front wheel's path, is given by

$$r_c \approx b / \sin\beta \qquad (7)$$

and where

$$\beta = \text{arc tan}\left\{\frac{(\sin\alpha \sin H)}{(\cos\alpha \cos L - \sin\alpha \sin L \cos H)}\right\} \qquad (7a)$$

Apparently Miller is aware of this relationship between the moment arms of the vertical and lateral forces, because he graphically illustrates equation 5a in his Figure 3b. Surprisingly, he does not use the relationship to extend the range of the small angle approximations for the torques M_{cr} and M_{cw}.

Incidentally, equations 4a and 4b follow from the principle of "virtual work" which can be used to show that

$$a_v = -\ \delta v/\delta\alpha$$

and

$$a_\ell = -\ \delta\ell/\delta\alpha$$

where a_v and a_ℓ denote the moment arms about the steering axis of torques resulting from vertical and lateral forces applied at either the wheel-to-ground contact point or the fork/wheel center of mass point. δv and $\delta\ell$ represent infinitesimal vertical and lateral displacements of any point on the steering axis relative to the point of the applied forces and arise from an infinitesimal rotation $\delta\alpha$ of the steering angle. This principle shows, by the way, that $a_1 = \delta h/\delta\alpha$. The algebraic signs, of course, are arbitrary, and only serve to define the direction of positive torque.

Now let $\vec{p}$ be a vector from any point on the steering axis to the point of the applied forces. Then $d\vec{p}/d\alpha = \vec{q}$, a vector normal to the plane of the wheel. But by definition, the angle between $\vec{q}$ and the vertical is Θ. Thus the vertical component of $d\vec{p}/d\alpha$ ($= \delta v/\delta\alpha$) is $|\vec{q}| \cos\Theta$, and the remaining lateral component of $d\vec{p}/d\alpha$ ($= \delta\ell/\delta\alpha$) is $|\vec{q}| \sin\Theta$. Therefore,

$$\delta\ell/\delta\alpha = \delta v/\delta\alpha \tan\Theta$$

and so

$$a_\ell = a_v \tan\Theta.$$

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New Design Needed

Your article in the October 1983 issue of *Bike Tech* on "The Physical Anatomy of Steering Stability" approaches but does not culminate a formula which would enable the long distance cycle tourist to find a frame optimum to his needs.

Any cycle tourist that is outfitted with a full set of panniers quickly finds that the stability of his ten-speed bicycle is woefully inadequate. Last summer in Scotland, I observed several touring cyclists on their way up the A9 into the Highland lake country. Every one of them was loaded down with front and rear panniers and camping equipment. Every one was having great difficulty steering his heavily laden cycle because of frame whip and an overloaded front fork.

These cyclists might be taken to task for attempting to utilize lightweight ten-speed frames for a service for which neither the tubing nor the frame was designed. Such criticism would be unfair, however, because there is no alternative offered the touring cyclist at the present time. I propose that you address the problem of frame whip and steering stability in a heavily loaded touring cycle. For starters, I suggest that you look at the way the front rack is mounted to the cycle. Surely, mounting the rack to the frame rather than to the fork would be a step in the right direction. This change would result in an entirely different set of forces bearing on the steering. (While I am not endorsing this bicycle, I suggest that you look at the Alex Moulton folding bicycle. It has a front rack mounted to the frame rather than the fork.)

Consider a cycle design using lightweight tubing and 20-inch or 24-inch wheels. What if the main tube of this frame were a horizontal member extending end-to-end just above the wheels? What if the front and rear luggage racks integrated with this main tube? Might not a frame designed like this allow heavy front and rear loads without whip and bad steering?

It appears to me that the lightweight touring cycle is due for a complete redesign. The problem with current frames is that they are designed for a Sunday outing on smoothly paved roads with only a rain cape and a few tools as baggage. They are not designed to cope with the potholed roads of Greece or the gravel trails of New Zealand.

And mountain bikes are not the answer. They are designed to withstand the rigors of rough terrain, not the rigors of carrying heavy loads. They would be plagued with the same overloaded steering problems as ten speeds.

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Credit Due

The photographs that accompanied the article "On Scott's Brake" in the December 1983 issue were taken by Michael Koenig.

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.