HUMAN POWER

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We are indebted to the authors, to Marti Daily and to Carolyn Stitson, whose dedicated help made this issue possible. Dave Wilson

Editorials

Internationalism

The IHPVA is often criticized, perhaps justly, for not being sufficiently international. It is something we all have to work on constantly. All the "higher" animals are territorial. Mankind easily reverts to this pattern. As I write this, one of the US presidential challengers is trumpeting the call of "America First!" I thought that that had disappeared in the thirties, a time when I remember my primary schoolteacher hugging me and saying "Aren't we lucky to belong to the best country on earth?" Pride in one's country and in one's group or team is good so long as it doesn't lead to a disparagement of other countries and groups. In Britain it was only slightly humourous to refer in those days to people unlucky enough not to have been born in Britain as "the great unwashed". A famous London Times headline is reputed to have stated "Fog in the Channel: Continent cut off" On my first visit to the USA I was entranced at the greater interest in and acceptance of people of other countries than I saw in my own country. Foreigners were treated as people having habits that were no so much strange as interesting. At the same time we were guilty of appalling racism. We in the USA have apparently progressed in this area so far in the last thirty years that we feel smug when confronted by occasional renewed appearances of throwback movements proclaiming the need to put the country, or some particular group, first. Other countries are also having outbreaks of right-wing advocacy and violence. There is at present a highly embarrassing war of words between a small minority of public people in Japan and the USA following a disastrous state visit by the president and a group of over-paid auto-company executives. (Why couldn't he have taken some of our HPV pioneers - people we could have been proud of?)

These reflections are partly the result of another act of kindness by a Japanese friend, in this case Akira Naito. We were very grateful to him for giving us his paper on HP helicopters in the last issue. He was appreciative of the help we had given in editing the paper. He has just sent a stunningly beautiful presentation of micro-origami - Parade of Cranes. (The folded-paper cranes have wingspans from about 25 mm to 0.7 mm, too small when mounted on the points of sewing needles to be seen without a strong magnifying glass). I hope to present it to a museum so that others may appreciate the craftsmanship and artistry.

I also feel, as I did when Ellen and I visited Japan, that in the face of many beautiful and subtle courtesies shown to us we may have been perceived as clumsy, even boorish. (No one gave us any impression of perceiving us that way). The point that I want to make is that, if we are to make the IHPVA truly international we have to keep on our guard not to disparage any practices of other groups, but to do our utmost to communicate, compete and cooperate in fun and friendship.

In this issue

Cover design by Bruce Padmore

Almost DTP

Human Power has relied in the past for its production on a network of volunteers and of one or two people who did professional work at well below market rates. Drafts and diskettes were shuttled from place to place around the country, sometimes suffering some delays and always surprising the editor somewhat. I would never know, until the final product turned up, exactly what the compositor had managed to squeeze in. For this issue I'm trying the experiment of producing most of it myself. I've bought a new, fast PC, Microsoft Windows, DOS 5.0, and Lotus Ami Pro. (If this sounds like an advertisement, let me reassure you that it has a purpose. On the title page of my last book I printed "*Produced on Lotus Manuscript*". When it didn't work as advertised, Lotus was fantastic. It brought out a new version of

(continued on p.4)

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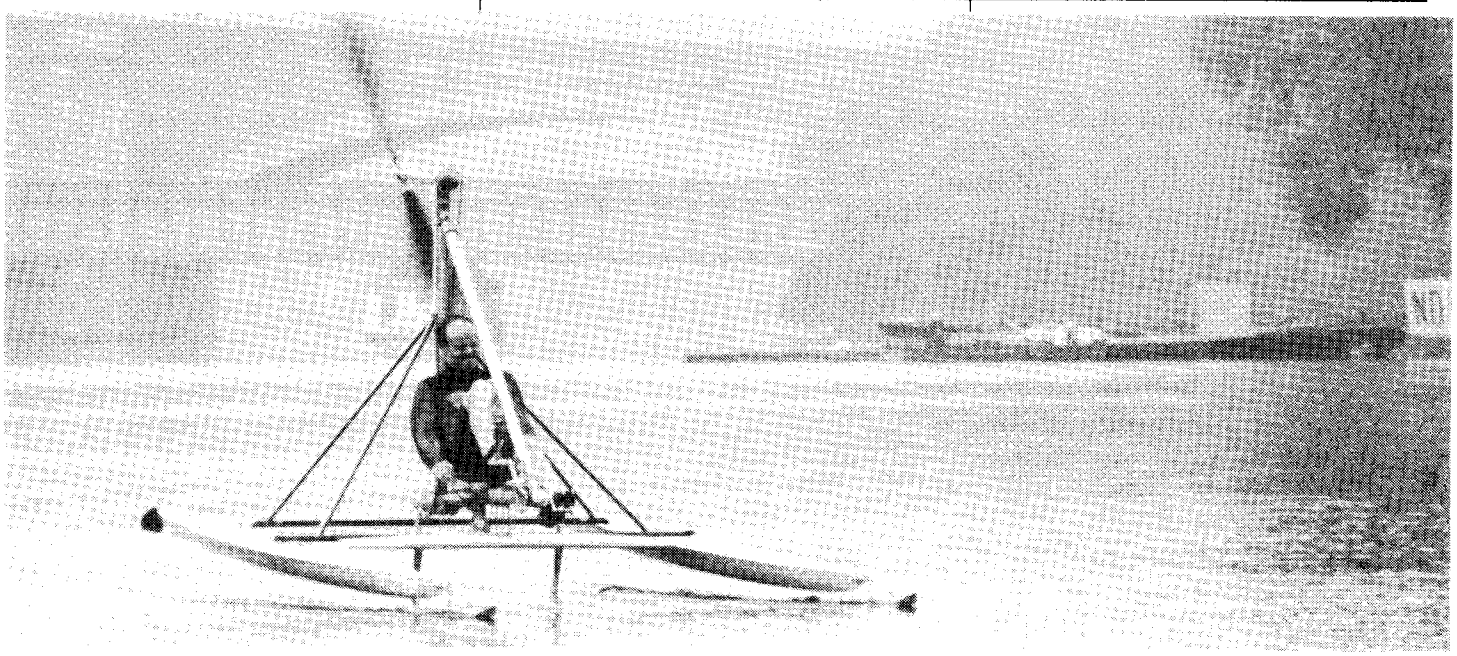

The *Decavitator* flying on the small wing in a practice run. *Copyright Steve Finberg*

Decavitator human-powered hydrofoil

by Mark Drela*, Marc Schafer# and Matt Wall+

Abstract

The Decavitator is a human-powered hydrofoil water vehicle designed for the fastest-possible speed over short distances. Since 1988, numerous versions of the underwater hydrofoil system, control and stability system, and pontoons were built and tested. In its present configuration, the vehicle consists of two kayak-type pontoons, with a central frame supporting the rider and the large air propeller. Two underwater hydrofoil wings are positioned directly under the rider. The vehicle has three operating modes: on the hulls, on two wings, or on one wing. In the fastest one-wing mode, the Decavitator in October 1991 set an official speed record (pending ratification) of 18.50 knots / 9.53 m/s over a 100-meter course, with an unofficial 19.59 knots / 10.08 m/s being the fastest measured speed to date. This article will outline the technical features and design philosophy of the latest version of the vehicle.

*T. Wilson associate professor, MIT Aero & Astro Dept.
#Graduate student, MIT Aero & Astro Dept.
+Graduate student, MIT Mech. Eng. Dept.

Introduction

The recent surge of activity in the development of human-powered watercraft has been sparked largely by the sanctioning of the relatively unrestricted watercraft category by the IHPVA. The novel Flying Fish [1] and the Hydroped [2] hydrofoil vehicles have substantially exceeded the performance of traditional rowed racing shells, whose development has largely reached a plateau. The race to develop the fastest water vehicle has further intensified since the announcement of the $ 25 000 DuPont Watercraft Speed Prize [3], which will be awarded to the first vehicle to exceed 20 knots /10.29 m/s, or to the record holder if the prize remains unclaimed after 1992.

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Manuscript largely on the basis of printing my book.) So far I'm amazed by the power of Ami Pro, and alarmed by the amount of juggling and time it is taking to learn how to do HP with it. But I'm hoping that I'll produce a style that I can follow faster for future issues. Please bear with the imperfections of this issue. And authors: please let me have your material on diskettes of either PC size in ASCII or almost any popular word processor - and we can handle Mac diskettes too with a little extra trouble. Perhaps in an issue or two I'll learn how to scan in illustrations. For now, Marti Daily will still have to work her magic with the printer.

Dave Wilson

Letters to the editor

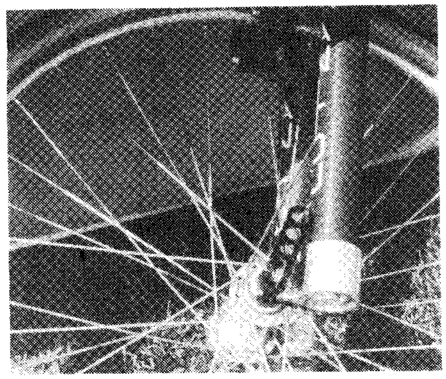
European "fashions"

I think that you rather missed the point in your HP 9/2 editorial. Most of our racing is tight circuit racing. Our experience is that short-wheelbase (SWB) bikes can be flung at corners in a way impossible for the cumbersome LWB designs. They are more compact and weigh less. Many of the continental designs have large wheels that roll and hold better on poor surfaces both when racing and [being used conventionally] on our roads.

The Bean and the Bluebell are both LWB, but they are not designed as circuit racers. The Bean is a very old design recently revived. I foresee a new wave of SWB streamliners. The Cutting Edge is a first.

We have a very active unfaired-racing scene, with competition between very good athletes who use all the skills of bicycle road racing. Unfaired machines often have a very-laid-back seat and large wheels. By contrast, faired machines tend to a more upright seat, which allows a more-compact overall shape. The Lightning is a good example of this. Almost all of our faired machines are "GT" types, many with fabric fairings.

The new development that Dave Wilson missed was suspension. Martin Stanbach and Walter Zorn both had front suspension: Walter with adaptedManitou MYB forks; Martin with a concentric-steerer setup. They cornered as if on rails on the rough surfaces of East Park and the town-centre. Even the Kingcycles, usually thought to be good handlers, could be seen skittering about in their wake.



A Manitou at the Euro-HPVSC, 1991 *Dave Wilson*

When combined with excellent composite fairings (with curious knee bulges) and fit riders they were unbeatable on the twisty and hilly circuits. They are also fully road-practical. Many of us are working on suspension for next year.

Jonathan Woolrich, 31 Burway Crescent, Penton Park, Chertsey, Surrey KT16 8QE, UK.

Early HPH?

I enjoyed [Akira Naito's] article on HPH in HP 9/2. Recently I came across some information about an early HPH that, if true, predated the Da Vinci III take-off by over 50 years. It was written up in "Flying Aces" Magazine, July 1939, p. 15:

"A woman, Joanna De Tuscan, has actually jumped a muscle-powered airscrew machine a short distance off the floor! It happened at Wayne University in Detroit, on June 6, 1938.

"In this machine, the operator's feet push bicycle pedals. The muscle power goes from the pedals through a two-to-one ratio set of pinion gears to a vertical shaft, and thence up to an airscrew which is over the operator's head and parallel to the ground.

"The operator starts heaving on the pedals with the airscrew blades at zero pitch - that is, they're knifing through the air with no tractive power and therefore with the least possible use of power.

"Then, when the legs are kicking as fast as they can be made to go, the operator abruptly gives a yank on the blade-pitch control. this makes the blades turn quickly to their widest pitch and take a hard bite at the air. And that speedy bite makes the machine jump upward."

From this [it seems that] the machine wasn't a true helicopter, and seems to have succeeded in taking off more due to the stored momentum of the spinning blades than to anything else.

Paul Dunlop, 4 River St., Mataura, Southland, New Zealand

"Bicycle Technology" etc.

Rob Van der Plas has sent me a copy of the revised (second printing) of "Bicycle Technology". Almost all the numerous errors have been corrected, but he doesn't seem to have changed his prejudices against anything other than upright bicycles.

With regard to fatigue failures of aluminum-alloy components. I wonder if the use of clamp-on "tri-athlete bars" has resulted in failures in the regular handlebars to which they are clamped. They must be clamped tightly, and a stress-raiser is thereby created.

Bas ten Brinke wrote from Holland about my article on front-wheel-drive recumbents - here is an extract from his letter.

Mike Eliasohn, 2708 Lake Shore Drive, apt. 307, St. Joseph, MI 49085, USA

The Flevo FWD

The purchase price of the Flevo bike is around $1000 (US), but we cannot export it to the USA because of US regulations. Someone may come here and buy one to take back, of course.

Re Flevo manueverability: Flevo owner Li Hock Hung of Singapore is quoted in Recumbent Cyclist (Jan-Feb 1991): "manueverability is limited to large turning circles - or watch out for instability. Because of this handling characteristics, speed has to be sacrificed." Now this is really ridiculous. Come to Holland and I will personally show you that every Flevo owner can "turn on a dime", as Marti Daily said. We agreed with other comments on FWD recumbents in Mike Eliasohn's article in HP 9/2.

Bas ten Brinke, NVHPV, Postbus 10075, 1301AB, Almere, Nederland

Loads on frames

As an unconditional enthusiast of those composite mountain and road bicycles, I decided trying to make carbon-epoxy tubes to assemble a frame with metal lugs. So I'm writing to ask for advice on the design of composite frames. I'm specifically interested in the loads carried by the frames of conventional diamond-frame mountain bicycles for design by finite-element analysis. In a recent search I found "Forces applied to a bicycle during normal cycling" in the Jl. Biomechanics, v.12 no. 7, pp 517-541, 1979. However, it's a rather conservative approach, since mountain biking is undoubtedly more aggressive than normal bicycling. Before undertaking an expensive search on international data bases I decided to ask for your help. Kindly send me a list of references on the subject: articles in bicycle magazines; papers; symposium proceedings; books.

Libanio C. de Souza, Smar Int'l Corp., 7240 Britmoore, suite 118, Houston TX 77041.

(Would someone be willing to help? I get a fair number of letters like this from people who think that I'm a free reference librarian. Dave Wilson)

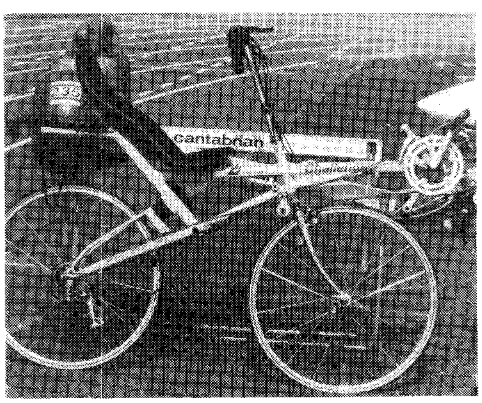
Flat-tire performance

I enjoyed reading Dave Wilson's piece in Cycling Science, since I too have cut far too many tires on my upright bike with worn brake pads. The last time it happened, my front 27x1-1/8" skinwall tire was dead flat by the time my speed was down to 15 mph on a severe downgrade before a busy intersection. About half of the braking was still taken by the front wheel. There was no loss of control, which I attribute to the fact that the tire was quite accurately made, and took on the cross-section of a new tubular, frming a rubber band that still encased the rim.

If tires could be made with a cirumferential strip near the middle of the tread under tension, they might be safe at speed when flat, yet not much slower than normal tires. Another possibility would be to mold them to the safe flat shape, so that they would only have a rounded cross-section when inflated.

These tricks would probably allow only limited cornering, but would suffice for most emergencies.

Bob Stuart, Original Car-Cycle Technology, Ltd., 1311 Victoria Avenue, Victoria, BC Canada V8S 4P4



"Challenge" SWB recumbent at the 91-Euro-HPSC - *Dave Wilson*

Book reviews

The new science of strong materials *and* Structures

both by J. E. Gordon

reviewed by Bob Stuart

Professor Gordon is one of the pioneers of the science of materials, lending his name to the process that makes fiberglass so much tougher than solid glass. He also understands the mind of a beginner, and is an excellent writer. His books are a wonderful way to learn design and engineering.

The two books overlap to a certain extent with "The new science of strong materials" concentrating on what is really going on between the atoms as a fracture progresses or is prevented. "Structures" covers this too, but has much more on the larger scale, including an English translation (from the math) of the highlights from "The design of structures of least weight" by A. Cox.

Both books frequently tell the stories of the difficult discovery of new principles, which makes them easy to remember and use. There are examples from many crafts and historical periods. Included are such asides as the story of the discoverer of the strength of glass fibers being transferred from the lab for his efforts. The discussion of the hardening of steel by nitriding in urea or ammonia includes the footnote "Of course, the iron has to be hot for the nitrogen to enter the metal. Dogs do not harden lamposts".

Just as a chain will always break at its weakest link, everything we build will present one easiest place for a crack to start. After reading these books, one can cast a canny eye over a design, and then arrange things so that the wekaest points will hold on until the stronger parts are under much more stress. If this is not done, much of the weight and strength is wa sted. Most of the tricks of the trade are covered, from alowing for corrosion to adding carbon fibers.

After giving us a good feeling for the best way to proceed with a design problem, Gordon includes an appendix tht can get one started in analysing the stresses involved, to help avoid building things too weak or heavy. The formulas for the stress and deflection of simple trusses, beams, shafts and so on are so simple that about thirty keystrokes on a pocket calculator will very often lead to an improved design and save weeks of trial and error in building.

I have not yet had an opportunity to read Gordon's latest book "Structures and materials", but I expect that it has the same high standard of entertaining writing and the most recent information.

Decavitator, cont. from p. 3

The Decavitator human-powered water vehicle, shown in figures 1 and 2, was designed expressly for the fastest-possible speed over short distances. It consists of two lightweight 17-ft / 5.2-m kayak-type hulls between which a frame supporting the recumbent rider and the large air propeller are placed. Two underwater wings (hydrofoils) are positioned under the rider via thin vertical struts. The smaller of the two wings is positioned beneath the larger wing. In addition, a small "canard" trim surface and small rudder arranged in an inverted-T are mounted at the front tip of each pontoon, similar to the systems employed by the Hydroped and Flying Fish vehicles. A surface-following skimmer controls the angle of attack of each trim surface, passively controlling the depth of each pontoon bow and thus giving roll stability. The rider controls the front rudders via a right sidestick, providing directional control. The sidestick also actuates larger rear rudders which work only when on the pontoons. The rider controls the wing submergence depth via a left lever.

Operation

The Decavitator has three basic modes of operation.

Low speed. Initially, the vehicle floats on the pontoons like a normal displacement boat. The propeller is relatively inefficient at these low speeds, and the maximum speed attainable in this mode is about 8 knots (4 m/s).

High speed. The initial foil-borne mode is entered by setting the two wings at their maximum lift angle and increasing the speed to about 7-8 knots / 3.5-4 m/s (with a 140-lb / 64-kg rider). As the wings gradually lift the pontoons out of the water, the drag drops and the speed further increases, eventually allowing the pontoons to be lifted entirely clear. The low-drag pontoons and the high aspect ratios of the wings give a very shallow "power hump", so that the transition

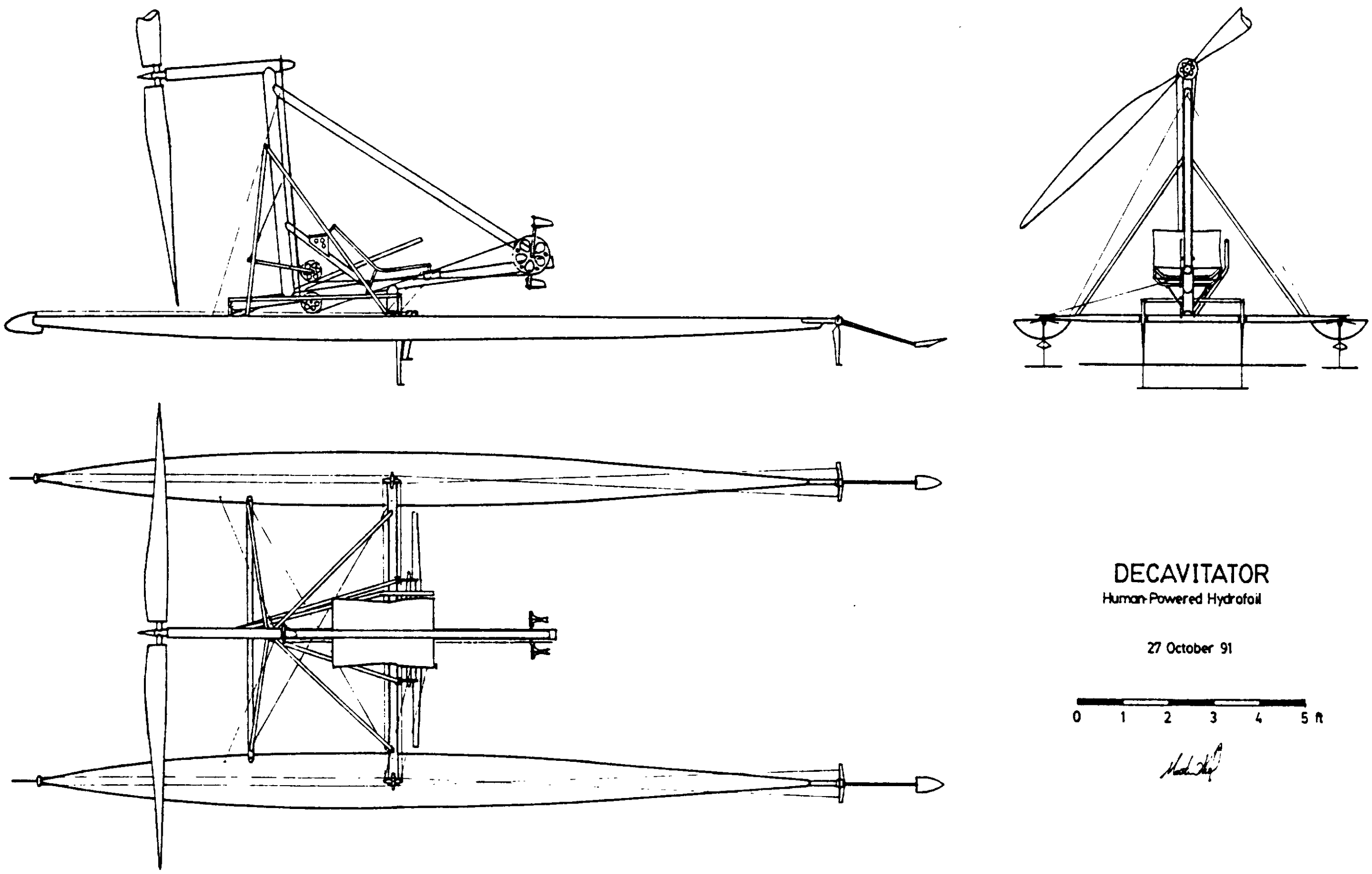


Figure 2 Three-view drawings of Decavitator, without fairings *Drawn by Mark Drela*

requires only a modest anaerobic effort for a few seconds. Once flying on the hydrofoils, the vehicle can be sustained by a fit cyclist at 9-10 knots / 4.5-5 m/s with aerobic power levels. A maximum effort produces about 15 knots (7.5 m/s).

Very High Speed. After unlocking a safety latch, the rider has the option to pivot the large wing up and out of the water, much like on one of the more recent Hydroped variants. The wing pivoting is accomplished by accelerating the vehicle to at least 14 knots / 7 m/s (a fairly hard effort), and then suddenly increasing the angle of attack of the entire wing system via the left lever, which drives the vehicle upwards. When the upper large wing breaks the water surface, rubber cords pivot it together with its mounting struts forward and up into a streamlined receptacle. The sequence is shown in figure 3. If the high power is sustained, the vehicle then rapidly accelerates on the remaining small wing to its maximum speed. The air propeller becomes very efficient in this operating mode.

Pontoons

Each 17-foot / 5.2-m pontoon hull is shaped like a modern open-water women's racing kayak, with the deck lowered by about 2 inches / 50 mm. A similar design is employed for the monohull Hydroped vehicle. Molded composite construction with a hard gelcoat finish gives very nearly the lowest drag attainable. Although such exotic pontoons might seem frivolous on a hydrofoil boat, their low drag is in fact crucial to the top-speed capability of the vehicle. Reducing pontoon drag permits higher takeoff speeds, which in turn permit smaller wings and higher maximum speeds.

Higher takeoff speeds also have the important effect of reducing wave drag associated with the two-dimensional wave train set up behind a lifting airfoil. This is quite independent of the "inverse ground effect" mechanism of the free surface which increases the induced drag of a 3-D lifting wing. As described in Hoerner [4], the 2-D wave drag scales inversely with the square of the chord-based Froude number and exponentially with the square of the depth-based Froude number: $C_{Dwave}/C_L^2 = 0.5gc/V^2 \exp(-2gh/V^2)$. This drag can dominate the overall vehicle drag if large-chord wings are used at low takeoff speeds. An earlier version of the Decavitator had a rather large takeoff wing of 5", 127 mm, average chord, and required excessive takeoff power due to the 2-D wave-drag mechanism - as clearly evidenced by the dramatic wave train set up behind the wing. Reducing the wing area by nearly half gave a larger Froude number, and produced a large power reduction despite the higher takeoff speed.

A further advantage of higher takeoff speeds is that it permits optimizing the propeller for higher maximum speeds. One useful feature of a racing-kayak hull shape is that it retains its low-drag characteristics when partially raised out of the water. This permits a very gradual and low-power transition to the foil-borne mode, where the wings gradually lift the pontoons as the speed is increased. The use of a rider-adjustable angle of attack of the wings is also important, as it permits the pontoons to remain at a nearly-level, low-drag orientation at all speeds.

Drive System

The rider is seated in a semi-recumbent position on an adjustable seat with Kevlar cloth webbing. The pedals are linked to the two-bladed 10-ft / 3-m diameter air prop via a 1/4-in / 6-mm pitch stainless-steel chain-drive with a 2:1 gear ratio. The propeller is of a minimum-induced-loss type, and has been designed with algorithms similar to those of Larrabee [5]. The propeller is designed to rotate at 250 rpm (125 rpm at the pedals) with maximum power at 20 knots / 10 m/s. Its pitch can be dock-adjusted to optimize its performance at lower speeds and power levels, and to compensate for wind direction. If the air/water density ratio is accounted for, the 10-ft / 3-m air propeller is equivalent to a 4-in / 100-mm-diameter water prop in terms of the non-dimensional thrust coefficient $T_c = 2T/\text{rho}V^2\text{pi}R^2$, which determines the induced or "slip" losses. At low takeoff speeds, the 10-ft air prop gives high disk loadings (large Tc) and poor efficiency relative to what could be obtained with an effectively larger 8-in / 200-mm water prop, say. At speeds close to 20 knots, however, T_c becomes sufficiently small to give efficiencies close to 90% even at maximum power. This high efficiency is also due to the prop blade lift coefficients being reasonably high at C_L=0.6 (the Daedalus prop airfoil is used), so that the blade-profile lift-to-drag ratios are fairly good. Ordinarily, a substantial blade C_L at high speeds result in a very large blade C_L at lower speeds, stalling the blades and making transition to the hydrofoils difficult. However, because of the high disk loading, the prop has a very substantial self-induction, or "slip", at low speeds (i.e. it draws air into itself). Together with the modest takeoff-power requirements of the low-drag pontoons, this self-induction is sufficient to prevent the blades from stalling above speeds of 5-8 knots / 2.5-4 m/s, depending on the geometric pitch setting.

Another very large advantage offered by the air propeller is that the wing struts do not need to enclose any drive system, and can be sized as small as material-stress and buckling limitations permit. Where it attaches to the small wing, each strut has only a 1-in / 25-mm chord and a 0.15-in / 4-mm thickness. A strut enclosing a chain or shaft transmitting 1 hp / 750 W would need to be far larger. In addition, the exposed hardware associated with an air propeller has negligible air drag, while a housing for an underwater propeller mount typically has a substantial drag penalty.

Hydrofoil/Strut System

The hydrofoil system consists of two fully-submerged high-aspect-ratio wings under the rider, and two skimmer-actuated trim surfaces on the pontoon bows. The larger 60x2.35-in / 1520x60-mm (span x mean chord) wing is placed about 6 in / 150 mm below the pontoon bottoms, and the smaller 30x1.4-in / 760x35-mm wing is placed another 6 in / 150 mm lower. Each wing is supported by two slender struts placed 26 in / 660 mm apart. The advantage of using two struts is that they do not need to carry significant bending moment, and hence can be made much smaller and have a lower overall drag than an equivalent single strut. Using two struts also greatly relieves bending moments on the wings, and permits much smaller wings to be used for a given material-stress limit. The wings employ a custom 14%-thick airfoil which has been tailored for the operating Reynolds-number range of 150 000 - 400 000, using the design principles and numerical simulation methods employed for the Daedalus-wing airfoils [6, 7]. The structural merit of the relatively thick airfoil allows smaller wing areas and less overall drag than the 10-12%-thick airfoils more commonly employed at these low Reynolds numbers. The thick airfoil also gives the rather wide usable lift-coefficient range $0.2 < C_L < 1.1$, which translates to low wing drag over a wide range of speeds. The ability of the large wing to perform well from 7 to 15 knots is particularly important for the Decavitator as it is brought to its maximum-

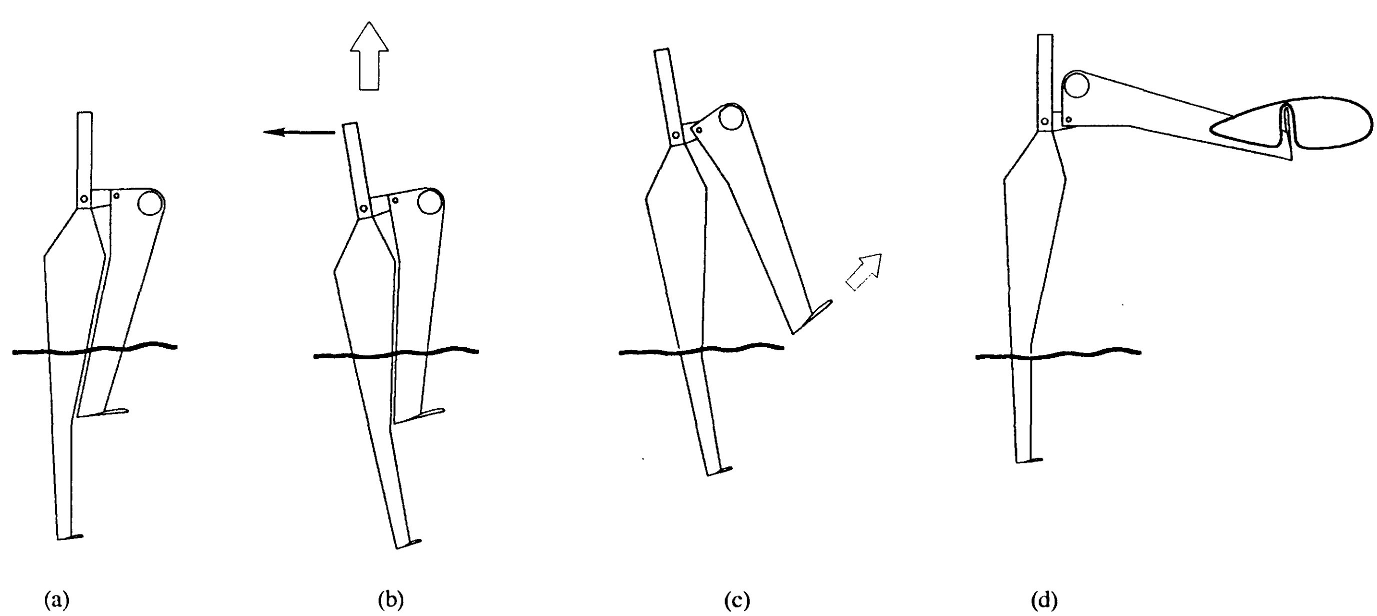


Figure 3 Transition sequence from double- to single-wing mode: the large wing pivots out of the water into a streamlined receptacle.

speed mode. Each of the two 9x0.85-in / 230x22-mm front trim surfaces is mounted at the bottom of a slender rudder in an inverted-T configuration. Each rudder pivots on two axes in a gimbal mounted on the pontoon bow. The pitch axis is controlled by a surface skimmer cantilevered forward from the gimbal, while the steering axis is controlled by the rider via cables linked to a right side-stick. The geometry of the skimmer/trim-surface mechanism is set up to lift the pontoon bow a few inches off the water surface at speeds over 6 knots / 3 m/s. This height is firmly maintained at all higher speeds, so that the vehicle is stabilized in depth and roll, and can pivot only in pitch about the pontoon bows. This pitching alters the wing's angle of attack relative to the water surface, so that for any given speed the boat rapidly seeks the one unique pitch attitude where the wing lift equals the vehicle weight. By altering wing angle of attack relative to the boat via the left lever, the rider can therefore precisely control the pitch attitude and hence the wing submergence depth. At low speeds, a large submergence depth is best to keep the large profile- and induced-drag contributions of the free surface in check. At high speeds, the viscous profile drag of the support struts becomes more dominant, and a very small submergence depth is optimal. The minimum workable depth is set by the need to avoid ventilating the wing by an errant wave trough. Loss of lift due to ventilation immediately drops the vehicle onto the pontoons. The pivoting of the large wing out of the water is an essential feature of the Decavitator's hydrofoil system. Removal of the large wing reduces the total underwater wetted area by a factor of three, giving a roughly proportional reduction in profile drag. This is partially offset, however, by a substantial increase in the induced drag due to the loss in total loaded span. Overall, a speed increase of about three knots is realized for the same power level.

Construction

The Decavitator makes extensive use of structural and manufacturing technology developed at MIT in the course of numerous human-powered-aircraft projects. All underwater surfaces are made via wet lay-up of solid carbon/epoxy vacuum-bagged in female molds. The use of carbon fiber is essential since the small wing dimensions push material stresses to the limit. The small wing, for example, experiences 100 000 psi / 690 MPa material stress with a 140-lb / 64-kg rider at 2 g, and hence could not be safely built even out of aircraft-grade solid aluminum. The struts connecting the pontoons are oven-baked tubes made of pre-preg carbon fiber formed around aluminum mandrels. These are also highly stressed, and the use of carbon fiber gives greater stiffness as well as weight reductions of many pounds over equivalent aluminum tubes.

Each pontoon shell is a pre-preg glass/carbon/Nomex/glass sandwich, and was baked inside a mold for an open-water women's kayak owned by Composite Engineering of West Concord, MA. The top of each pontoon is permanently sealed off with a glass/Nomex/glass deck. Internal plywood bulkheads hold the strut-attachment bolts. The fuselage frame supporting the rider and drive system is constructed of thin-walled large-diameter aluminum tubes joined with Kevlar/epoxy lashings in lieu of welds. Carbon-fiber tubes were rejected for the frame from durability considerations. In retrospect, a carbon-tube frame clearly would not have survived the numerous modifications and general abuse seen by the frame over the vehicle's three-year lifetime. The seat is likewise constructed of lashed thinwall aluminum tubing with a Kevlar cloth webbing, and employs adjustable mounts for different-sized riders. The drive system employs standard bicycle cranks and pedals, lightened somewhat by drilling. The chainwheels and sprockets for the 1/4-in- / 6-mm-pitch chain were custom-made from high-strength 2024-T4 aluminum plate by numerically-controlled machining.

Each propeller blade is a hollow shell with a hard Rohacell-foam shear web, bonded to an aluminum-tube root stub. The shell surface is a Kevlar/Rohacell/Kevlar sandwich, laid-up wet and vacuum-bagged in a female mold. Carbon-fiber rovings are incorporated into the shell sandwich for bending strength. The propeller shaft is a thin-walled large-diameter aluminum tube.

Further developments

Possibilities for further increasing the Decavitator's performance include the following.

Smaller takeoff wing. Since the effort required to lift the pontoons off the water is quite modest, the area of the large wing could be decreased somewhat. The areas of the front trim surfaces could be decreased proportionately as well. The reduction in wetted area would reduce the considerable effort needed to achieve sufficient speed for the transition to the single-wing mode. The rider would then have more energy available at maximum speed.

Aero fairing. Although all major exposed tubes and struts have already been carefully faired, the aerodynamic drag near 20 knots / 10.3 m/s still consumes between 25% to 35% of the propulsive power, most of this being drag on the rider. Enclosing the rider in a high-quality aerodynamic shell would theoretically push the maximum speed past 20 knots. Naturally, for record-setting runs it is desirable to operate the vehicle with the fastest legal tailwind (3.22 knots / 1.67 m/s) to reduce the air drag to an absolute minimum.

Larger rider. The benefits of increasing rider size on a hydrofoil vehicle are significantly smaller than on a bicycle. The actual benefits depend on the relative fractions between profile and induced drags. With the maximum legal tailwind, the Decavitator's induced drag is about 27% of the total at 18 knots / 9 m/s, and 20% at 20 knots / 10 m/s, so a larger rider would have some advantage. However, the vehicle's hydrofoil system is already very highly stressed with the 140-lb / 64-kg design rider weight, and a significantly heavier rider would require larger underwater surfaces to provide greater structural strength. Also, the heavier rider would need to expend disproportionately more power to lift the pontoons and when preparing for the single-wing operating mode, unless the wing areas are increased. In either case, much of the larger rider's advantage disappears. **Larger propeller**. As mentioned earlier, the air propeller is relatively inefficient at lower speeds due to excessive disk loading. Increasing the diameter would therefore give more thrust at low speeds for the same power input, giving faster transition and acceleration. This may significantly conserve the rider's energy and hence permit a higher power level to be sustained over the 100-meter course, although this is difficult to quantify. Offsetting this potential benefit is the increase in size and weight of the supporting frame, and an increase in the nose-down moment of the high thrust line. The latter must be overcome primarily by the small front trim surfaces, and these would need to be larger to avoid stalling at low speeds, which would in turn carry a drag penalty at higher speeds. Likewise, the larger prop would be more prone to blade stall at low speeds. This would require reducing the design blade lift coefficients, which in turn would reduce the blade-profile lift-to-drag ratios and lower the efficiency at maximum speeds. It appears that the tradeoffs inherent in the larger air propeller are complex enough to defy a reliable analytic optimization, and trial-and-error may be the right recourse.

Cleaner large-wing configuration for recreation. The current hydrofoil system has two separate struts on each side for the large and small wings, in order to permit the large wing to pivot out of the water. The two struts on each side are arranged one behind the other with a small gap. This produces a significant drag penalty when the vehicle is operated on both wings. For a recreational vehicle, the power levels in this mode could be significantly reduced by removing the small wing and the double-strut system, and relying only on the large wing supported by two slender non-pivoting struts.

Conclusions

The key design features employed on the Decavitator have resulted in a substantial maximum-speed increase over alternative human-powered vehicle concepts. In particular, the air propeller, pivoting large takeoff wing, solid-carbon-fiber hydrofoil construction, and low-drag pontoons combine to allow a very small underwater drag area and high propeller efficiency at top speed. Additional gains can be realized primarily with improved above-water streamlining.

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Decavitator specifications

Vehicle weight		48 lb	22 kg
Rider weight (design)		140 lb	64
	(max)	160 lb	73
Rider position		semi-recumbent	
Overall length		20 ft	6.1 m
Overall width		8 ft	2.4 m
Air-prop diameter		10 ft	3.0 m
Drive	1/4"-pitch stainless-steel chain		
Gear ratio	2:1 prop to pedal speedup		
Large-wing	area	140 in^2	0.09 m^2
	span	60 in	1520mm
Small-wing	area	42 in^2	0.027 m^2
	span	30 in	760 mm
Trim-surface	area	7.5 in^2	.0048m^2
(each of two)	span	9 in	230 mm
Vertical-strut	area	10-30 in^2	
(depends on mode)			0.006-0.02 m^2

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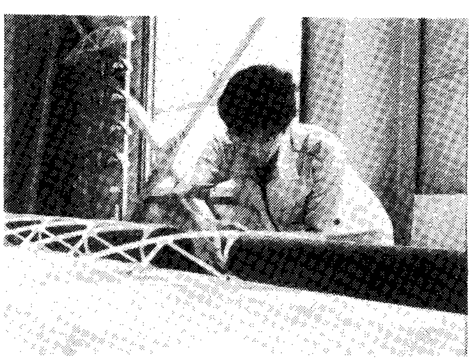

HP's Japan editor, Toshio Kataoka, working on an HPH rotor blade.

CORRECTION

We omitted two paragraphs from Robert B. Fearing's "Pedaling with paddle-wheels, or how to build your own" in HP 9/1. These should be steps 4 & 5 on page 11. Apologies!

4) Build paddle wheel.

Wheel construction is shown in fig. 7. Use almost any kind of wood. The wheel should be robust enough to resist damage when running over floating logs. Balance the wheel statically for smoother pedaling. Compensate for the unbalance of the 90° cranks and the weight of the connecting rods on the crank pins. Add steel plates as weights required. (This sounds like a steam-locomotive balance procedure.)

5) Build crank shafts.

A smooth-running crank system is obtained by assuring that the pairs of cranks driving the paddle-wheel cranks are the same length and at the same angle (90°). A fixture is essential for welding and checking; see figure 8. A fixture could be made using a "flat" plywood base with plywood "V" blocks. Drill all the shaft and crank pin holes in the crank webs. Sort pieces to obtain matched lengths for the critical cranks. The pedal-crank arms must also be accurate enough to assure good alignment. Typical crank joints are shown in fig. 8. Make sub-assemblies of all the elements that are parallel. Check each combination of crank arm and two pins (see fig. 9B) for parallelism in both planes. Adjust by brute force as required. The materials are ductile. Weld paddle-wheel drive flanges (see figs. 6 and 7) to shaft and check for straightness before assembling cranks. Make final assembly of crank parts, using fixture to align parts for tack welding. Check the crank-pin locations with the finished shaft located on the "V" blocks at the journals. If the pedal crank assembly (similar to figures 6B or 6C) needs adjusting, adjust only the center web (this was the last piece assembled). The web can be sawn through in the center. Shim any gaps at the cut and weld up cut. There should be no measurable weld distortion caused by this weld.

IN SEARCH OF THE MASSLESS FLYWHEEL

by John S. Allen

Human power, as commonly transmitted through pedals and rotating cranks, peaks once every 180 degrees of crank rotation, with deep "dead spots" in between. Placing the two cranks 180 degrees out of phase results in in two power peaks per turn of the crank. In addition, the muscles of the leg can drive the foot in any direction, if weakly in most -- so the dead spots aren't as bad as with single-cylinder steam engines, treadle sewing machines and the like, that can actually hang up at dead center and must be hand-started. The small amount of torque that the rider can apply at the top and bottom of the pedal stroke makes it possible for a bicycle's drivetrain to include a freewheel, without the need for a flywheel in the crankset to bring the cranks over the dead spots.

In a bicycle, the unavoidable mass of the bicycle and rider takes the place of a flywheel, maintaining a relatively steady forward speed despite the uneven power application. This works very well at normal riding speeds, but poorly when climbing a very steep grade at a speed below three or four miles per hour (two m/s) -- so the rider compensates with a "pigeon walk," throwing upper-body mass backward and forward to even out the bicycle's forward speed and to put added downward force on the rear wheel during the power phase of the pedal stroke. At very low speeds, and especially on soft surfaces, the ability to shift body mass gives an upright bicycle some advantage over a recumbent. Unfortunately, no type of bicycle gives any climbing advantage to a rider with excess mass!

The flywheel effect requires low rolling resistance and a rigid connection through the drivetrain to the road surface, as you rapidly discover when pedaling through deep gravel or climbing a slippery hill. (Nonetheless, only a dirt-track motorcycle or an all-wheel-drive vehicle can outclimb a bicycle on a slippery surface, since the bicycle benefits from having most of its weight over the drive wheel when climbing, and from rapid, sensitive control over drive torque!)

HP-alternator problem

I became aware of the importance of the flywheel effect after I built a human-powered device that lacked it. This was an automotive alternator mounted on a bicycle, with a two-stage chain drive to bring the rpm up to the required range. Unfortunately, an automotive voltage regulator works to keep the alternator's output constant regardless of how fast it is turning. Consequently, the input torque requirement increases as the generator turns more slowly. This works fine with an automobile engine, which has a multicylinder engine and a flywheel, but it worked poorly for me: the pedals were difficult to push over the dead centers or to accelerate to running speed.

The dead-center problem -- though not the startup problem -- can be solved by a conventional flywheel, using rotational inertia. I've seen at least one description of this venerable idea in *Human Power*, in an electrical generating system used on a sailboat to power an automatic steering system.

But my generator was mounted on a bicycle intended also to be ridden: one goal in assembling it was to promote human power in a parade from the seat of my moving bicycle, through a powerful public-address system. I also wanted to be able to pedal the generator when the bicycle was stationary, so I could not drive it directly off the rear wheel and use my own mass as the flywheel. A conventional flywheel would be heavy, making the bicycle harder to pedal up hills, and would act as a gyroscope, affecting steering and balancing. The search for a solution to these problems led me to consider some alternatives to flywheels.

Conventional flywheels

A conventional flywheel has a high-mass high-speed rim, so that variations in energy input and output cause only small percentage changes in its rotational rate. The energy which the flywheel stores and releases corresponds only to its changes in rpm. The high average rotational speed does not contribute to energy storage or release in steady-state operation, but does increase rolling and aerodynamic friction, and can lead to cause backlash in a low-rpm human-powered system in which the flywheel must be geared up to run at high rpm. A flywheel also makes both starting and stopping more difficult.

It does not matter for a conventional flywheel when or in what amounts energy is input and extracted. Short or long, light or heavy pulses of energy input or output make little difference to it, as long as it has sufficient capacity to accommodate them. If the pulses are too long and/or heavy, you move up to a larger, more massive or faster-spinning flywheel. But in a human-powered system, especially a human-powered vehicle, we want a lighter flywheel. If we design a device that requires a particular input and output -- tailored to the human engine and the task at hand -- we can achieve this goal.

A no-flywheel alternative

The lightest flywheel is no flywheel at all, and is realizable in the case of our electric generator charging a battery. All that is necessary is to add a tachometer sensor to the voltage regulator, so it cuts out the generator below a certain rotational rate. This idea is nothing new to people who build wind generator systems. One approach is to use a centrifugally-actuated mechanoelectrical switch borrowed from electric typewriters. (See "Marshall Price's 'Basement-Built' Windplant," in Mother Earth News, Issue 100, July-August 1986, p. 103).

Taking advantage of the chain-and-sprocket drive, we can also use the principle of the Hammond organ: a coil of wire wound around a bar magnet with one pole placed near passing steel sprocket teeth will generate an alternating current increasing in frequency and intensity as the sprocket spins faster. Rectifying and smoothing this output will generate a dc control signal that can cut in the generator at the desired rotational rate. Just as with a wind-power system, an ammeter and state-of-charge meter also must be supplied and heeded; since the system is designed to use input power as available, it cannot raise electrical output to keep the battery fully charged as power demand increases.

A flywheel accomplishes two purposes: to accommodate varying energy input, and to smooth energy output; but other devices may achieve one of these goals without the other. The conventional voltage regulator and battery smooth the output but do not accommodate to the input. The cadence-sensing voltage regulator, on the other hand, accommodates the varying input from the human engine by varying the output to the battery.

Despite this difference, the "feel" of a cadence-sensing voltage regulator will be similar to that of a bicycle with a freewheel: very little mechanical resistance up to the cadence at which the generator cuts in; though, unlike with the bicycle, the "wall" at that cadence will be "soft" if the the rider pushes down hard: in this case, conventional voltage regulation will set in and reduce the load at the pedals. This problem is relatively unimportant compared with the dead-center problem. A more conventional bicycle-like feel might be achieved by sending excess power to an auxiliary load, such as a second battery in need of charging.

The control device might be designed to auto-adapt to changes in preferred cadence by slowly raising and lowering the cut-in cadence in response to changes in power input. Such a feature would be especially useful when the generator is mounted on a bicycle like mine, intended to be ridden while generating electrical power. Control circuitry might also be designed to mimic the effects of different chainwheel shapes, since opinions differ as to which is preferable.

Capacitors for short-term storage

If some electrical output is to be used while pedaling, a large capacitor (in effect, an electrical flywheel) in parallel with the battery is desirable, to avoid a battery discharge and loss in efficiency between pedal thrusts. If we do not need to store up energy for use later, we can dispense with the battery and use only the capacitor, which is essentially 100-percent efficient. Let us examine whether we can easily obtain a large-enough capacitor to even out power delivery through one pedal stroke.

Let us assume that our human power source is delivering 375 watts of power (about 1/2 horsepower) at a cadence of 100 rpm. This is more or less a worst-case situation, representing the highest power output which a top-rate human engine can maintain for a sustained time. Since there are two power phases and two coasting phases per rotation of the pedals, we make the simplifying assumption that the capacitor must store energy for 1/4 crank rotation and release it for the next 1/4. Then, the capacitor must store 375 x 60/400, or 56.25 watt-seconds (joules) of energy.

Let us assume that we are using a 12-volt battery. This charges at 14.4 volts and discharges at 13.2 volts. The difference between these voltages represents a power loss -- an efficiency of only about 92 percent. To avoid this loss, the capacitor must prevent the voltage from going below 13.2 volts.

Taking the equation $P = V^2/R$ or $R = V^2/P$, our 375-watt load at 14.4 volts is equivalent to an electrical resistance of 0.552 ohm. The current is 26.06 amperes.

A one-farad capacitor, approximately the largest commonly available, will deliver one ampere-second when charged to a potential of one volt. In our example, when charged to 14.4 volts, the capacitor holds a total of 14.4 ampere-seconds. In the 0.15 second corresponding to one quarter of a crank rotation, it must deliver current at the rate of 26.06 amperes, for a product of 3.909 ampere-seconds.

The actual behavior of a capacitor is not to deliver a constant current until exhausted, and then cut off; actually, the current and voltage together decay exponentially. Our 3.909 ampere-seconds are more than a quarter of the total charge in the capacitor, and extracting them will reduce its voltage by more than a quarter -- well below our 12.2-volt minimum.

Another way to put this is that the 1.2 ampere-seconds to discharge the capacitor from 14.4 to 13.2 V corresponds to 1.2 amperes times 13.8 (average) volts for 1 second, or about 16.6 joules. (In this calculation, we have ignored the small difference between the arithmetic average and the geometric mean of voltage).

The one-farad capacitor is not large enough to store all the energy needed, though it fails by factor of only about 8. As long as fluctuations of a fraction of a volt are acceptable to the power-using device, the one-farad capacitor would be just about large enough with a current demand of 50 watts -- a low-to-average bicyclist's output. Also, recall that the capacitor need be large enough only to store power which is not going into the battery. For example, if we are running a radio drawing 50 watts and charging a large battery which can absorb 500 watts, we need a capacitor capable of handling only the 50-watt load.

Mechanical solutions

If voltage fluctuations are unacceptable, if more energy is needed than a capacitor can conveniently store, or if we are powering a non-electric device, then we must look elsewhere, toward a mechanical solution.

One possible device is a mechanical input-power regulator that operates as does our tachometer sensor on the electrical generating system, by somehow varying mechanical loading or mechanical advantage. Achieving such control is easy in a fluid-pumping system such as a water pump, air pump or hydraulic press.

In fact, there are classic examples of regulated pumping systems: the player piano and reed organ use the pneumatic equivalent of a dual mechanical ratchet drive with spring-loaded return stroke. They limit pedal force and regulate output air pressure by dumping excess air volume through a relief valve. The person pumping the bellows quickly learns that there is no advantage in pumping more air than the air chest can store, and that steady airflow and pressure can be maintained by using a quick return stroke, so the power phases for the two feet overlap.

A more efficient arrangement to pump gases or liquids -- though it would not maintain steady flow -- would be a dual-piston pump operated by two crank throws between the pedal cranks, driving two connecting rods 180 degrees out of phase so the maximum power demand would be at the part of the pedal stroke when the most power is available. For greater efficiency, our power regulator could use mechanical-advantage change rather than power-dumping. For example, we could simply place a spring in each connecting rod between crankshaft and pump piston. The spring would be equipped with a limit stop so it would deflect only when the pressure on the piston exceeded a predetermined limit.

As with the pump organ, there is no speed regulation with this arrangement, only an adaptation of the force requirement to the characteristics of the human power source. Speed regulation would require a mechanical governor which would, for example, close a valve, allowing pressure to build up in the pump once the desired cadence was reached.

A crankshaft-and-connecting-rod arrangement like that of the proposed pump can also be connected through a pair of ratchets to a mechanical load. This arrangement is suitable for a winch or a jack, working against weight or friction and whose power requirement is proportional to drive speed. The power input required at the pedals then varies sinusoidally between a low and high value, since the load advances at a rate that also varies sinusoidally. The peak power demand, as in our other examples, should be at the crank angle at which maximum rider power is available.

Another approach for a winch is to wind the cable on a rectangular plate, as is commonly done with children's kite-string holders. As the plate turns around a central axis, the rope winds on at an approximately sinusoidally varying rate. Such a winch must use flexible rope or string rather than stiff cable, to flex over the edges of the plate. A bicycle chain on a hyperelliptical chainwheel could achieve similar results while allowing the use of conventional derailleur gearing to vary the output ratio.

In many applications, however, the connection between the human engine and the load is lossy, making the load itself into a poor flywheel, but the load must advance steadily. A steady load on an electrical generator is one good example. A human-powered boat or airplane is another: its propeller is nearly idling when the pedals are at dead center. The propeller's rated efficiency depends on fluid-dynamic characteristics calculated for a given power input, and serious losses in efficiency are unavoidable when the power input is uneven.

Spring-mass energy storage

One solution to this problem is a human engine consisting of two or more well-matched riders, with the cranks 90 degrees out of phase. But for a single-rider device, we can take our inspiration from the bicyclist's slow-speed "pigeon walk" discussed earlier. If we include in the drivetrain a device that in effect rocks backward and forward, we can effectively even out the power input.

This device could be a spring, deflected by a connecting rod on a crankshaft turning twice as fast as the pedal cranks. The crankshaft should be phased so that the spring stores energy at the strongest parts of the pedal stroke and releases it at the dead centers. Given the same assumptions as in our example of electrical power storage -- 375 watts power output by the human engine at a cadence of 100 rpm -- the spring must store the same 56.25 joules (newton meters) of energy. For example, we could use a spring with a constant of 225 newtons/meter (166.0 lbf/ft) operating through a distance of 0.25 meter (0.82 ft or about 10 inches). A more compliant spring would be more typical, since most riders would not produce as much power.

The spring device would work equally well at any cadence, but it would not adjust itself to different levels of force input -- probably not a problem with a turbine or propeller, which typically optimizes in a narrow range of torque and rotational speed. A variable-rate spring (with coils closer together at one end, so they are fully compressed before those at the other end) could be made stiffer for heavier power applications by manually applying a preload.

Placing the power-evening spring device on the output shaft would avoid any problem with backlash, but would require the output shaft to turn at twice the pedaling cadence -- actually, within the range of common practice with the propellers of human-powered boats and airplanes. Another option to avoid backlash would be to place the device on an intermediate shaft on the way to the output. A third option would be to drive the spring from a two-lobed cam on the pedal crankshaft, or to use a pair of carefully-designed variable-rate springs actuated by two connecting rods opposite one another on a crank throw on the pedal crankshaft itself. All of these options could provide the appropriate twice-per-crank-rotation energy-storage and -release characteristic without backlash.

Almost needless to say, the energy-storage device must be designed for the lowest possible frictional loss, or it can swallow up any efficiency gain that it might realize. The spring should run free, without a sliding guide, and all connecting-rods or cam followers should use rolling-contact bearings. Fortunately, the low rpm of bicycle power production favor such solutions.

Mechanical resonator

A second type of device that can smooth power input when the output speed must be steady is a mechanical resonator. Unlike the spring device described above, this adjusts automatically to different levels of power input. It is especially suitable to a stationary device such as a human-powered lathe, in which extra mass is tolerable and loading may vary considerably, though the pedaling cadence remains relatively constant.

I propose a device like the balance wheel of a spring-wound watch. The balance wheel consists of a flywheel driven by a ratchet escapement and connected to the body of the watch by a spiral torsion spring. In our device, we leave out the ratchet drive and connect one end of the torsion spring to the flywheel and the other end to a rotating shaft of the drivetrain. Actually, two equal torsion springs attached to the flywheel and driveshaft 180 degrees apart would be preferable, in order to cancel radial loads on the bearings supporting the flywheel.

We select the mass and spring to resonate somewhere between 150 and 220 Hz -- twice the expected pedaling cadence. This is the predominant component of unevenness in pedaling output. Any unevenness in shaft speed at this rate will drive the resonating mass and spring system so it stores energy (winds up) during the powered part of the stroke when the shaft is turning faster, then overshoots and releases energy (unwinds) at dead center, when the shaft is turning more slowly. The oscillation of the system have to store a maximum of about one quarter the energy delivered in a full turn of the cranks.

For these reasons, the flywheel can be lighter than a conventional, brute-force flywheel and/or can turn more slowly. We must still bring the flywheel up to speed when starting out, and as we do, it will require an energy input; but this will not be as great as with a conventional flywheel.

Lag and overshoot when starting and stopping can be minimized by rotational limit stops, also desirable to prevent overstressing the spring. We might also consider pre-winding and latching the spring so we can release the stored energy as we start. This would allow the flywheel to assist rather than hinder startup in a critical application like bringing a human-powered boat up to planing speed.

If our device uses a constant-rate spring, it would work best at only one cadence, though, as mentioned above, it would self-adapt to different power inputs at that cadence. A variable-rate spring could make the device adapt to different cadences, at the expense of some harmonic generation, perceptible as "jiggle" at the pedals, due to nonlinear operation. For example, a spiral spring can be designed so that some of the coils wind tightly onto each other near the limits of travel. The spring constant then increases with increasing displacement, raising the resonant frequency of the system. Another way to broaden the cadence range is to use two or more coupled resonators.

Here's a rough-and-ready calculation for the simplest case of an oscillating flywheel: for the same rider as before, delivering 510 watts (375 foot pounds per second) at a cadence of 100 rpm, the (2.3-kg) 5-pound rim of a flywheel will have to oscillate through a linear distance of 3.43m (11.25 feet) to store and release the energy that will take the cranks through one quarter-turn. If, for example, the flywheel is 762 mm (2.5 feet) in diameter, it has to oscillate through 756 degrees, alittle more than two turns, with respect to the shaft to which it is attached. This appears realizable, though I have not yet built a model.

The rotational inertia and spring constant are noncritical as long as they combine to produce the correct resonant frequency: at that frequency, the system's mechanical impedance goes to a very high value. In order to optimize the oscillatory travel for a flywheel of a given rotational inertia, however, the rotational rate of the shaft driving the flywheel must be chosen so that the torque that the spring delivers to and from the shaft at its working limits of deflection equals the peak torque that is required to even out the power input of the drive system.

If the shaft turns too slowly, the spring cannot deliver enough torque unless it winds and unwinds too far, and the flywheel hits the limit stops. If the shaft turns too fast, the spring does not wind and unwind to the full extent possible; a softer spring and lighter flywheel could achieve the same results.

A 2.7-kg (5-pound) flywheel, with perhaps as much mass again for the spring and supporting framework, would certainly be tolerable in a human-powered boat, though the devices discussed earlier that use only springs are probably more suitable for a human-powered airplane.

Closure

I've described a few possible devices, some well-known and some as yet unbuilt, to adapt the uneven power output of the human engine to various loads. All of these devices achieve a flywheel effect or something like it without a conventional, brute-force flywheel. I've seen quite a number of human-powered devices that could be more useful or efficient if they incorporated such devices, and I think that developing such devices is an interesting and fruitful object for human-power research. I hope that I have provided some food for thought, and I am very interested in hearing from anyone who tries out one of the ideas I've described.

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WHAT IS AND WHAT IS NOT A HUMAN-POWERED VEHICLE AND WHY
by Rob Price

It is always a problem to decide which of the many vehicles and "people accessories" that abound in the world might be considered to be human-powered vehicles. This article attempts to categorize these devices and decide why some are, and some are not, HPVs. Guidelines are also developed that may be used to determine in general whether a machine can be considered to be an HPV. The International Human Powered Vehicle Association requires driver control of and brakes on vehicles used in their land competitions, so methods of guiding and stopping devices are also discussed.

DEFINING SOME TERMS.

"Human-powered vehicle" is a term with several sub-meanings. "Vehicle" indicates that something is supported. "Powered" infers that the vehicle moves. "Human-powered" indicates that one or more person(s) is or are providing the energy required to move the vehicle. Though not stated, it can be inferred that the human power source is aboard the vehicle, that is, the vehicle supports the human, and that the human is able to control where the vehicle goes, and where and when it stops.

The foregoing definition could be interpreted to include running shoes, which have been developed over time to dramatically increase speeds of athletes. But there is something about a running shoe that does not fit the accepted meaning of a human-powered vehicle.

Impedance matching is an important concept in electrical engineering but is also used by mechanical engineers, and is especially important when working with the limited human power outputs used to drive HPVs.

The driver of a car must shift gears, or the transmission may do so automatically, when the engine is running either too fast or too slow to produce power efficiently. The transmission provides an impedance match between the engine's and car's speed and power requirements.

Humans can produce widely varying power outputs over a wide range of muscular rates and displacements, but most outputs, rates and ranges are very inefficient, which can lead to early exhaustion and even injury. To produce power with maximum efficiency humans need to operate over a narrow range of muscular rates and displacements. If a bicycle is geared too low, where the rider has more energy available than is required to propel the vehicle at its maximum attainable speed, then the impedance match for that rider is not optimum. In this case the rider runs out of pedalling rate (rpm) before he runs out of energy to push the pedals harder. The opposite is also true where the gear is too high, so the rider is operating below an efficient speed and runs the risk of muscle and joint injury.

A fixed-gear track bike can have the gear ratio altered to suit rider and track conditions. A derailleur-equipped bicycle's gears can be changed while being ridden to optimize rider output over varying riding conditions.

To be rated a human-powered vehicle, there must be a way that the machine provides for a reasonable machine-to-rider impedance match. This is usually provided on wheeled machines by a drive mechanism.

Coupling speed is the speed at which a machine's drive train is accelerated to equal the speed of the machine and couples to allow power transfer. Scarce energy and much of the power stroke are used to bring the rider's power-producing limbs and the drive mechanism to coupling speed, when a machine is traveling at high speed, before the limbs can be used to input power.

A standard bicycle requires most of a pedal stroke to engage the drive when beginning to pedal again after coasting.

Bicycles are constant-drive machines, so the coupling process is done only when the rider begins to input power after coasting. Devices with intermittent power input, such as ice skates, Nordic skis, skateboards, scooters, and some HPVs, need to achieve coupling speed on each power stroke. This is indicative of poor efficiency, hence a poor impedance match. Poor impedance matching is inherently inefficient.

The coupling-speed and constant-versus intermittent-drive concepts are discussed in detail in the HPV Drive Trains chapters of the forthcoming HPV Handbook being edited by Allan Abbot and David Gordon Wilson.

WHEELED AND NON-WHEELED MACHINES.

There are many devices that can support a person, many by attaching to the user's feet, which are designed to augment movement and be controlled by their riders. The list is long, but divides into just two groups: those with wheels and those without wheels. The wheeled category further divides into wheel-driven and wheel-idling sub-groups, discussed later. In the unwheeled category there are three sub-groups: aircraft, watercraft and land machines.

HPAs AND HPBs.

Air is a gaseous medium characterized by low friction. There are two airborne HPV possibilities: gliders and human-powered aircraft, or HPA. Glider lift is provided by updrafts, caused by terrain or thermals, once the airplane is towed to flying speed. Gliders are human controlled, but not human powered. Current HPA designs are brought to flying speed, maintained there and controlled by human power, via an efficient impedance-matching drive system to a propeller, so they are HPVs. Current HPA designs take off and land at very low speeds, and tend to roll on small 50- to 150-mm- (2 to 6") -diameter wheels for their short takeoff and landing runs. Once power input is stopped, HPAs land and stop quickly without the need for brakes.

Water is available in two forms useful to vehicles, liquid and solid, or ice. Rowboats, racing sculls, canoes and kayaks are vehicles that utilize human power via arms working oars or paddles through liquid water. Human-powered boats, HPBs, have been built that utilize a drive train to turn a screw propeller or paddlewheel for motive power.

Paddles and oars have large flat areas on their outboard ends that are dipped

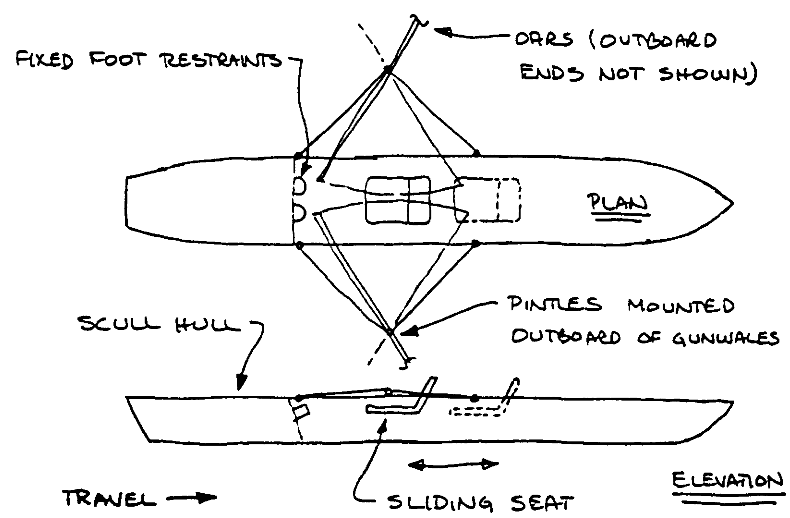

Figure 1 Rowing-scull design features

into the water and push against the resistance of the water to move the boat in the opposite direction. The human delivers power to the paddle or oars via the arms. On paddled boats, such as kayaks and canoes, one arm acts as the fulcrum and the other dips the paddle into and pulls through the water. Kayaks use a double-ended paddle and the paddler's two hands are stationed a few feet apart near the center. Canoes use a single-ended paddle with one hand gripping the end and the other about a third of the way out the length of the paddle.

The paddler dips one end of the oar then paddles a few strokes on one side of the boat while providing a fulcrum for the paddle end with the other hand. The paddle then changes hands so the action is moved to the opposite arm for the next series of power strokes. In this way power is balanced on both sides of the boat and both arms, and the boat goes in a fairly straight line atop the water.

Rowed boats use two oars for each rower, one for each hand Each oar has a pintle, or pivot, mounted into each gunwale, which is the top of the side of the boat. Pintles allow the outboard ends of the oars to be lowered into and raised out of the water and moved forward and aft, but not revolved. The rower pulls on the inboard end of the oars. Putting the pivots outboard of the rower reverses the direction of oar motion so the rower faces aft instead of forward, where paddlers face. Rowers may brace their feet against the boat hull and move their torsos forward and aft, bending at the waist, to increase the stroke length and to use the trunk and leg muscles to assist the arms. [Rowers may also use one long oar, called a "sweep", in eight-oared shells and similar boats].

Turning of paddled and rowed boats is accomplished by working only one paddle or oar, dragging one oar while working the other, working the paddles or oars in opposite directions, or, for canoe paddles, setting one end in the water behind the boat and pushing sideways, like a rudder. Prop and paddlewheel boats generally use rudders for directional control. Since water is a high-viscosity fluid, boat speed decays quickly, eliminating the need for brakes, although most drives can be reversed to stop quickly.

Paddled boats cannot be considered to be HPVs because impedance-matching options are limited to changing hand position on the paddles. Kayaks aredesigned for use in running water and the paddles are used more for directional control and for fending off obstructions than making headway. [But the Aleuts wouldn't agree - ed]. Row-boat oar lengths are determined by boat width, which determines distance between the pintles. The inboard oar ends must not overlap so they can be worked simultaneously, and optimum outboard- to inboard- length ratio is less than 2:1. Rowboats do have sufficient impedance matching to be HPVs. Racing shells, for solo or multiple rowers, mount the pintles well outboard of the gunwales on brackets to greatly increase oar length to make a higher drive ratio. Sculls are speed-limited by the rate at which the rowers can stroke, rather than water friction. At high speeds the effective stroke is limited by the need of the rowers to synchronize the oars with the relative water flow, coupling speed, before dipping the oars and applying power. Some shells, Figure 1, use sliding seats to allow the legs to assist the arms and to increase oar stroke length more than can be done in a fixed-seat rowboat. The impedance match is improved by the use of the seat-slide mechanism, and sculls are good examples of HPVs. Propeller and paddlewheel-driven HPBs are also good examples of HPVs because the speed-changing or crank drive provides a good impedance match.

Ice skates attach to the feet and provide a low-friction way to glide over solid water. Ice is characterized by a very low coefficient of friction because the skate blade is normally lubricated with a thin film of liquid water. This is accomplished by using blade edges that are very narrow, resulting in a tiny contact area on the ice. The high pressure melts the ice as the skate blade slips along. Foot placement in yaw, pointing left or right, and roll, blade directly under or off to either side of the centerline of the foot, purportedly determines the direction of travel. The forward tips of the skate blades often have teeth, so acceleration and braking are done by raising the heel and digging the blade toe into the ice. When accelerating at higher speeds the skate blades may mark the ice in a narrow herringbone pattern, where the rider shifts weight from one foot to the other near the end of the stroke, and the forward component of the slight angle serves to accelerate. An alternative method of braking is toslide the skates sideways so that the blades shave off a thin layer of ice, quickly absorbing the rider's kinetic energy. Speed skaters can achieve high speeds, but long strokes to bring the legs to coupling speed with the ice at high velocities indicate a poor impedance match, preventing ice skates from being considered HPVs.

WHEEL-LESS LAND VEHICLES.

Earth is generally rough and characterized by a high coefficient of friction, so most land vehicles include wheels to smooth the ride and change friction from sliding to rolling. An exception occurs when the ground is covered with snow. After a little packing the coefficient of friction of snow trends toward that of ice. Snowshoes, toboggans, sleds, snowboards, and skis are favorite wintertime human accessories.

Snowshoes are simple devices designed to increase the surface area of the foot of the user to prevent falling through the crust atop deep snow. Nordic skis, even after they have broken through the crust, are much more efficient. Snowshoes are designed only to sap the strength of the best human engine, thus are not HPVs. Sleds and toboggans are purely gravitypowered, are unsteerable and have no brakes, so cannot possibly be HPVs.

Skis come in two major varieties: alpine, or downhill; and Nordic, cross-country or X-C. Alpine skis may be turned by rolling the ankles in the desired direction, which pulls the outer edge off the snow and digs the inside edge into it. The skis are narrower in the center which presents a curved edge to the snow, causing the turn. Alpine skis may be stopped by snowplowing, which is rolling both ankles inward, pointing the fronts of the skis toward each other, then forcing the feet apart, plowing up a vee-shaped ridge of snow. The skis may also be slid sideways the same way as ice skates. Alpine skis are entirely gravity-powered so cannot be called HPVs, although potential stored energy of gravity may come from human power, so if you walk up the hill you can call your skis HPVs.

Nordic skis are able to ascend gradual slopes due to the fishscale-shaped or stepped bottom surfaceconstruction. This provides a one-way clutch against the snow, so that they do not slide backward down gentle grades. Skiers use inertia and poles to augment the uphill struggle until the grade gets too steep; then they may ascend making marks in a herringbone pattern similar to that explained in the ice-skating section, or may step sideways, skis parallel, making marks like a caterpillar-tractor tread up the slope. The skis may also be removed and carried on grades over about 0.5%. It is possible to steer these skis, which are longer, narrower and less tapered than Alpine skis, but most Nordic skiing is done in snowmobile-prepared tracks, grooves in the snow which function like railroad tracks, eliminating the need to learn the elusive steering technique.

Like Alpine skis, stopping on Nordic skis may be accomplished by snowplowing, and sometimes by lifting and plowing only one ski out of the track, to maintain directional control. An alternative is to drag the baskets of the poles in the soft snow next to the tracks. Basket brake force may be increased by placing the poles between the legs and using the seat area as a fulcrum, a favorite of men contemplating castration. As with Alpine skis, the quickest way to stop is to fall over. Though Nordic racers can move very fast, long arm-with-pole and leg strokes are necessary to reach coupling speed before the limbs can input power. Despite the bottom surface clutches, there is no impedance-matching mechanism, so Nordic skis cannot be considered HPVs.

Snowboards are a wheel-less skateboard on which both feet rest, which prevents the problem of the two skis moving in different directions. Like Alpine skis these are entirely gravity-powered so are not HPVs.

Concluding this part, the only non-wheeled vehicles considered to be HPVs are propeller-driven HPAs, propeller- or paddlewheel-driven HPBs, rowboats and rowed racing shells. Paddled boats did not qualify. Air and water propellers could also be considered to be wheels, though the direction of vehicle travel relative to the axis of wheel rotation is at right angles to that of a conventional land wheeled vehicle. No wheel-less land, that is ice or snow, vehicles met the criteria.

WHEELED VEHICLES.

Because earth and pavement are characterized by high coefficients of friction, wheel-less vehicles will not slide easily on them as they will through air, or on water, ice or snow, making wheels necessary. Wheeled vehicles can be divided into two categories: those with power transmitted through one or more of the wheels and those where all the wheels idle, or are not driven. Undriven wheeled vehicles are reviewed first.

Rollerblades use several round-edged wheels in tandem of about 50-mm (2") diameter to give the rider the feel of ice skates. Rollerblades are built onto boots worn on the rider's feet. The path rollerblades make when accelerating is a narrow herringbone pattern as explained in the section on ice skates. There is no steering mechanism, so control is by picking, aiming and placing each foot in the desired direction of travel. Stopping rollerblades is accomplished by rotating the ankles as with ice skates, but by raising the toes instead of the heels, the brake pads being mounted in a safer location beneath the heels. A version of rollerblades for summer use on ski slopes uses a flat belt like a caterpillar tractor tread to offer more contact area over the uneven surface.

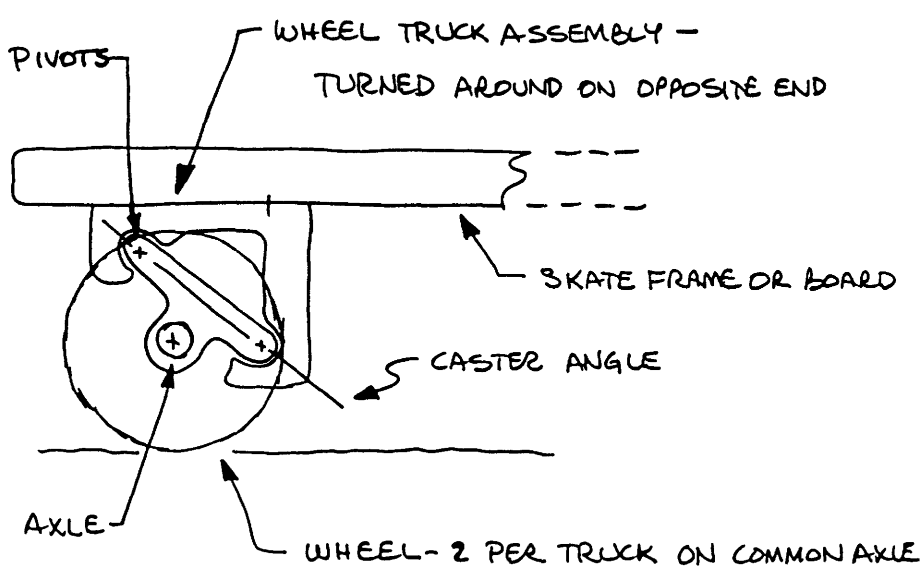

Figure 2 Skateboard steering mechanism

Roller skates are attached to or mounted on boots or shoes and have two wheels each at the front and rear ends, each pair on a common axle. These run 30 to 50 mm (1 to 2") in diameter and are placed about 50-mm apart. In simple designs there is no steering mechanism. The side-by-side wheel configuration is designed to aid a young rider's balance. On more sophisticated designs the wheel pairs turn as the rider's ankle is rolled in the direction of the turn, as illustrated in Figure 2. The forward axle turns in the direction of the turn and the rear axle opposite, allowing for very-short-radius turning circles. Braking is similar to ice skates, where friction pads rest under the toes, accessed by raising the heels.

Skateboards may be gravity powered, where speeds over 25 m/s (60 mph) have been recorded, or one foot may control the board while the other pushes against the ground to incite motion.

Skateboards use the roller-skate steering design, illustrated in Figure 2, but with a wider track, or distance between the wheels, of 100 to 200 mm (4 to 8"). Skateboard wheels are about 50 mm in diameter. The steering mechanism uses a high negative caster on the forward truck, where the steering pivot intersects the ground well behind the axle centerline, and a high positive caster, intersect forward, on the aft truck. This turns the axles inward at the front and outward at the rear as the board is leaned into a turn. These terms are explained in "Human-Powered Vehicle and Suspension Design," HP 7-3, (Spring 1989).

In the 1960s Mickey Thompson brought a four-wheel-steered race car to Indianapolis, where the rear wheels steered outward as on skates. As practice went on the rear steering was adjusted down to the point that it was eliminated by race day. Only slow earth-moving equipment use the concept now. Some modern cars have reintroduced the all-wheel-steer concept but they steer the rear wheels in the same direction as the fronts [in some cars the rear wheels steer in the contrary direction at certain speeds - ed], and steer the rear wheels only a few degrees.

Braking a skateboard is accomplished by rotating about the rear axle, raising the front axle off the road, until a brake pad on the rear edge of the board scrubs along the ground, or by rotating the board in the same way but flipping the board into the air and jumping off simultaneously, catching the board as the rider decelerates on foot.

Sidewalk scooters are an old device which have seen a resurgence in recent years. They help children ease into skateboarding, and the balance learned on scooters makes learning bicycle balance a very easy task. Scooters are comprised of two wheels with a platform between for resting the feet. Power is input by pushing off the ground as on a skateboard. The front wheel is turned by a fork fitted into bearings as on a conventional bicycle, including a handlebar on a long stem so the rider may steer while standing. Scooter wheel sizes vary from 120 to 300 mm (5 to 12") in diameter. Older machines had no brakes but newer models use bicycle-type rim brakes on the rear and sometimes front wheels.

Rollerblades, roller skates, skateboards and sidewalk scooters are all characterized by a lack of drive to the wheels, and because they have the same poor impedance match at speed, where coupling speed is a problem, they cannot be called HPVs.

WHEEL-DRIVEN VEHICLES.

Conventional wheelchairs use the rider's hands to drive two rear wheels of approximately 600-mm (24") diameter. The wheels are driven independently via drive rings slightly smaller than the tire diameter and mounted to the wheels. The wheels may be powered separately to negotiate corners or in opposite directions to turn the chair in place. Small front wheels which caster freely are used to prevent forward tipover, but the rear wheels are set close to the center of gravity of the rider to allow the chair to be tipped back onto its rear wheels to negotiate steps and curbs. Wheelchairs are a fixed-gear arrangement and stopping is done by gripping the drive rings or running the palms against them. In addition crude brakes can be set once the machine is stopped to prevent drifting on slight inclines.

Racing wheelchairs use a smaller drive ring to increase the effective gear and some use a single non-swiveling front wheel which rises off the ground under power and is placed in the new desired direction of travel by careful use of differential power input, steering the chair while the front wheel is airborne. Wheelchairs, even the racing variety, do not have an efficient impedance-matching drive and have the coupling-speed problem at high speeds, so cannot be considered to be HPVs.

A type of Chinese tricycle uses an interesting hand-crank drive. Three 700-mm- (27") -diameter wheels are arranged two at rear, both driving through a differential, and one forward, steered via a tiller. The frame supporting the front end is built around one side of the chair while the other side is open for mounting and dismounting.

A vertical shaft is mounted to the frame near the front of the seat which has an arm and a handle thatis cranked to make the machine go. The other hand steers the tiller and actuates a standard bicycle brake lever. As shown in Figure 3, the vertical crankshaft has a bevel gear at the bottom that engages a similar

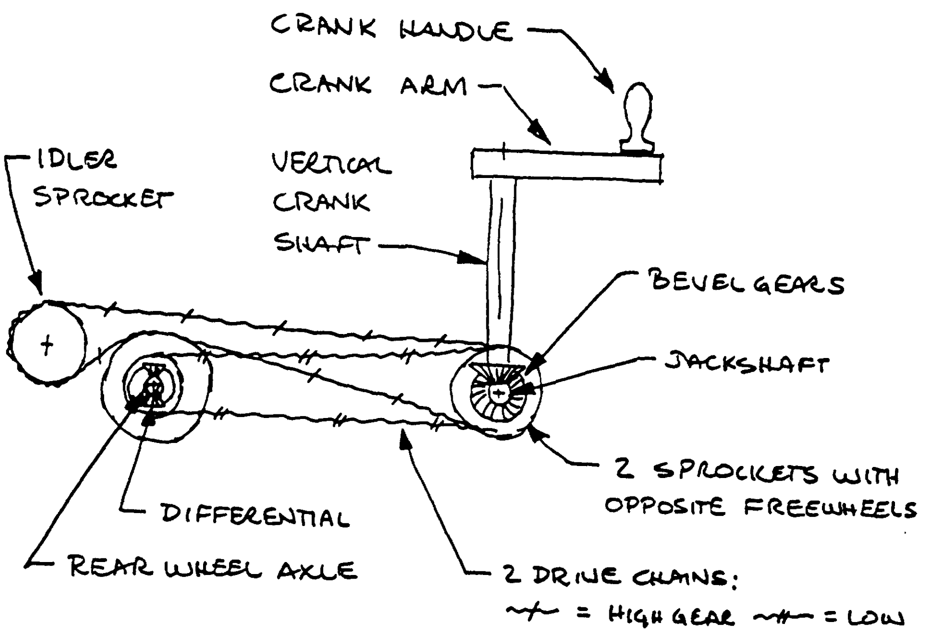

Figure 3 Chinese hand-crank tricycle drive

bevel gear on a jackshaft that runs cross-wise under the plate where the rider's feet rest. Two freewheels engage sprockets on the jackshaft near the center of the trike. The freewheels are arranged for opposite engagement, so that one engages and the other freewheels when the crank is turned in either direction. Two chain drives run from the jackshaft sprockets rearward to the differential on the rear-wheel axle. One chain runs in a simple loop to a sprocket on the differential mechanism case. The other chain runs to a different-diameter sprocket on the differential case but the chain runs from the bottom of the jack-shaft sprocket over the top of the differential sprocket, around an idler sprocket and back to the jackshaft sprocket. This reverses the drive direction, so that cranking the handle in one direction engages one drive ratio and reversing the crank direction engages a different ratio. Because the bevel-gear pair and chain drives may be arranged to produce a variety of ratios and it is a constant-drive machine, this Chinese tricycle is a good example of an HPV.

A basic wheel-driven HPV is the Honda "Kick'N Go," which adds a drive mechanism to a conventional sidewalk scooter. This single-speed, lever-actuated, intermittent-drive machine was marketed by Honda motorcycles around 1980. The drive lever, which may be pumped by either foot, is pivoted just forward of the rear wheel. The lever arc is rearward from 15 degrees aft of vertical to 5 degrees above horizontal, for a sweep of 70 degrees. The lever is 250-mm (10") long and connects to an idler sprocket 90 mm (3.5") from the fulcrum. The drive is taken through 1/4" (6.2 mm) pitch roller chain. One end of the chain is fixed to the frame; it wraps around the lever idler, runs over a 14-tooth drive sprocket on the wheel axle, around another idler, then around a third idler, and the other end is fixed to the frame, as illustrated in Figure 4. The first idler acts to double the effective lever arm, the second increases the chain wrap around the drive sprocket and the third reduces the extension of the spring, which stretches on the power stroke and returns the lever on the retract stroke. The drive is coupled to a 180-mm- (7")-diameter rear wheel through a roller clutch 12-mm (1/2") inside diameter x 16-mm (5/8") long. Each lever stroke advances the scooter 1.3 m (51") making for a gear number of 410 mm (16"), just right for a child. The Kick'N Go utilizes standard scooter steering for the 230-mm- (9") -diameter front wheel and a hand brake that pushes a metal pad against the rear tire face.

Sidewalk pedal cars are designed for small children and are safer than the single-wheel-forward tricycles they graduate onto later. A pendant lever-crank mechanism is used to propel these popular cars. Adult versions using standard circular cranks or lever pedalling have also been produced. A hand-powered variation was owned by the author decades ago, but these have not been seen since. Because they have impedance-matching mechanisms, they are HPVs.

Sidewalk tricycles and the large-wheeled "ordinaries" of the 19th century have no discernable drive mechanism, but the diameter of the drive wheel is tailored to the leg length of the rider and the crank length is tailored to allow a comfortable leg stroke. The effective gear number of the machine is the wheel diameter. Children's tricycle wheels run in a range of 220 to 300 mm (8 to 12"). Though there is no mechanism, there is an effort to make the drive-wheel diameter match the power capability of the rider, so both may be considered HPVs.

Track bicycles use a single-ratio step-up sprocket-and-chain drive to allow use of a smaller drive wheel than the ordinary, making its impedance-

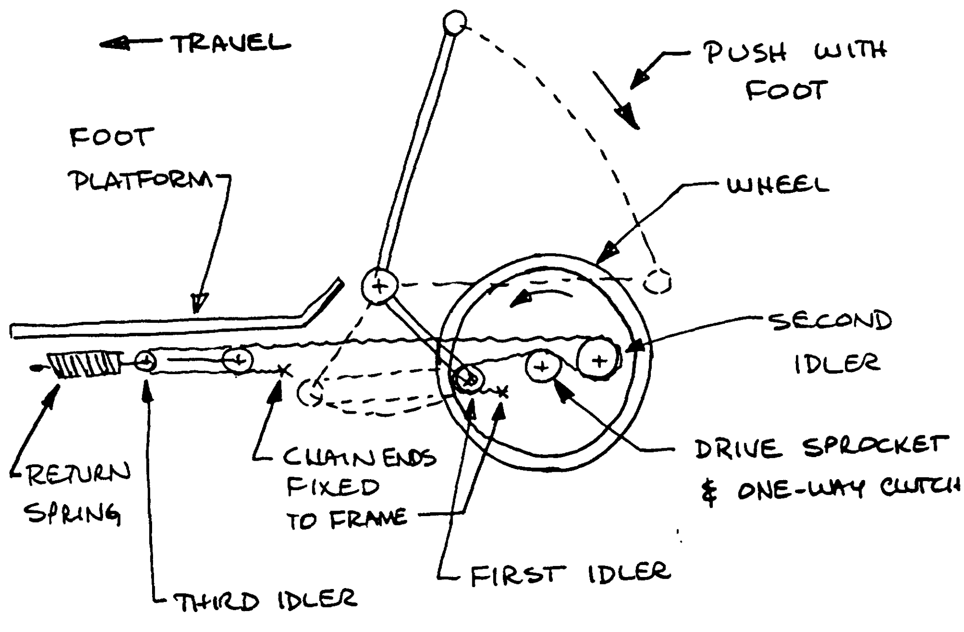

Figure 4 Honda "Kick'n-go" drive

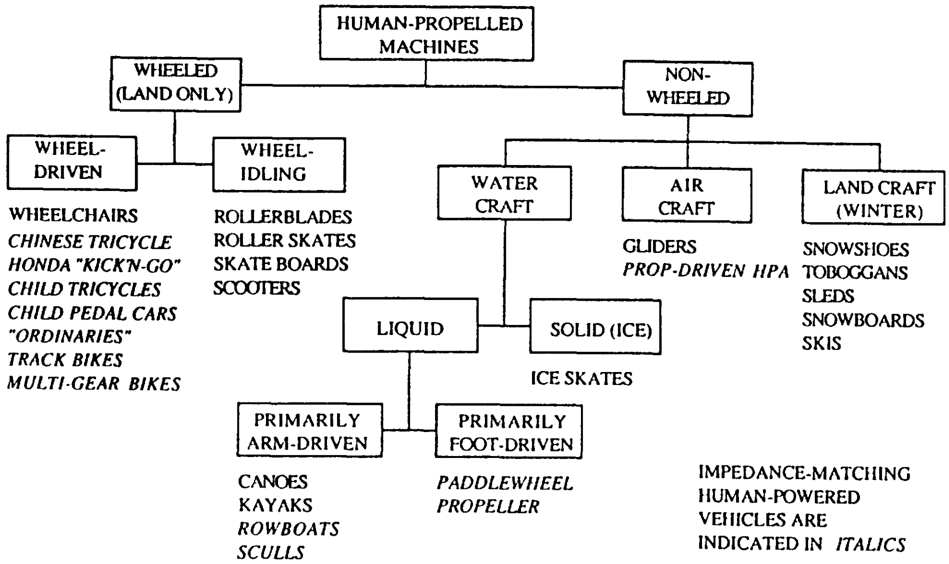

Figure 5 Human-propelled machinery versus human-powered vehicles

matching system more visible. Track bikes also share with ordinaries and sidewalk tricycles the ability to stop the machine by reversing the pressure on the pedals, so these machines are seldom fitted with separate brakes.

Standard bicycles are often fitted with multiple-ratio gearing to allow optimization of pedalling speed and power output over a very wide range of operating speeds and conditions. This is the ultimate in impedance matching but often requires a gear chart to discern which of up to 21 ratios is the next higher orlower. And finally, virtually all the human-powered vehicles Human Power readers build use complex impedance-matching drive trains, so will be true HPVs.

Chinese tricicyle and customer being weighed. Photo: Rob Price

CONCLUSIONS.

This article has attempted to describe many of the devices people use as vehicles, to decide which are human-powered vehicles and to generalize the characteristics necessary for consideration as an HPV. The vehicles reviewed, the categories they fit into and whether they fit the impedance-matching drive definition are tabulated in Figure 5.

Examples of HPVs include propeller-driven aircraft, prop- and paddlewheel-driven boats, rowboats and racing shells. Interestingly, no winter accessories passed the test. Among wheeled vehicles the Honda Kick'N Go scooter, pedal cars, sidewalk tricycles, the hand-cranked wheelchair, ordinaries and conventional bicycles are included, but none of those wheeled vehicles where the wheels are no driven.

A final definition of an HPV is a vehicle that carries its human power source and moves, maneuvers and stops in a controlled manner. Further, a true HPV must be impedance matched to utilize human power efficiently, which is usually accomplished via wheels and mechanisms.

EXTRAS OR THINGS TO TRY.

An easier-steering skateboard could be made by eliminating the steering action of the rear truck while allowing it to lean relative to the board. This would be easier to learn on, because the steering effect would be about halved, but would require different tooling for the front and rear trucks, which are identical on current designs.

A skateboard could be modified to use the Kick'N Go drive, using three sets of gears. The rear axle could still lean and both wheels would be driven when going straight and a positraction-type drive would result.

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CYCLING SCIENCE 3/3-4

This double issue, dated September and December, 1991, was the last under the editorship of Chester R. Kyle, co-founder of the IHPVA. (Cycling Science will continue under another publisher, with Chet's continued association). This issue has 64 pages, and included three articles by Chet Kyle himself (on alternative bicycle transmissions, the effects of cross winds upon time trials, and wind-tunnel tests of aero bicycles). Matt Weaver has an article on his "Cutting Edge". There's a useful article by Kohi Danh et al on frictional resistance in bicycle-wheel bearings, and another on the aerodynamics of bicycling clothing by Brownlie et al. John Stegmann has four pages to himself to present his view of front-wheel-drive recumbents. He thus competed directly with Mike Eliasohn's long-announced article on the same topic in the last issue of Human Power (9/2), to which John contributed. I am not an unbiassed reviewer when a rival journal tries to scoop us. Mike Eliasohn collected articles on many different FWD recumbents and reported on various points of view, and I thought that his was the better piece.

More on hull shapes for pedal power: "kawak"

by Augustus Gast

In Human Power 9/1, Spring 1991, Shields Bishop makes an excellent discussion in favor of catamarans as a choice for pedal-powered craft. Here I would like to join the discussion on the side of monohulls, while describing a class of boats ("kawak") in development here in British Columbia.

Shields argues that monohulls achieve sufficient stability by means of wide, flat bottoms or deep, ballasted keels, resulting in greater wetted area than in a catamaran of similar stability. There are at least four counterpoints to make:

(1) catamarans actually incur a large wetted area which has not been adequately reckoned;

(2) because the monohull can accomodate a lower center of gravity (CG) than the catamaran, additional beam in a monhull can be small;

(3) slight outriggers, which do not touch the water under calm-to-moderate conditions, can enhance the sea-keeping range of a monohull at no hydrodynamic penalty; and

(4) a slender monohull will usually be longer than a catamaran of like displacement, reducing wave drag on the monohull.

Shields has provided useful formulae in his discussion. Let me follow that lead. The volume displacement is

$V=pLBd$

where L is length, B is maximum beam, d is draft and p is sometimes called a "prismatic" coefficient which will depend upon the particular hull shape. L and B are both taken at the load water line. For the semi-circular underwater crossection which Shields recommends, $d=B/2$. Wetted area can be written

$A=cLB$

where c is another coefficient that depends upon specific hull shape.

Let us compare the monohull with the catamaran, assuming the same volume displacement. (That is, I assume that ballasted keels are not popular for human-powered boats.) For the monohull, we can rewrite

$V=p_1L_1B_1^2$ and for the catamaran $V=2p_2L_2B_2^2$, where p_1 is a modified prismatic coefficient (expressed in terms of B rather than d) and a factor of 2 occurs in the second formula because the catamaran has two hulls. Wetted areas for the monohull and the catamaran are likewise written $A_1=c_1L_1B_1$ and $A_2=2c_2L_2B_2$. From the relations for V, we have

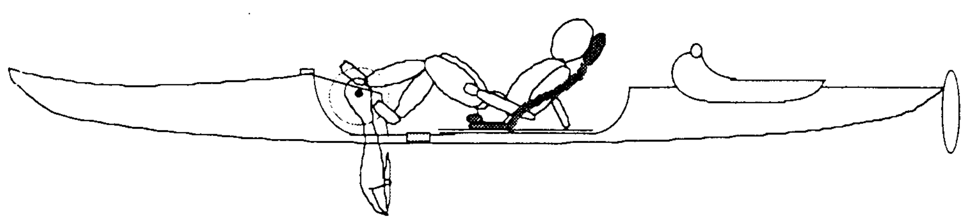
$A_1=c_1\sqrt{VL_1/p_1}$ and

$A_2=c_2\sqrt{2VL_2/p_2}$.

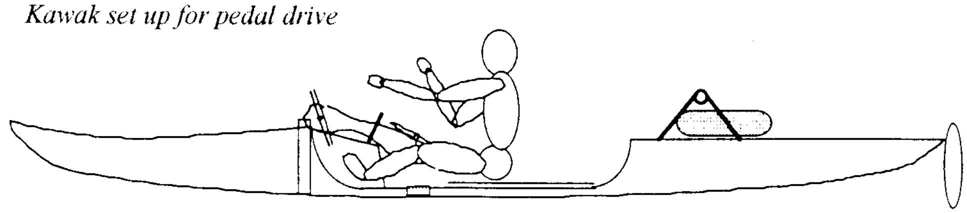
Thus, "all other things equal", the catamaran would carry $\sqrt{2}$ more wetted area than the monohull, roughly a 40% penalty! Of course "all other things" are never equal. The monohull will usually have $c_1<c_2$, $p_1<p_2$ and $L_1>L_2$. Decreased p_1 and increased L_1 both tend to increase the wetted area of the monohull -- just as Shields has pointed out. Decreased c_1 favors less wetted area in the monohull. Importantly, the question must be: by how much?

The answer to this question depends upon specifics of hull shape. Certainly it is true that a wide, flat-bottomed monohull may indeed carry larger wetted area (on account of small p). However, this choice for a human-powered boat is likely to be avoided. Instead, consider point (2) above. The pilot of a catamaran is obliged to sit at some elevation between the two hulls. In a narrow, pedalled, monohull, a recumbent cyclist may have such a low CG that very little "additional" beam will be needed for stability. Experience has suggested that boats can be as narrow as permitted only by the human torso (with bicycle crank) -- from 410mm (16 inches) on the narrow side to a generous 510 mm (20 inches). At the narrower end of this range, underwater sections become nearly semi-circular, and c and p have values quite like the catamaran. More generally, it seems the monohull will be penalized around 10-20% in its $c/\sqrt{p}$. As well, the slender monohull will tend to be longer than the catamaran, perhaps 5.5-6.1m (18 to 20 feet) in a monohull compared with 4.9m (16 feet) (say) in a catamaran. Thus, one may incur a further 10% penalty -- less than the 40% penalty on the catamaran side.

Despite low CG, one may still feel nervous (on a longer trip, subject to uncertain sea states) in a monohull of



Kawak set up for pedal drive



Kawak set up for paddling

A kawak in the Straits of Georgia, Vancouver, showing the aft-mounted outriggers.

B=480 mm (19 inches), L=5.8m (19 feet) (say). A cyclist, without paddle at ready, may not employ the braces which would assist a conventional kayaker in a developed sea. The answer to this appears to be outriggers. But these are not outriggers that run in the water, generating wetted area and drag. Rather, we use low-volume (10-litre) outriggers, supported above the waterline, well aft of the cockpit. In the kawak design (see figure), this location keeps the outriggers out of the way while paddling with a conventional kayak paddle. The location also minimizes occasions in sea states when splash from an outrigger is thrown onto the pilot. Ten-litre outriggers have prevented capsize in any sea state yet encountered. However, the low volume has proven useful in deliberate capsizes when it is found that the time from full-over capsize until the boat is righted and re-entered is less than 20 seconds (an important consideration in colder water.) With such added safety margin, one feels assured in building a main hull with characteristics similar to a catamaran hull.

Point (4) concerns length. As we've seen, A tends to increase as $\sqrt{L}$. A monohull (with outriggers) may be 20% longer than a corresponding catamaran (5.8m vs 4.9m, 19 ' vs 16', say). Greater length of a monohull implies about 10% penalty in wetted area. However, at the speeds that pedal craft operate, wave drag becomes increasingly important relative to friction (wetted area). Wave drag is a strongly increasing function of $S/\sqrt{L}$, where S is speed. Increased wetted area on account of L is more than offset by decreased wave drag. Thus, the monohull may achieve lower drag than a catamaran at the higher speeds for which wave drag is signficant.

A suggestion of the difference in drag between catamaran and kayak-type hulls can be seen in drag tests on a Sea-Cycle catamaran (Human Power 8 (4), winter 90) and tests on six kayaks reported in Sea Kayaker 3 (3, winter 86) and 3 (4, spring 87).

Finally, it must be said that there are many reasons to build pedal-powered boats. Considerations of speed and drag, though important, are only a few among many considerations. Various other arguments may favor either the catamaran or the monohull. Let me close with a brief account of "kawak". [The word is from the Salish native dialect, meaning "to fly" or "it flies". Pronunciation stresses the second syllable, roughly "kwok".]

Kawak most resembles an open-cockpit kayak including a daggerboard-like trunk through which one inserts a drive unit for pedal drive. The feature which defines the kawak (as a type of boat) is this quick conversion (a few seconds) between being pedal-powered and being a more conventional kayak. In shallows, in weed, or in uncertain waters, the kawak has all the versatility of a kayak. Then, with a stretch of open water to cross, the kawak converts (in seconds) to pedal drive, opening up greater speed and -- especially -- greater range possibilities.

In proof-of-concept prototype, a kawak was assembled from a Valhalla Surfski hull, using a SeaCycle drive unit. Ongoing developments include both the use of a more conventional kayak (nicer long-range touring features) as well as effort toward a boat built purely for racing boat. New drive units are being developed for the newer boats.

Experience to date with the prototype kawak has been encouraging. We have not made an athletic contest out of this. Rather, we have found that ordinary people can expect to sustain cruising speeds of 3 m/s while my assistant (46-years old, with no particular athletic ability) peaks to 5 m/s. There is no doubt even at prototype stage that stronger athletes would turn in higher performances. But kawaks are for everyone from children through seniors, offering comfortable day trips of 30 km (20 miles) and more for people of very ordinary ability. (Athletic users can plan daily trips in excess of 60 km, 40 miles.)

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(Augustus Gast is a consultant physicist).

Advances in flow visualization using liquid-crystal coatings

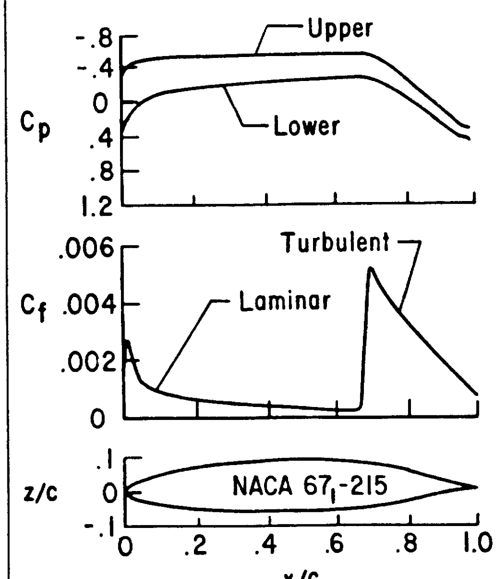
by Bruce J. Holmes and Clifford J. Obara

(The following is from a NASA "technical support package, LAR-14342 sent in by Mark Bruce, New Canton, OH, USA. The full paper is SAE no. 871017. Bruce Holmes of NASA Langley addressed an HPV-builders' workshop in Cambridge MA on the subject about six years ago).

Very large reductions in drag coefficient can be obtained by shaping a body so that it produces laminar, instead of turbulent, flow in the boundary layer - the air right against the surface. Here is an example taken from the paper showing the very large drag penalty from turbulent flow.

While one can use advanced computational fluid mechanics to design enclosures to produce laminar flow, in practice there are many differences between the theoretical and actual conditions. Thus being able to see where transition to turbulence occurs gives the fairing builder the knowledge of where to change the shape or the roughness to preserve laminar flow.

The advantages of liquid-crystal coatings vs the traditional sublimating chemicals, china clay and oil coatings are the reversibility of the indications, the greater clarity of the display, and the low toxicity. The surface is first painted matte black, and then a liquid-crystal film is sprayed on. Colors indicate skin friction. Refer to the full paper for details of where to get the liquid crystals, etc. *(Reviewed by Dave Wilson).*



Skin-friction and pressure distributions for a NACA 671-215 airfoil

Design for a wind+human-powered quadracycle

by Wally Flint

This vehicle uses a pedal drive mechanism similar to a bicycle but augments the power with symmetrical airfoils extending vertically from the vehicle (with the leading edges pointing forward). Airfoils are more efficient than sails, permitting higher speeds, but sails provide greater power at low speeds. For this application airfoils are preferable because we can use human power to reach speeds at which the airfoils become effective.

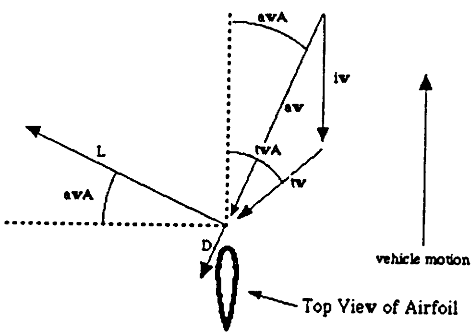


Figure 1 Definitions

In this article the standard equations that describe the lift and drag on the airfoils can be found in any textbook on aerodynamics or wings. Figure 1 defines the terms and angles used in computing the propulsive force of the airfoils. "Apparent wind" (aw) is the vector sum of "true wind" (tw) and "induced wind" (iw). "True wind" is the wind you feel when the vehicle is at rest. "Induced wind" is the wind produced by the motion of the vehicle. Note that the induced-wind vector always has the same magnitude as the vehicle-velocity vector, but is pointed in the opposite direction. "awA" (apparent wind angle) denotes the angle between the apparent wind and the vehicle's path of motion; twA (true wind angle) the angle between the true wind and the path of motion. "L" is lift and "D" is drag.

To understand where the propulsive force comes from note that lift is by definition the force which is at right angles to the oncoming airstream (apparent wind). Similarly, drag is by definition the force which is in the same direction as the apparent wind. If the apparent wind angle (awA) is large enough and if the lift-to-drag ratio is large enough then the net force produced by the airfoil will have a forward component (although it will also have a much larger side component). Thus, the forces on this vehicle are exactly analogous to the forces on a sailboat - the only differences being that airfoils are used to generate the forces instead of sails and wheel friction is used to resist the side force instead of a centerboard.

It should be possible to rotate the airfoils as a unit, so that the leading edges can point to the right or left as in figure 2. Thus when awA becomes larger than the stall angle for the airfoils, one can simply point the airfoils more in the direction of the apparent wind.

For a given magnitude of apparent-wind, the smaller the awA the smaller the forward component of lift. In the following equations I will assume that awA is less than the stall angle and therefore the airfoils will be pointed directly forward. In this case the airfoil angle of attack is equal to awA. The following formulas give the awA and the magnitude of the apparent wind vector (|aw|):

$$awA = \arctan \frac{tw \sin(twA)}{iw + [tw \cos(twA)]} \qquad (1)$$

$$[aw] = \frac{tw \sin(twA)}{\sin awA} \qquad (2)$$

Figure 3 gives data at low Reynolds numbers for the E-169 airfoil[1] and figure 4 gives the airfoil coordinates. In our case if we assume a chord of about 200

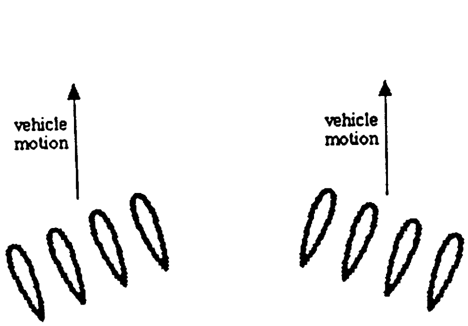
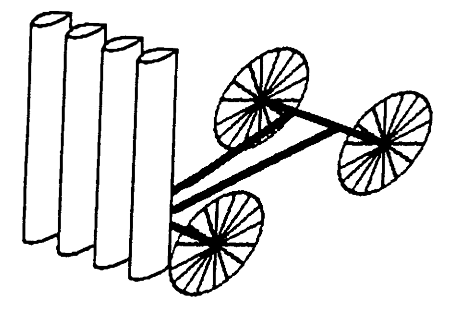


Figure 2 Rotatable airfoils



Airfoil-vehicle arrangement

mm (0.6 feet) and an apparent wind speed of about 13.5 m/s (30 mph) then the Reynolds number Re= $\rho[aw](chord)/\mu$ =187,000 where ρ is the density of air (1.24 kg/cu.m.) and μ is the absolute viscosity of air (1.79×10^5 Ns/m^2).

The lift of a single airfoil is $L = C_l \; 0.5 \rho \; area \; |aw|^2$ where C_l is the lift coefficient and "area" is the area of the wing. From figure 3 the lift coefficient is equal to 0.1 awA (awA in degrees). Then $L = 0.062 \; awA \; area \; |aw|^2$.

The actual lift will be less than that described by the above equation because of the close proximity of the other airfoils. If two wings are separated by a distance of 1.5 times the chord length, then the resulting lift generated by either wing is equal to 0.92 times the lift predicted by the above equation[2]. This applies to two wings. I don't know what the correction factor is for three or four wings. These additional wings are a disadvantage in that they no doubt make the 0.92 correction factor even smaller. There are, however, some advantages to having more than one wing. For one thing the vortices from adjacent wing tips tend to cancel each other which tends to lower the induced drag. Another advantage is that the equations we will be using to calculate drag assume that both wing tips are away from any obstructions, but in our case the lower wingtip is close to the ground and, in addition, it may terminate into the body of the vehicle. Both of these factors tend to further reduce the effect of wing-tip vortices. Thus I will assume that these effects will make up for the fact that the 0.92 correction factor may be too large when using more than two wings. In addition, we will find that there is enough room to separate the airfoils by a

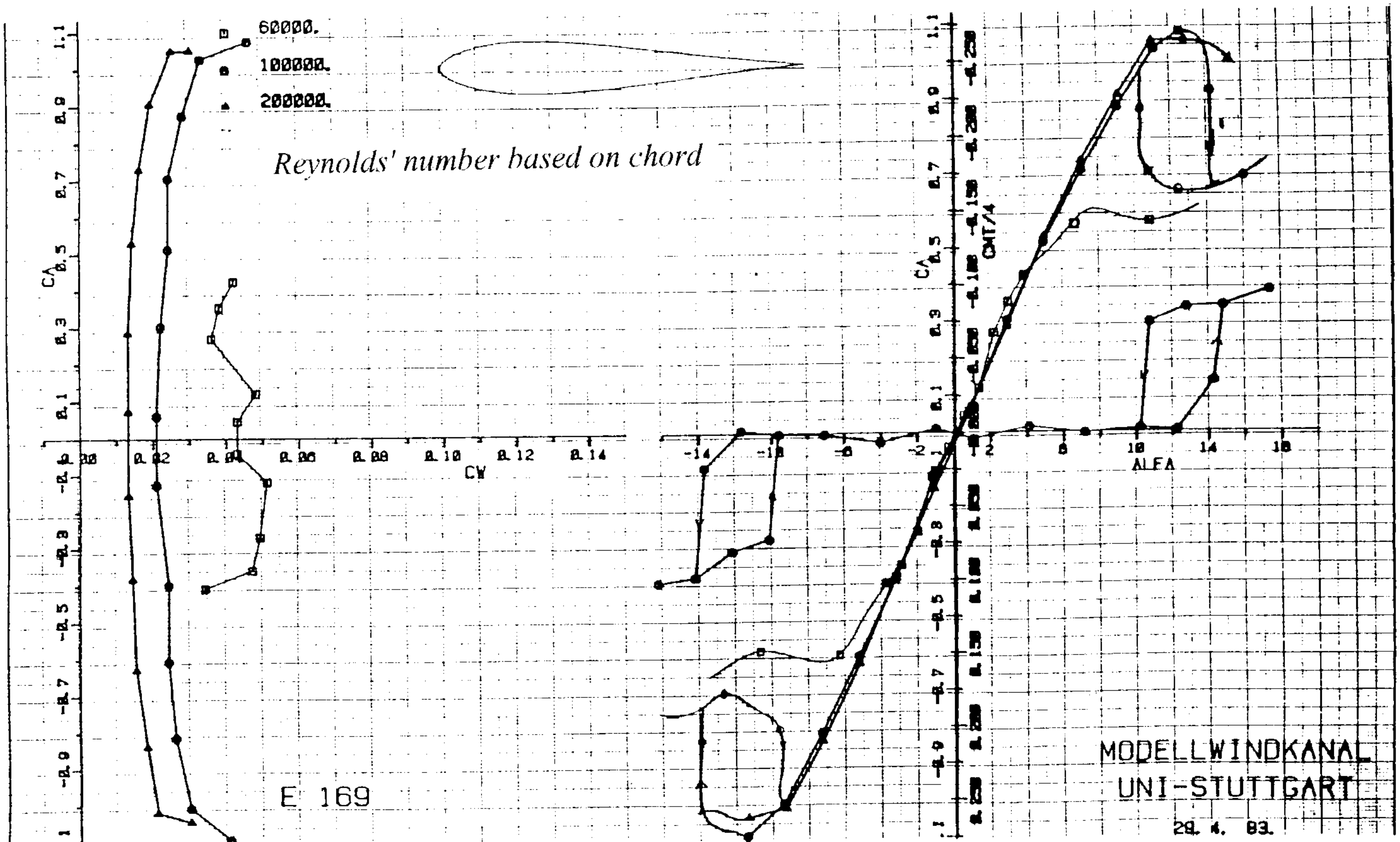


Figure 3 Data from Althaus (ref. 1) on airfoil performance at low Reynolds numbers.

distance greater than 1.5 times the chord length. Substituting area = span x chord into the lift equation and including the 0.92 correction factor gives:

$L = 0.057$ awA span chord $|aw|^2$ (3)

From figure 1 the forward component of lift (FCL) is: L sin(awA). Since we care only about small values of awA (awA < stall angle) then we can say that sin(awA) is approximately equal to awA (awA in radians). If awA is in degrees then sin(awA) is approximately 0.0175 awA. This gives the forward component of lift <u>for a single airfoil</u>:

FCL = L sin(awA) =
9.98×10^{-4} awA^2 span chord $|aw|^2$ (4)

The equation for drag is

$D = (C_p + C_i)$ 0.5 rho span chord $|aw|^2$

where C_p is the "profile-drag coefficient" (labeled CW in figure 3) and C_i is the "induced-drag coefficient". For rectangular wings(2):

$C_i = 1.1\ C_l^2$ chord π span)

(This equation usually has aspect ratio in the denominator but I have substituted aspect ratio = span/chord for a rectangular wing). Substituting $C_l = 0.1$ awA gives:

$C_i = (0.0035$ awA^2 chord)/span

From figure 3 we see that C_p is roughly 0.025 over our range of interest. Putting the values for C_p and C_i into the drag equation we have:

$D = (0.00217$ awA^2 chord^2 $|aw|^2) +$
$(0.0155$ span chord $|aw|^2)$ (5)

From figure 1 the backward component of drag is: D cos(awA). For small values of awA, cos(awA) is approximately equal to 1, so the backward component of drag is simply D.

The net forward force (NFF) acting along the path of motion provided by a single airfoil is equal to the forward component of lift (FCL) minus the backward component of drag:

Net Forward Force = NFF = FCL - D =
$\{(9.98 \times 10^{-4}$awA^{2}span chord) - (0.00217 awA^2) chord^2 - (0.0155 span chord)$\}$
$|aw|^2$ (6)

We would like the forward force of the airfoils to balance the backward force of the wind resistance acting on the vehicle alone (without the airfoils). Note that the backward force due to wind resistance that acts on the airfoils has already been included in equation 6. To estimate the wind resistance we might be able to achieve we begin with values quoted for the Van Valkenburgh prone quadracycle with fairing(3). This vehicle has a frontal area of 0.46 sq.m. and a coefficient of drag (C_D) of 0.14. I will use a frontal area of 0.51 sq.m. and $C^D = 0.25$. The wind resistance (in Newtons) is:

wind resistance = (0.6812x0.46x0.25
$|aw|^2) = 0.07833\ |aw|^2$ (7)

Since airfoils are not easy to make, we might limit ourselves to a maximum of four. (In this case the total NFF will be four times the value given by equation 6.) We want to have enough propulsive force to operate in worst-case wind conditions. I am taking these conditions to be a wind large enough, a twA large enough, and a vehicle velocity small enough to give an angle of attack (awA) of at least 9 degrees. (Later we will investigate the performance of the vehicle at specific true wind speeds, twAs and vehicle velocities.) Now substitute awA = 9 into equation 6, multiply the equation by 4 (to give total NFF of four airfoils), and equate with equation 7 (to express the fact that the total propulsive force will equal the wind resistance given by equation 7).

$\{(0.261$ span chord) - (0.703 chord$^2)\}$
$\times |aw|^2 = 0.07833|aw|^2$ (8)

NR	X/T	YO/T	YU/T
1	1.00000	0.00000	0.00000
2	0.99893	0.00006	-0.00006
3	0.99572	0.00027	-0.00027
4	0.99039	0.00073	-0.00073
5	0.98296	0.00147	-0.00147
6	0.97347	0.00248	-0.00248
7	0.96194	0.00369	-0.00369
8	0.94844	0.00503	-0.00503
9	0.93301	0.00649	-0.00649
10	0.91573	0.00808	-0.00808
11	0.89668	0.00986	-0.00986
12	0.87592	0.01187	-0.01187
13	0.85355	0.01411	-0.01411
14	0.82967	0.01660	-0.01660
15	0.80438	0.01934	-0.01934
16	0.77779	0.02231	-0.02231
17	0.75000	0.02552	-0.02552
18	0.72114	0.02893	-0.02893
19	0.69134	0.03252	-0.03252
20	0.66072	0.03626	-0.03626
21	0.62941	0.04011	-0.04011
22	0.59755	0.04401	-0.04401
23	0.56526	0.04793	-0.04793
24	0.53270	0.05179	-0.05179
25	0.50000	0.05553	-0.05553
26	0.46730	0.05908	-0.05908
27	0.43474	0.06238	-0.06238
28	0.40245	0.06533	-0.06533
29	0.37059	0.06786	-0.06786
30	0.33928	0.06987	-0.06987
31	0.30866	0.07127	-0.07127
32	0.27886	0.07196	-0.07196
33	0.25000	0.07189	-0.07189
34	0.22221	0.07107	-0.07107
35	0.19562	0.06952	-0.06952
36	0.17033	0.06723	-0.06723
37	0.14645	0.06422	-0.06422
38	0.12408	0.06052	-0.06052
39	0.10332	0.05618	-0.05618
40	0.08427	0.05131	-0.05131
41	0.06699	0.04597	-0.04597
42	0.05156	0.04025	-0.04025
43	0.03806	0.03441	-0.03441
44	0.02653	0.02821	-0.02821
45	0.01704	0.02250	-0.02250
46	0.00961	0.01604	-0.01604
47	0.00428	0.01011	-0.01011
48	0.00107	0.00500	-0.00500
49	-0.00000	0.00000	0.00000

DICKE/T...= 0.144 RUECKLAGE/T= 0.279
WOELBUNG/T= 0.000 RUECKLAGE/T= 0.001
PROFILTIEFE...= T

Figure 4 Profile E 169 coordinates from ref. 1

Later I will show that the top speed of the vehicle is maximized when span = 2.18 m and chord = 178 mm. For now simply note that these values satisfy equation 8. At the local U-haul rental place I found out that a small U-haul truck requires 2.64 m clearance. If we assume that the lower tips of the airfoils are going to be about 300 mm off the ground, then a span of 2.18 m would give us a vehicle that is not quite as high as the small truck. What about the width? My Ford F-150 pickup is 1.93 m wide. This gives us room to space the airfoils about 600 mm apart. The 0.92 correction factor included in equation 3 assumed the airfoils were separated by a distance equal to 1.5 x chord, but here we have separated them by a distance of 3.4 x chord.

Equation 8 seems to state that the airfoils will supply a forward force equal to the backward force of wind resistance at any vehicle speed (any value of $|aw|^2$). But remember that as the speed of the vehicle increases, the awA decreases. The maximum vehicle speed for which our equations are valid is that speed which reduces the awA to 9 degrees. A further increase in speed will result in awA < 9. Beyond this speed we cannot expect the forward force of the airfoils to balance the backward force of the wind resistance.

How often will we encounter "good wind conditions"? Look at figure 1. Hold the wind speed (tw) and vehicle speed (iw) constant and then rotate the tw vector through 360 degrees. At what values of twA is awA < 9? Equations 9 and 10 (which were derived by applying the law of sines to figure 1) help us to answer this question. The answer depends on the relative magnitudes of tw and iw. There are three situations which occur.

1.iw < tw

When iw < tw, there will be a range of values of twA, symmetrical about twA = 0, such that whenever twA is within this range the magnitude of awA will be less than 9 degrees. This range of values of twA (in degrees) is given by equation 9 with $awA_{(max)}$ = 9 degrees. Equation 10 (also using $awA_{(max)}$ = 9) gives a negative answer when iw<tw, and this negative number should be discarded.

2.(tw/sin(9)) > iw > tw.

In this case there will two ranges, one symmetrical about twA = 0 as before, and another symmetrical about twA = 180. Equation 9 gives the range symmetrical about twA = 0. Equation 10 gives the range symmetrical about twA = 180.

3.iw>(tw/sin(9))

In this situation awA < 9 for <u>all</u> values of twA; the two ranges have merged with each other and equations 9 and 10 have no solution.

$$\text{twA range} = 2 \arcsin(iw \sin(awA_{max})/tw) + 2\, awA_{max} \qquad (9)$$

$$\text{twA range} = 2 \arcsin(iw \sin(awA_{max})/tw) - 2\, awA_{max} \qquad (10)$$

Let us consider a wind speed of 6.7 m/s (15 mph) and a vehicle speed of 13.4 m/s (30 mph). Equation 9 states that the range symmetrical about twA = 0 is 54.5 degrees. Equation 10 states that the range symmetrical about twA = 180 is 18.5 degrees. If the direction of the road is random then we will encounter a twA falling into one of these regions

((54.5+18.5)/360) = 20% of the time. Perhaps it would be better to say how often we will encounter a value of twA giving awA greater than 9 instead of less than 9. This would give us a rough evaluation of how often we can expect to encounter "good wind conditions". The accompanying table presents this figure at various wind speeds and vehicle speeds. The table should be read as in the following example (using the wind speed = 15 mph row and the vehicle speed = 40 mph column): when the wind is 15 mph, we should be able to drive at 40 mph 73% of the time. (This assumes that the driver provides only enough power to overcome the rolling resistance of the vehicle.)

At awA = 0 the airfoils do nothing but increase the drag. It's easy to figure out how often the airfoils contribute some forward force (NFF > 0). Recalling equation 6 for the NFF of a single airfoil:

$$NFF = [(0.000998\ awA^2\ span\ chord) - (0.00217\ awA^2\ chord^2) - 0.0155\ span\ chord)] \left[aw^2\right] \quad (6)$$

NFF is positive when the expression in the brackets is positive. Putting span = 2.18m and chord = 0.178m into that expression gives:
$0.0003185\ awA^2 - 0.006015$.
The minimum value of awA for which this expression is positive is awA = 4.35 degrees. Consider a typical bicycle speed of 6.7 m/s (15 mph) and a wind speed of 2.2 m/s (5 mph). Equation 9 with awA_{max} = 4.35 gives 35 degrees; equation 10 gives 17.6 degrees. We expect to encounter awA<4.35 about ((35+17.6)/360) = 15% of the time. Thus, with a wind of 2.2 m/s (5 mph), we can expect to drive 6.7 m/s (15 mph) 85% of the time without the airfoils adding additional drag to the vehicle.

Suppose we are going directly into the wind (awA = 0). How much is the drag increased by the airfoils? Putting awA = 0 into equation 6 (and remembering to multiply by 4) we get:
$4\ NFF = -0.00222\ |aw|^2$. Dividing this by the equation for wind resistance (equation 7) shows that the wind resistance will be increased by 30% at awA = 0.

Now let's address the issue of speed. We know from equation 8 that the airfoils will at least counterbalance the wind resistance at any vehicle speed and any wind speed as long as awA ≥ 9. Thus, given a fixed true wind speed and direction, the vehicle speed is limited to the value which causes awA to equal 9. Applying the law of sines to figure 1 gives equation 11, which tells us what the vehicle speed will be when awA reaches 9 degrees.

speed limit = iw = tw (sin(twA-9)/sin(9)) (11)

The speed is also limited to the value which causes the lift to become so large that it causes the vehicle to topple over. The vehicle will begin to topple over when the torque of the airfoils about the wheels on one side is equal to the torque due to the weight of the rider and vehicle (see figure 5).

If the vehicle and rider weigh 890N (200 pounds) the torque will be 3.0.963x890 = 859 N-m. For a given airfoil, the component of lift that points directly to the side is L cos(awA) (see figure 1). If the lower tips of the airfoils are 300 mm (1 foot) off the ground then an integration of the torque at each height will show that the net torque produced by all four airfoils is 5.578L cos(awA). We write 5.578L cos(awA) = 858.7 to get the maximum allowable L. In the equation

$L = 0.057\ awA\ \ span\ \ chord\ |aw|^2$,

the value of awA will always be 9 degrees. This is because awA is really angle of attack in this equation. Since awA will be greater than 9, the airfoils will be turned into the wind until the angle of attack is equal to 9. (If awA were less than 9 then the speed would have already been limited by equation 11.) But we cannot use awA = 9 when it shows up in other places, such as

PERCENTAGE OF TIME PROPULSIVE FORCE BALANCES WIND RESISTANCE

tw (mph)	vehicle speed (mph) 15	20	25	30	40
5	69%	57%	43%	22%	0%
10	85%	80%	74%	69%	57%
15	90%	87%	83%	80%	73%
20	91%	90%	87%	85%	80%
25	92%	91%	90%	88%	84%

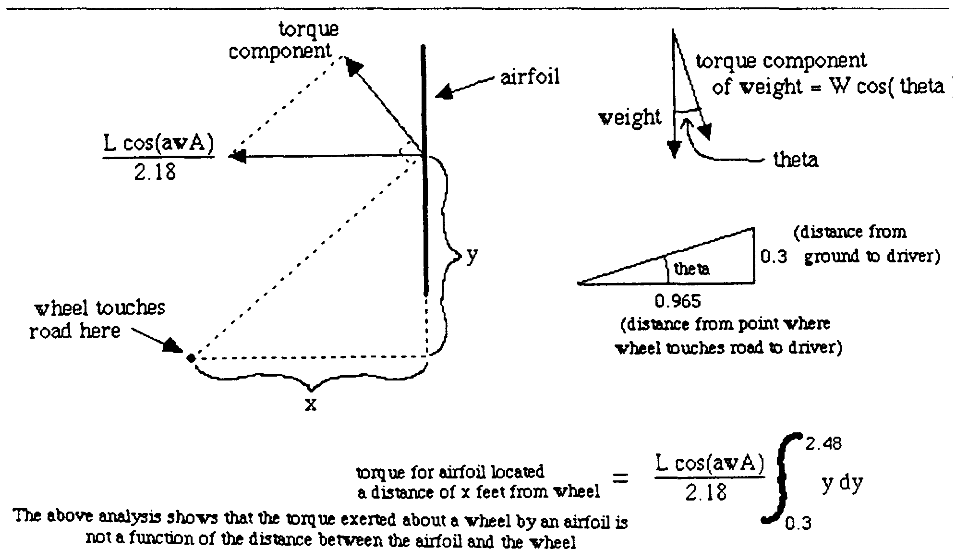


Figure 5 Toppling forces on wind-powered vehicle

TOP SPEED (mph) AS A FUNCTION OF WIND SPEED AND DIRECTION

tw (mph)	twA (degrees) 15	22.5	45	45+22.5	90	90+22.5	90+45	180-22.5
5	3	7	19	27	32	31	26	12
10	7	15	38	55	62*	62	52	33
15	10	22	51*	56*	62*	68*	72*	50
20	13	30	48*	54*	61*	69*	76*	67
25	17	35	44*	51*	60*	70*	79*	82

5.578 L cos(awA) = 858.7. Actually, if the driver adjusts the angle of attack to some value less than 9 degrees then higher speeds are possible. But here we are only interested in getting approximate values so I will go ahead and use 9. Putting the known values into the lift equation gives: $|aw|^2$ cos(awA) = 773.2

From figure 1:

aw = (tw sin(twA)/sin(awA))

Substituting for aw in the former equation leads to:

$$\sin(awA)\tan(awA) = (tw^2 \sin^2)(twA)/773.2)$$

Since I am working with a hand-held calculator I will use the approximation:

$$\sin(awA)\tan(awA) = 3.185 \times 10^{-4} awA^2 - 1.04 \times 10^{-4} awA - 1.77 \times 10^{-4}$$

This approximation works well enough for 9 < awA < 30. Making this substitution and rearranging gives equation 12:

$$6.125\, awA = 1 + \sqrt{21.87 + 152.41 tw^2 \sin^2(twa)} \quad (12)$$

Now if we know the true wind speed and direction, we can use equation 12 to compute the value of awA at which the vehicle will be on the verge of turning over. We can manipulate equation 1 to get equation 13 which gives the corresponding value of vehicle speed (iw).

$$\text{speed limit} = iw = (tw \sin(twA)/\tan(awA)) - tw \cos(twA) \quad (13)$$

Given tw and twA, the top speed of the vehicle is the smaller of the two values given by equation 11 and equation 13.

I have chosen span and chord to maximize the speed at which the vehicle topples over. To see this solve equation 8 for span:

span = (0.3/chord) + 2.69 chord.

Integrating the torque at each height on each airfoil shows that the total torque = k chord ($span^2$ + 0.6096 span) where k is a constant. Substituting for span in the last equation gives:

total torque = k (7.24 $chord^3$ + 1.64 $chord^2$ + 1.614 chord + 0.1829 + 0.09/chord)

Now take the derivative of torque with respect to chord:

$$(d(\text{total torque})/d(\text{chord})) = k\,(21.72\, chord^2 + 3.28\, chord + 1.614 - 0.09\, chord^{-2})$$

To find the chord that minimizes the total torque, set this equation equal to zero and solve for chord. This gives chord = 0.178. The corresponding span that satisfies equation 8 is span = 2.18.

The values marked with an asterisk in the above table highlight the real challenge in this design: how to decrease the vehicle's tendency to topple over. Increasing the wheelbase would increase the moment arm of the torque due to the weight of the vehicle and rider. But if we want to drive on the road then we can't increase the width of the vehicle. One possibility is to reduce the torque due to the airfoils by reducing the wind resistance of the vehicle. Lowering the wind resistance lowers the amount of propulsive force required to overcome it. This in turn lowers the amount of lift required of the airfoils which lowers the side force tending to topple the vehicle over. The large side force creates other problems. What happens if the cycle hits a patch of sand? Will the large side force cause it to slide off the road or into the oncoming lane? What about wind gusts? What would happen if the road suddenly dipped? In this case the rider and vehicle temporarily exert less torque about the wheels but the torque due to the lift remains constant. A lot of further design work and testing would be needed before it would be safe to drive this vehicle on the road like a regular bicycle.

Another important question is how often we can expect winds of 5 - 7 m/s (10 or 15 mph) or more. Even in areas that typically have low winds, this range of wind is not that unusual. But trees, buildings and other obstructions can severely attenuate the wind. In addition these obstructions introduce turbulence and it must be remembered that the airfoil wind tunnel data were taken at low levels of turbulence.

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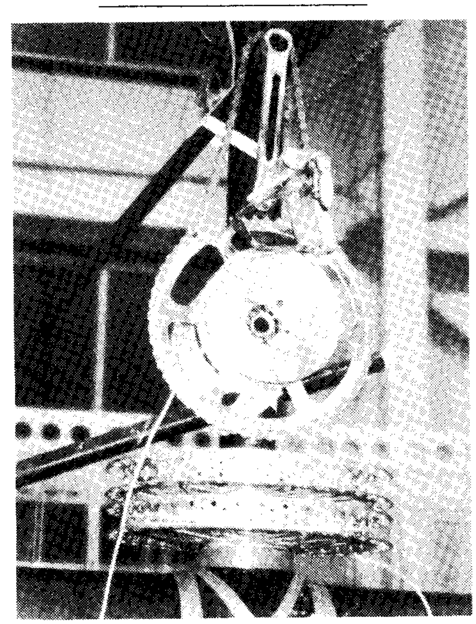

Mitubachi HPH drive Photo: Toshio Kataoka

MODELLING ENERGY CONSUMPTION ON THE TRICANTER HPV+

by John K. Raine* and Maurice R. Amor**

ABSTRACT

This paper reports an investigation into the energy consumption of a recumbent commuter tricycle with and without aerodynamic body fairings, over various driving cycles. The development of the University of Canterbury Tricanter vehicle design is first described, and the determination of its drag characteristics in three configurations is outlined. Predictions of the vehicle energy consumption given by a computer model for standard driving cycles are compared with that for a bicycle. Conclusions are drawn regarding the most energy-efficient form of the Tricanter for commuter and touring use.

INTRODUCTION

Increasing public concern over environmental pollution by motor vehicles continues to stimulate interest in human-powered and light moped vehicles for commuter use where terrain, powered-vehicular traffic density and road design permit. The history of human-powered vehicles (HPV) is well summarised by Whitt and Wilson (1982), and by Gross, Kyle and Malewicki (1983). Distinctions in HPV type have become evident in recent years (IHPVA,1986). Whereas the machine designed for speed-record attempts focuses on minimum weight, drag coefficient and frontal area, the commuter or touring vehicle is likely to have a more upright and comfortable driver position, and superior steering and cornering stability, but some sacrifice in weight and drag.

The University of Canterbury Tricanter has evolved through three prototype stages as a final-year B.E. student project over a five-year period. Our original objective was to develop a recumbent vehicle suitable for commuting and touring, with attention to vehicle ergonomics, weight, dynamic behaviour and cost.

The Tricanter HPV was tested bare, with a frontal aerodynamic half body and with a full aerodynamic body. Coast-down and tow testing were used to determine rolling-resistance and aerodynamic-drag coefficients. These data and figures from Gross et al. (1983) for a touring bicycle were used in a vehicle energy-consumption computer model (Raine & Epps, 1988) to find the relative energy efficiency of the different vehicle configurations. In particular, we wanted to assess the trade-off between the extra inertial energy consumption caused by the weight of aerodynamic fairings and the energy saving they give through reduced aerodynamic drag.

VEHICLE DESIGN DEVELOPMENT

Desirable design features identified for the vehicle were:

(i) high level of driver comfort and drive-train efficiency;

(ii) ease of use in urban and touring conditions;

(iii)low aerodynamic and rolling resistance;

(iv) transmission to provide a wide range of tractive effort at the road to facilitate hill climbing and high-speed touring; and

(v) low vehicle weight with good steering and handling.

We chose a semi-recumbent tricycle for development, with two steered and braked wheels at the front and a driven wheel at the rear. This is similar in principle to the former world-speed-record-holding Vector Single, e.g. as described by Gross et al (1983), but with a more upright driver position and wider front track in the interests of safer vision and stability on tight corners.

Whilst the initial student team in 1985 was keen to build a fibre-composite monocoque chassis, cost constraints led to the design of a Mk 1 vehicle based on a tubular AISI-4130-steel space-frame chassis. Frame dimensions were chosen to accommodate human shapes within the 95th percentile (Damam, Stoudt and McFarland, 1966) and to give a good compromise between leg-pedal interaction and head height for good visibility. This vehicle had a wheelbase of 1200 mm and a track of 750 mm .

Chassis stressing on this and later prototypes was based on a driver mass of 80 kg and a maximum pedal force of 1000 N. The chassis was also designed for dynamic loads of

(i) 4.5g vertical load applied through one wheel only to simulate impact with a kerb, and

(ii) a combination of 1.5g horizontal, axial or lateral, and 3g vertical loads, to simulate hitting a kerb whilst braking or cornering.

A photograph of the Mk 1 vehicle is shown in Figure 1 (Raine et al., 1986). This machine had a 27-inch rear wheel, 20-inch front wheels, a fibreglass go-kart seat, 18-speed gears, Ackerman steering with linkage to a joystick, and

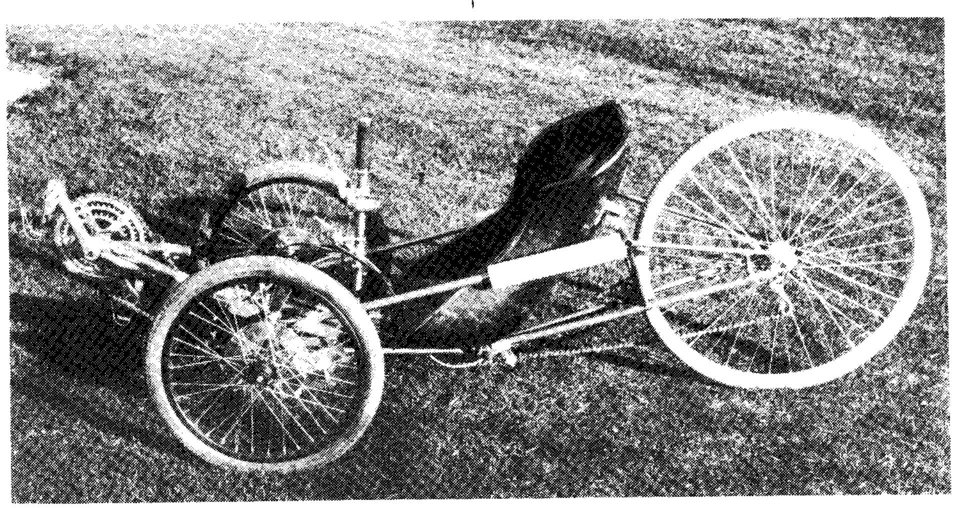

Figure 1 The Mk-1 prototype Tricanter HPV

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hydraulic front disc brakes. These brakes were so effective that the planned rear caliper brake was omitted. Proprietary bicycle running gear was used wherever possible.

Concurrent with vehicle design work, wind-tunnel modelling was done to determine an ideal enclosed aerodynamic fairing shape for the vehicle. The final model shape, shown in Figure 2, achieved a CD = 0.13, much lower than expected from the open-topped real vehicle. Road tests showed the vehicle to have high levels of comfort, cornering and braking power. However, at a little over 25 kg it was heavy and lacked torsional stiffness. The low-pressure BMX front tyres also had high rolling resistance.

Later prototypes used a simple fabricated cruciform chassis with main backbone and front transverse members in 54-mm- and 41.3-mm-diameter mild-steel tubing respectively, and the seat/chain stay assembly in 12.7-mm-diameter tubing, all wall thicknesses being 1.2 mm. The Mk 3 Tricanter has an unladen weight of 20 kg, with a wheel base of 1070 mm and 750 mm track.

An ALGOR finite-element analysis was done on the Mk 3 prototype chassis by Lovegrove (1991) to identify worst-case stresses for the loading events given above. This indicated that chassis strength is suitable for driver masses of at least 100 kg. Further design refinement by Lovegrove (1991) for lower manufacturing cost should see a Mk 4 machine built late in 1991 with a weight approximately 3 kg lower than on the Mk 3, weight having been removed from the front stub-axle assemblies and steering components, seat brackets and position-adjustable pedal bracket. The Mk 4 will also have slightly lighter steel tubing in the chassis. A further weight reduction in the chassis of approximately 1 kg could have been achieved, with no loss in stiffness, by changing to larger-diameter tubing and fitments in 6351 aluminium alloy, but this has been postponed for the time being to keep manufacturing cost down.

The Mk 3 vehicle is shown in figure 3. It has 20 x 1 inch wheels all round with high-pressure tyres. Underslung handlebars operate the Ackerman steering through a linkage, with the following geometry:

front-wheel camber -1.5°
static toe-out 0°
king-pin inclination 10°
scrub radius 40 mm
caster angle 9°
caster trail 40 mm.

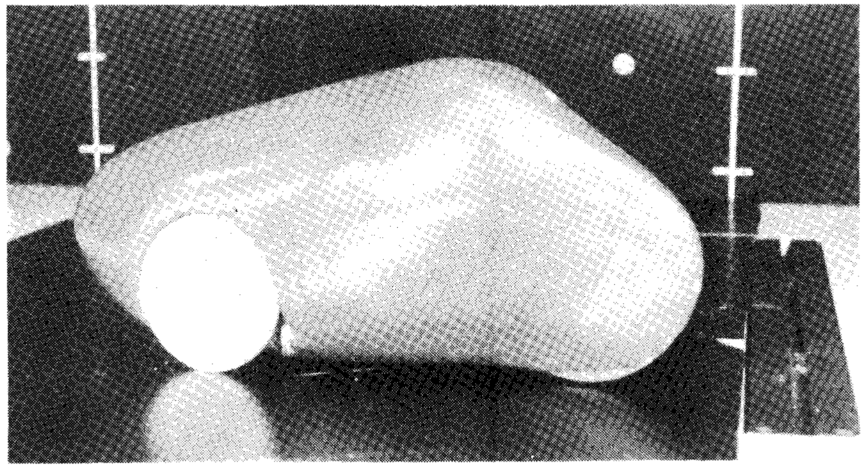

Figure 2 The final wind-tunnel model (ideal closed top)

The adjustable hammock seat is in woven nylon canvas. Aluminium alloys 6063 and 6351 are used to reduce weight in the seat brackets and steering componentry. The vehicle has 21-speed gears with top gear equivalent to a 100-inch-diameter rear wheel, i.e. a rear-wheel rotation of five times pedal cadence, and bottom-gear equivalent to a 30-inch rear wheel. This vehicle also uses two proprietary cycle disc-brake units at the front, with a single hand lever operating the hydraulic master cylinder.

Cornering and braking power are of a high order. It is possible to provoke lifting of an inside front wheel at high cornering accelerations, but well beyond what we feel are adventurous performance limits on this type of machine. The driver's centre of mass has been kept low and well behind the front wheels, to prevent forward pitching of the vehicle under heavy braking. Average decelerations of 0.95g to rest from just under 40 km/hr (11 m/s) have been measured, substantially higher than those safely achievable on a bicycle.

Aerodynamic front-half and full bodies were built in fibreglass on a male mould for the Mk 2 prototype and developed further for the Mk 3. Cost constraints prevented the use of light composites for the body, but the bodies used provided realistic variants for drag study purposes.

VEHICLE DRAG CHARACTERISTICS

Determination of vehicle road load

For a road vehicle, the equation describing the power required to overcome resistances to motion can be written:

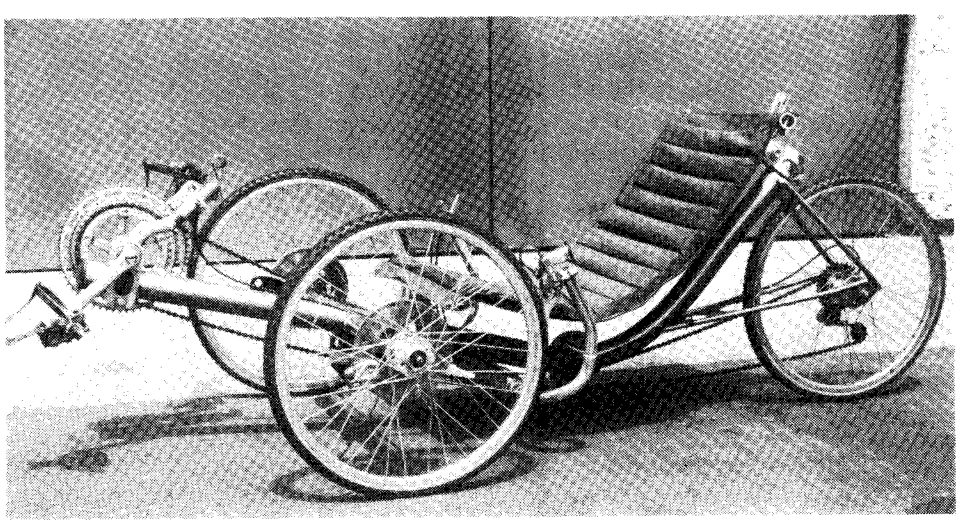

Figure 3 Mk-3 prototype Tricanter HPV

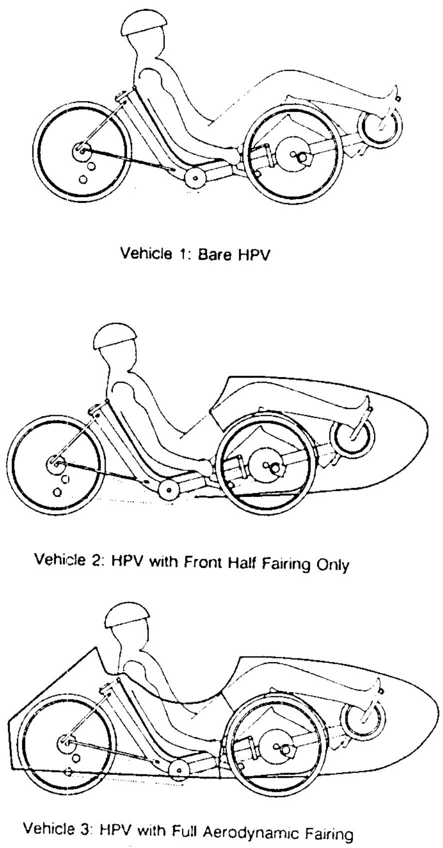

Figure 4 Tricanter test configurations

$P = \{Mg(\sin\theta + C_R + C_{RV}V) + \frac{1}{2}C_DA(V+V_w)^2 + M_e dV/dt\}V$...(1)

where

P = power to overcome resistances to motion, W

M = mass of vehicle plus rider, kg

g = acceleration due to gravity, m/s2

θ = angle of inclination of road to horizontal

C_R = speed-independent coefficient of rolling resistance

C_{RV} = speed-dependent coefficient of rolling resistance (more sophisticated forms of Equation 1 may include V^2-dependent coefficients of rolling resistance)

V = vehicle velocity relative to the road, m/s

Vw = ambient head-wind velocity, m/s

ρ = density of air, kg/m3

C_D = drag coefficient of the vehicle

A = frontal area of the vehicle, m2

M_e = equivalent mass of vehicle allowing for rotating inertias of drive train and wheels, kg, approximately 1.035M for the Tricanter, and 1.045M for the touring bicycle.

t = time, seconds.

On a flat road in still air, and ignoring the speed-dependent component of rolling resistance, which is normally small at low speeds, equation 1 reduces to

$$P = \{C_R Mg + (1/2)\rho C_D AV^2 + M_e dV/dt\}V \quad (2)$$

The resistance coefficients, C_R and C_D, may be determined by coast-down testing. For a vehicle freely decelerating on a level road (P = 0), the resistance forces in equation 2 are balanced by the inertia term, $M_e dV/dt$, which is negative under deceleration. The coast-down method involves the determination of vehicle deceleration as a function of speed while the vehicle decelerates on the road in neutral, in this case free-wheeling. A coast-down force-versus-velocity curve is then determined and may be fitted with a quadratic expression that satisfies equation 2. C_R and C_D may then be found from the quadratic coefficients. Coast-down testing is described in more detail by SAE J1263 (1980), and Hindin & Raine (1986).

C_R may also be found by tow testing of the vehicle on a flat road at near zero speed, using a spring balance or load cell. Wind-tunnel testing may be used to corroborate C_D values, but scale effects and lack of flow similarity in simpler wind-tunnel installations can give doubtful results.

Tricanter configurations and road-load coefficients

The Tricanter was road tested in a number of configurations (McMillan, 1988; Amor, 1989), three of which are reported here, together with data for a low-handlebar sports cycle ridden with in a touring straight-arms position rather than in a racing crouch. Values for C_R and C_D for the bicycle were obtained from Gross et al.(1983).

We performed the coast-down tests at the RNZAF Wigram Airbase, Christchurch, using the main runway, in fine cold weather with wind velocity along the track ranging between 2 and 10 km/hr (~0.56 and 2.8 m/s). Paired runs in opposite directions were made and a data-averaging process used to minimise the effect of head/tail wind. Values of the rolling-resistance coefficient, C_R, were also determined from very-low-speed tow testing with the same driver load. We have quoted the latter here, as they were unaffected by ambient wind and considered more accurate than C_R values from the coast-down tests. Vehicle frontal area was measured by photographing with a telephoto lens, then area calculation from the photograph by planimeter, scaling with a known transverse dimension. Tricanter configurations are shown diagrammatically in figure 4 and a view of the Mk 3 prototype with full body in figure 5.

The vehicle data are summarised in Table 1. Also included is the Mk 4 development of the Tricanter with lower vehicle mass and a body with reduced aerodynamic drag (to be developed), still with an open-topped cockpit. The value of C_D for Vehicle 3 is higher than for Vehicle 2 because of projection of the open rear body around the rider's neck and below the line of the frontal body (the latter to allow clearance for handlebar arc of action). This resulted in increased drag, and gives higher energy consumption. A full-body drag coefficient of around 0.4 should be

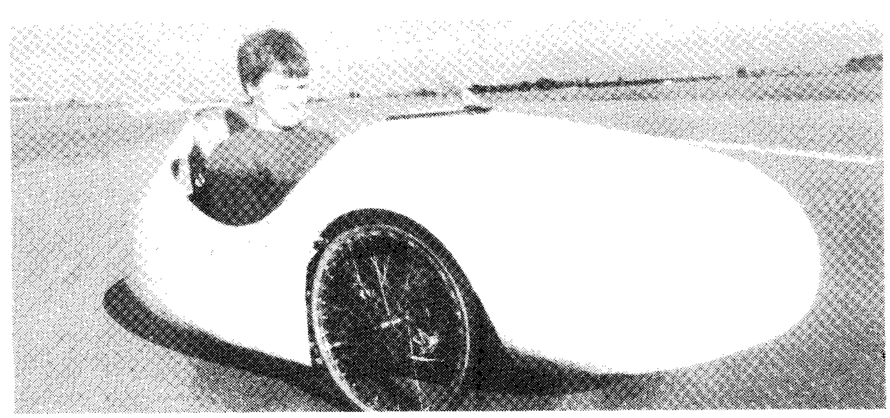

Figure 5 View of Mk. 3 Tricanter with full aerodynamic body

achievable on the Mk 4 machine described above. The bare-HPV drag coefficient of 0.92 for the Mk 3 prototype agreed well with the value of 0.91 determined in 1/5th-scale wind-tunnel tests (Amor, 1989) of a geometrically similar model.

THE VEHICLE ENERGY-CONSUMPTION SIMULATION

Driving-cycle energy consumption for the HPV was simulated using a vehicle energy-consumption model (Raine and Epps, 1988) developed for use in conjunction with the University of Canterbury methanol-fuel research programme.

The computer model, written in Waterloo Fortran 87 and run on an IBM PC/AT, steps through standard fuel-consumption and emissions driving cycles, calculating the required road-load power at one-second intervals. The road-load simulation can include constant, V- and V^2-dependent coefficients of rolling resistance, and builds in head or tail wind. It can also model the effects of driver error in following the demand-velocity-versus-time path.

For the purposes of the present work the computer model was run using the simplified road-load power equation 2, and assumed zero driver error in the following of driving cycles. The total energy consumption over a driving cycle, the cycle energy, CE, is determined by taking the following sum:

$$CE = \Sigma_{cycle} P.t \qquad (3)$$

where t = 1-second interval.

Note: If P becomes less than zero at any time under deceleration, it is set to zero for the calculation in equation 3.

Using simple menu commands, the operator may change any of the variables in the road-load equation, and may also do perturbation studies in which the sensitivity of the cycle energy consumption (CE) to changes in individual parameters is evaluated. The model also gives a breakdown of the percentage of CE used in overcoming inertia, rolling resistance, aerodynamic resistance and gradient.

The model was run with three driving cycles, for which data are given in table 2. The modified AS 2077 (1979) urban and highway motor-vehicle driving cycles, and the Christchurch bicycle-urban-commuter driving cycle are illustrated in figure 6. The most relevant is the last of these, which represents a typical journey from Amor's residence to the University. The cycle is over almost flat terrain, about 20% of the distance being through city streets (office blocks), and the remainder through suburban areas (low-density low-rise residential buildings). Ten sets of traffic lights are negotiated. The cycle was recorded using a video camera mounted on the Tricanter HPV to log speed and time from on-board instruments.

Our objective in the HPV energy-consumption modelling was to compare CE for different configurations of the Tricanter and for a touring bicycle. A further aim was to look at the effect of road gradient and head wind.

RESULTS AND DISCUSSION

Results are given in table 3 for the computed reference cycle energy, CE, for each of the five vehicles, on a flat road with no ambient wind. Energy consumption for the bare HPV is the datum against which other vehicle configurations are compared.

Table 3 shows that the HPV with only the front half fairing gives a substantial reduction in CE for all three driving cycles. It is also clear that the extra mass of the full aerodynamic body is unacceptable unless accompanied by a large drop in drag coefficient. The bicycle is seen to consume more energy than the bare HPV, but ridden in a full racing crouch, with reduced C_D and frontal area, A, it would have a slightly lower CE than the bare HPV. The projected Mk 4 Tricanter, 15% lighter, with a 13% lighter full aerodynamic body (C_D =0.4), achieves better than 22% lower CE than the bare HPV over the Christchurch Cycle.

The results in table 3 also reflect the average speed of the respective cycles. Inertial energy consumption is relatively

TABLE 1: VEHICLE ROAD-LOAD DATA

	VEHICLE CONFIGURATION	FRONTAL AREA A m^2	ROLLING RESISTANCE C_R	AERODYNAMIC RESISTANCE C_D	TOTAL MASS M kg
1	Bare HPV	0.45	0.006	0.92	98
2	HPV + Front Fairing only	0.54	0.006	0.51	107
3	HPV + Full Fairing	0.55	0.006	0.67	111
4	Touring Cyclist	0.53	0.004	1.00	89
5	HPV - Mk 4 Development	0.54	0.006	0.40	105

Note: 1. In each case the rider was a male of 188 cm height and 78 kg weight.
2. To the 20 kg bare mass, the frontal half fairing added 7 kg and the full fairing 13 kg. 2 kg extra mass is present as rear panniers on HPV 2.
3. The future Tricanter, with full aerodynamic fairing, is projected to achieve a drag coefficient of 0.4, with 17 kg bare vehicle mass and 10 kg aerodynamic fairing.

TABLE 2: DRIVING-CYCLE DATA

PARAMETER	DRIVING CYCLE		
	CHRISTCHURCH BICYCLE	MODIFIED AS2077 URBAN	MODIFIED AS2077 HIGHWAY
Distance km	6.67	5.23	5.61
Cycle Time sec	1200	1256	766
Max Speed km/hr	30.0	31.4	32.7
Av. Speed km/hr	20.0	15.0	26.4

Note: Speeds in AS 2077 Urban Cycle are reduced by a factor of 0.56, and in AS 2077 Highway by a factor of 0.34 to achieve the modified form. AS 2077 Urban also has the period of the cycle from t = 198 sec to t = 316 sec removed to avoid unrealistically high speeds.

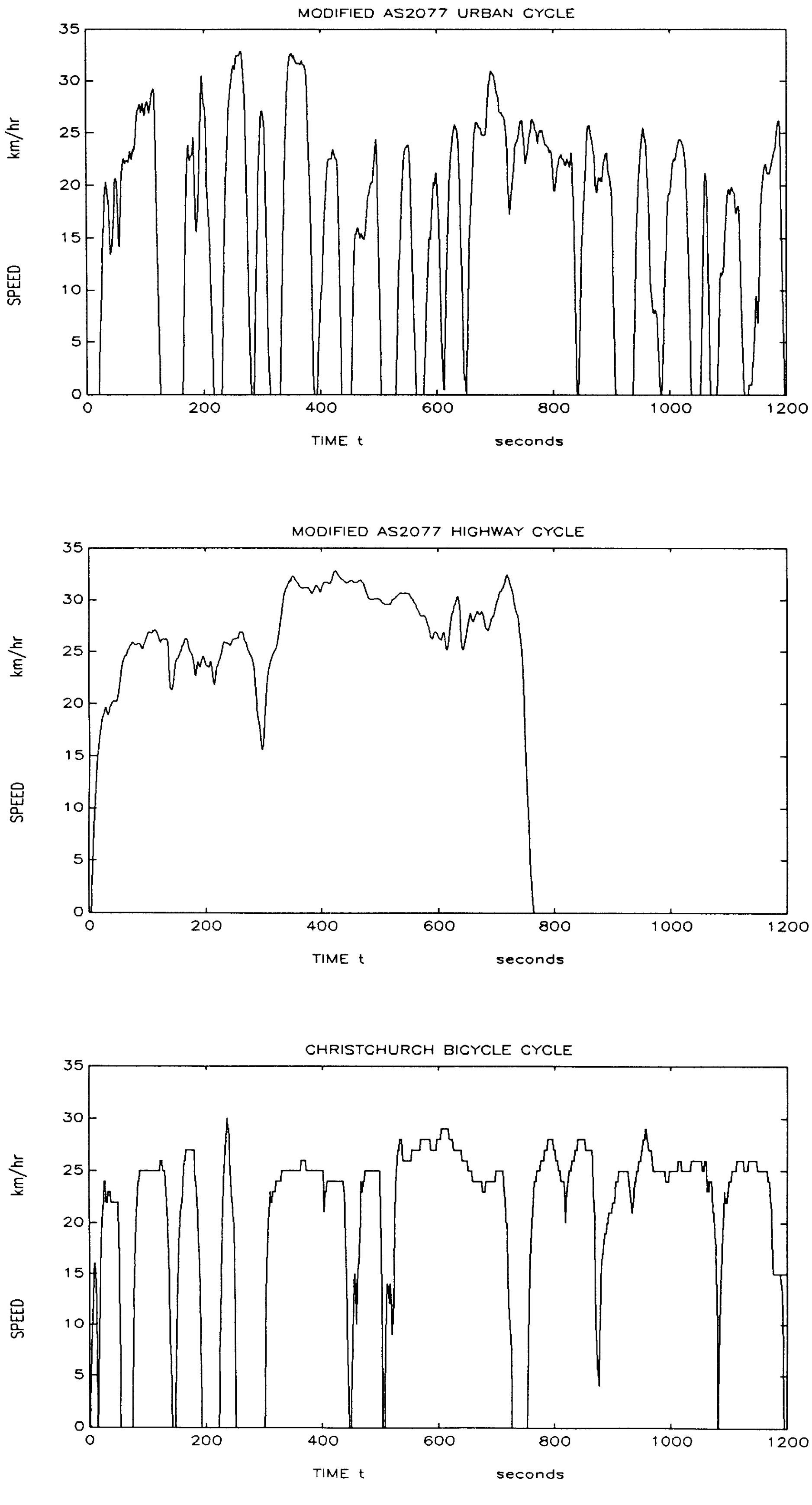

Figure 6 Vehicle energy consumption in driving cycles

greater in the two urban cycles, whilst aerodynamic drag is more important in the AS 2077 highway cycle which is representative of energy consumption for cycle touring on the open road.

The proportions of cycle energy consumed in inertial acceleration, rolling, and aerodynamic resistances are shown for the flat road/still air case in table 4. We were particularly interested in studying the effect of gradient and head-wind perturbations to the model when deciding whether to include an aerodynamic body on the Tricanter for general use.

To explore gradient, the model was run with constant gradients ranging from 0% to 10%. The gradient effect is very strong. CE values relative to CE1 are plotted against gradient in figure 7. CE1 is the Cycle Energy for vehicle 1, at gradients G%, given by

$$CE1 = 138.7\{1 + 46.2G/(100^2 + G^2)^{1/2}\} \text{ kJ} \quad (4)$$

It is seen that the CE advantage held by the (necessarily heavier) vehicles with aerodynamic fairings is eroded as gradient increases, due to the extra work to be done against gravity. At very steep gradients, the gravitational load dominates, so that CE relates quite closely to all-up mass.

At a gradient of about 2.8% the bicycle, vehicle 4, starts to undercut the bare HPV, vehicle 1, which in turn achieves a lower CE than vehicle 2 with the front half fairing for gradients over 3.4%. Vehicle 5, the future development of the HPV, maintains an advantage in CE until a gradient of about 5% is reached, where the bicycle becomes the most energy-efficient machine. The bicycle, being lightest, comes into its own on climbing steep hills.

For each of the five vehicles, the computer model was run with head winds, V_w, ranging from 1 to 20 km/hr (0.278 to 5.56 m/s). CE values are plotted against head-wind speed for the Christchurch bicycle cycle in figure 8, relative to CE for the bare HPV in still air. Figure 8 shows that the advantage enjoyed by the HPV with the front half fairing gradually increases as the head wind increases. The cyclist riding with straight arms on a sports bicycle is at an increasing disadvantage. Predictably, the vehicle with best aerodynamic-drag characteristics copes best with the head wind.

The comparisons made in figures 7 and 8 make no reference to duration of

TABLE 3: PERCENTAGE CHANGE IN ENERGY CONSUMPTION, CE, COMPARED WITH BARE HPV

VEHICLE CONFIGURATION		ENERGY CONSUMPTION DRIVING CYCLE		
		CHRISTCHURCH BICYCLE	MODIFIED AS 2077 URBAN	MODIFIED AS2077 HIGHWAY
Reference CE for Bare HPV		138.70 kJ	120.82 kJ	120.70 kJ
1	Bare HPV	0%	0%	0%
2	HPV + Front Fairing only	-14.37%	-8.14%	-21.20%
3	HPV + Full Fairing	-0.87%	+2.89%	-4.66%
4	Touring Cyclist	+10.03%	+5.12%	+15.59%
5	HPV - Future Development	-22.40%	-14.76%	-31.59%

TABLE 4: PROPORTIONS OF BASIC CYCLE ENERGY CONSUMPTION, CE, CONSUMED BY VARIOUS COMPONENTS OF VEHICLE ROAD LOAD, *percent.*

RESISTANCE: I = INERTIAL R = ROLLING A = AERODYNAMIC			ENERGY CONSUMPTION DRIVING CYCLE		
			CHRIST-CHURCH BICYCLE	MODIFIED AS 2077 URBAN	MODIFIED AS2077 HIGHWAY
VEHICLE CONFIGURATION			% CE	% CE	% CE
1	Bare HPV	I	19.71	39.59	4.01
		R	26.69	21.26	27.08
		A	53.60	39.15	68.91
2	HPV + Front Fairing only	I	30.69	49.17	6.95
		R	30.43	23.48	35.49
		A	38.88	27.35	57.55
3	HPV + Full Fairing	I	23.96	44.72	5.27
		R	28.69	22.09	30.67
		A	47.35	33.19	64.06
4	Touring Cyclist	I	16.29	33.72	2.84
		R	21.24	17.94	20.56
		A	62.47	48.34	76.60
5	HPV - Future Development	I	35.51	52.91	8.74
		R	32.02	24.41	39.72
		A	32.47	22.68	51.54

human power output at various power levels, or to vehicle drive-train losses. Kyle and Caiozzo (1981) give a table of transmission efficiencies from which 98% may be taken as an average figure to apply here. Kyle and Caiozzo (1981) also graph duration of human power output for tests on a number of average recreational cyclists ranging in age from 20 to 47 years old. Standard and modified bicycle ergometers were used. The duration curve for an average of five cyclists is reproduced in figure 9. The average cyclist can maintain about 0.27 kW over the 20-minute duration of the Christchurch bicycle cycle, ignoring speed variations which will make the cycle more arduous in reality. For the bare HPV driven over the Christchurch cycle on a flat road in still air, the CE of 138.7 kJ corresponds to an average power dissipation at the road of 0.116 kW, or 0.118 kW allowing for drive-train losses. In figure 7, an average power of 0.27 kW over the Christchurch bicycle cycle corresponds to a gradient of 2.8% (at which peak power from rider = 0.43 kW at 30 km/hr) or a relative CE of 2.29 for the bare HPV. Other test data (Whitt & Wilson, 1982) indicate that a first-class athlete might average about 0.38 kW over the same 20-minute cycle.

Limits on duration of human power output mean that comparisons of CE for different vehicles are probably relevant only for gradients less than about 3.5% for the conditioned cyclist. Whilst gradients up to 3.5% tend to level the performance of vehicles 1, 2 and 4, a light vehicle with good aerodynamics such as vehicle 5 will still be more energy efficient. The light bicycle remains the ultimate steep-road HPV.

The maximum head wind of 20 km/hr corresponds to an average power output from the rider of the bare HPV of just under 0.27 kW. It would therefore appear that all vehicles except the bicycle, vehicle 4, could complete the Christchurch cycle into a 20 km/hr head wind, but with a maximum road speed touching 30 km/hr, peak power output from the rider of the bare HPV would be about 0.47 kW. i.e. higher speeds during the cycle would test the stamina of the rider.

Conclusions above regarding performance of the different vehicles executing the driving cycle in a head wind or on an incline must be treated as indicative only, in view of speed variations during the cycle and limits on duration of human power output.

A MOTORISED TRICANTER?

The Mk 1 Tricanter prototype was run with a 49-cc Velo Solex moped engine mounted over the 27-inch rear wheel. The high position of the engine resulted in some sway on corners, but good straight-line performance. Addition of a similar wheel-friction-drive motor over a larger-section 20-inch tyre on the rear wheel of the Mk 3 Tricanter could give a very workable vehicle with good handling and braking combined with a cruising speed of 30 km/hr. A 49cc-engined version of the vehicle could afford the bulk of a more refined aerodynamic body, and enjoy the simpler vehicle licensing and design rules attaching to under-50cc vehicles.

CONCLUSIONS

The Tricanter commuter HPV development project has led to a compact and robust recumbent tricycle with excellent cornering and braking characteristics. Road testing and computer simulation of the vehicle in different aerodynamic configurations have shown that the bare vehicle should have slightly lower energy consumption than a low-handlebar sports bicycle ridden in a straight-arm touring position. Results also show that the addition of an aerodynamic body can reduce energy consumption over typical driving cycles provided that the aerodynamic drag coefficient is low enough to offset the effect of added body mass. Vehicles with aerodynamic bodies show a predictable advantage in head winds. On inclines, the heavier more-aerodynamic vehicles suffer, but can retain an advantage over the bare vehicle if they are low enough in C_DA. For example, a vehicle of total mass 29 kg, with 78-kg rider and C_DA less than 0.28 m^2 would consume less energy than an 11-kg bicycle for the Christchurch bicycle driving cycle executed on gradients up to about 3.5%.

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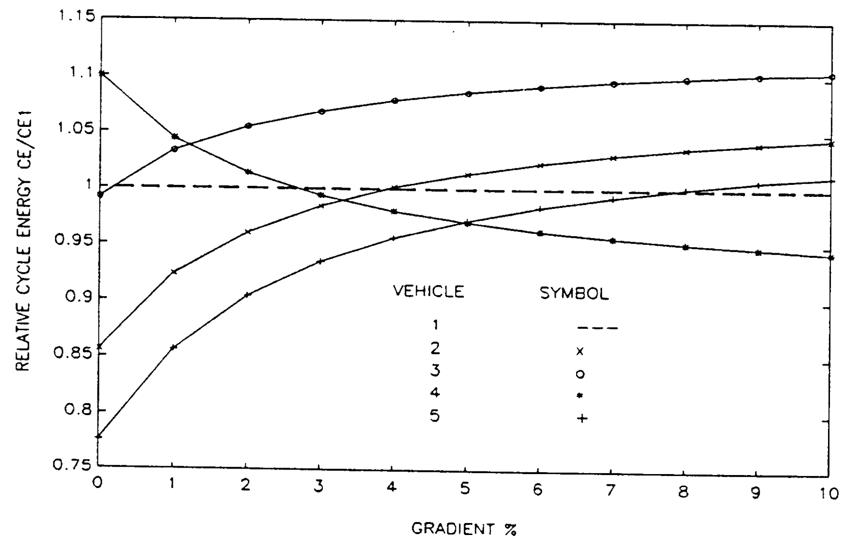

Figure 7 Influence of road gradient on cycle energy

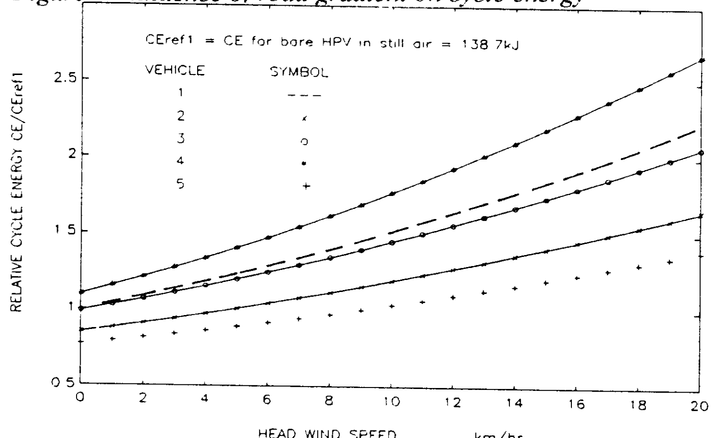

Figure 8 Influence of head wind on cycle energy

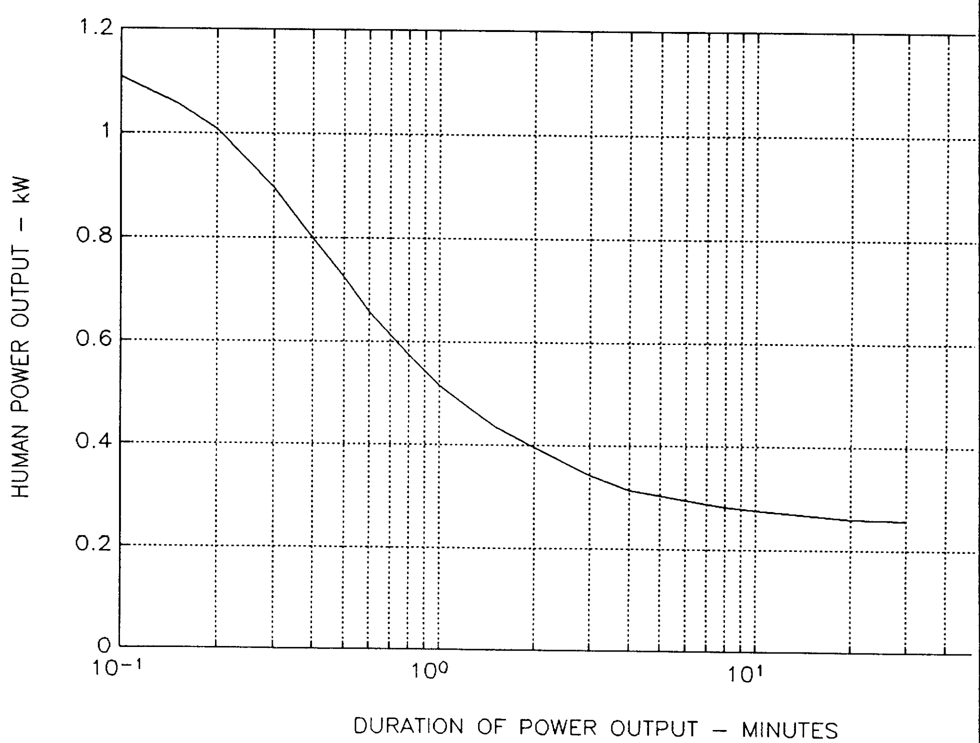

Figure 9 Duration of human power output (after Kyle & Caiozzo, 1981)

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John K. Raine, School of Engineering, University of Canterbury, Christchurvh, New Zealand, FAX 64 3 642-705 phone 667-001

RICHARDS' ULTIMATE BICYCLE BOOK

A book review by Dave Wilson

Richard Ballantine has been joined by Richard Grant in the lavish production of the latest edition of his book on bicycles and bicycling, thereby changing the position of the apostrophe in the title. Richard Ballantine produced his "Richard's Bicycle Book" in 1972, and, according to a note on the cover, it has since sold over one-million copies world-wide. That is strong testimony both to the quality of his writing and to the interest in bicycling.

Ballantine has also done much for the HPV movement. I first met him over ten years ago in Germany where we were attending a bicycling conference in Bremen. We appeared on German TV. I had brought with me an Avatar 2000 which I demonstrated to, apparently, good effect. Several were later bought by various people in Europe, and small companies were started to produce recumbents with strong similarities. Richard Ballantine bought one for himself. He had it reviewed for his new magazine *BICYCLE!* This review was, I believe, the longest, most thorough, and most enthusiastic ever devoted to a new bicycle. The entire color cover of the issue was given to the Avatar and a very striking model. Ballantine's Avatar was borrowed by Derek Henden in London who designed a fairing for it, renamed it the Nosey Ferret and, later, Bluebell, and, with a vacationing Australian lawyer, Tim Gartside, riding began winning almost all the races they entered, first in Europe and then at the IHPSC in the USA. Ballantine's Avatar thereby ended the supremacy of the Vector recumbent tricycles in the 200-m speed championships and in other events. In his magazine and his books, Richard Ballantine has spread his enthusiasm for HPVs as well as for bicycles, and to him must be given a large part of the credit for the new sport of HPV racing in Europe and elsewhere.

In the "Ultimate Bicycle Book" HPVs are an integral part from the cover flap on. It is the most beautifully illustrated bicycle book on the market, with photographs that have to be described as stunning (the photography is by Philip Gatward, and appears to be almost entirely specially done for the book). The treatment of the various types of bicycles for different types of racing and recreation is also broader than I have ever seen: it is almost encyclopaedic. I have never been able to find a good definition of criterium racing, for instance, but it is given a two-page spread here, with more on time-trial bikes, on the Tour-de-France bikes, and much on mountain bikes. The material is up to date, with good authoritative information on frame and wheel design and materials. HPVs have far less than exhaustive treatment, but there are three short sections. There is more than in any other general book on bicycles.

The only sour note to mar this paeon of praise is that I wish the authors had asked a bicycle historian to check the section on bicycle evolution. They repeat the oft-debunked myth about the unsteerable two-wheeled "celerifere" supposedly invented by de Sivrac. There was no such vehicle. (I confess that I have helped in some measure to perpetuate the myth of the existence of any form of unsteerable "bicycle" in Bicycling Science. And I did have my chapter checked by a bicycle historian). Also, the name of the rider, Faure, of the record-breaking Velocar recumbent of the thirties is misspelled.

In other respects, this beautiful book is a delight. It is informative and entertaining. At $29.95 it could be regarded as a bargain. It is bound to lead to greater acceptance of HPVs. For this alone we owe Richard Ballantine and his co-author Richard Grant (a rival bicycle-magazine publisher) a debt of gratitude.

Dave Wilson

THE SECOND INTERNATIONAL HUMAN-POWERED-SUBMARINE RACE FROM THE PERSPECTIVE OF A SeaDAWG

by Cory Brandt

Two years ago seventeen teams (of the nineteen teams that registered) got together to race submarines around a 1,000-meter kidney-bean-shaped course. Due to logistics, foul weather, and technical problems, only a 100-meter straight-line sprint was run. Only nine of the seventeen teams arrived able to finish.

This year the weather cooperated. Thirty-four of the 36 submarines that entered were in West Palm Beach, Florida ready to race.

The races are organized by the H.A. Perry Foundation and are intended to spark an interest in ocean engineering and to foster advances in hydrodynamics, propulsion, and life support for subsea vehicles. The entries came from large corporations, small businesses, universities, and even garage tinkerers. The teams flew from as far as Berlin, Germany and drove from as far as Vancouver, British Columbia.

In the fall of 1990, I and thirteen other University-of-Washington mechanical-engineering students got together and decided to work on an entry for the 1991 race. The result was the SeaDAWG (figure 1). It was quickly discovered that designing and building a submarine is a very time-consuming process. Like many of the teams down in Florida we had the occasional all-night work party.

General rules and course description

The submarines were required to have two occupants: a pilot and a propulsor (the "stoker"). The pilot was not permitted to input any power that would contribute to the forward momentum of the submarine. He (or in a couple of cases she) was in charge of steering, navigation, trim and ballast, and life support. The stoker's job was to be the engine: he was not permitted to engage in any other activities.

Both occupants had to be fully enclosed, and the submarines were required to be fully flooded. This meant that the occupants had to use SCUBA gear. Each submarine had to have 150% of the amount of air necessary to run the course, as well as having a separate tank for ballast. The air pressure was measured just before and just after running the course. If there was not enough excess the competitors were to be disqualified.

Each submarine was allowed one practice run down a 100-meter straight-line course. A timed 100-meter sprint was run and the time achieved determined the seeding. The fastest eight submarines were given a by for the first round. If a submarine was not able to complete the 100-meter sprint in under ten minutes, it was disqualified and thereby eliminated from all further racing.

Initially two submarines were to race side-by-side going around a 400-meter oval course twice. However, due in part to fear for diver safety, the 800-meter race was shortened to 475 meters for all except the final race.

Rules for safety were fairly stringent. Each submarine had to have a surface buoy, an emergency-release buoy with a deadman switch for both occupants (thus if the switch were released the deadman buoy would surface alerting surface crews of a problem), strobe light mounted on the submarine, and a spare supply of air on the person of both occupants (most teams used Spare Aires). Of these rules the surface buoys created the most problems.

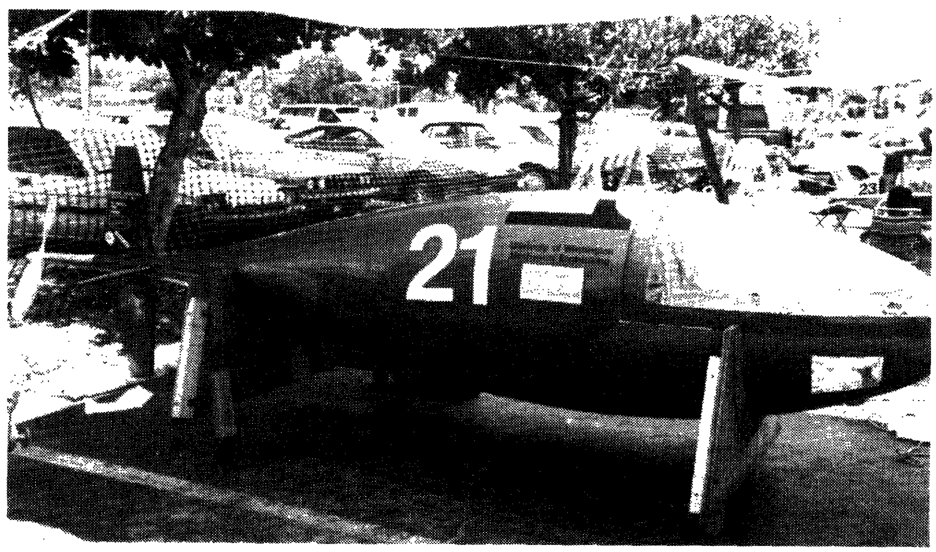

Figure 1 The SeaDAWG

Description of entries

There were many different hydrodynamic theories put to use. Some, like the Borti 1 from Berlin, attempted to make their submarine as small as possible. By making the submarine small they decreased the wetted-surface area and the frontal area, which reduce the drag. Others made their hulls a little larger but strove to eliminate boundary-layer separation (such as the SeaDAWG) or to have a mostly laminar-flow body (such as Team Wahoo).

Most teams strove for efficiency in the propulsion systems. The majority of competitors used a standard bicycle crank, but some used linear drive systems. Team Wahoo was the only team to use hand-and-foot cranks.

The majority of the entries used two-bladed propellers. Team Effort used a 12-bladed propeller. Using hydraulics their pilot could control the blades and steer the submarine. The SubHuman II team was one of about a half-dozen teams to use counter-rotating propellers.

Non-standard propulsion

Five of the submarines broke away from using propellers and went with something completely different.

The U.S. Navy's Subdue used a radially extended linear impeller (paddle wheel). It was not very reliable and according to a member of the Navy's team it couldn't keep up with the Squid (the

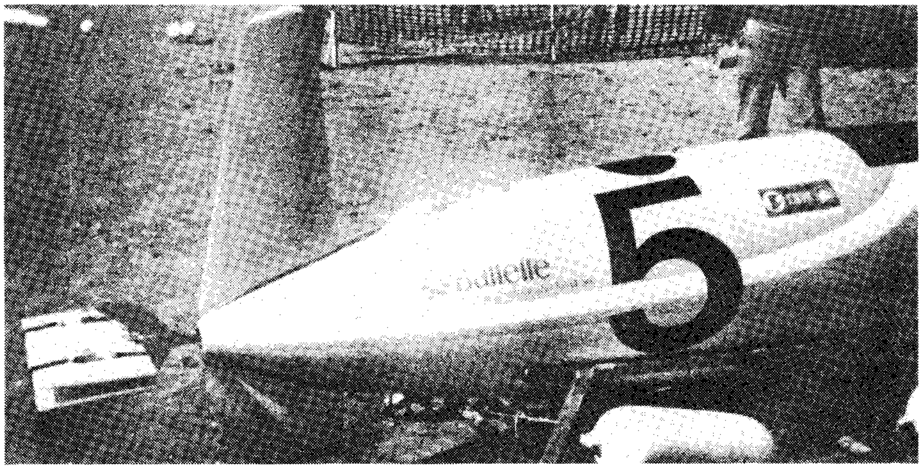

Figure 2 Battelle's "articulated linear thrust engine" (ALTEN) drive

Navy's other entry) even on a good day. However, it was a valiant effort and was unlike anyone else's entry.

Battelle's submarine used a "articulated linear thrust engine (ALTEN) drive". It was essentially two flat plates hinged at the back of an arm (figure 2). On the outward-stroke it would open like a clam shell creating a wall that would push the submarine through the water. On the inward-stroke the two plates would collapse together to make essentially a flat plate.

F.S.I., known to most competitors as the Tri-Dental, was the only submarine that attempted to use the body of the submarine (the hull) to aid in the forward propulsion. The stoker used his arms to bend the front of the submarine about a hinged axis. He used his legs to power a fin in the back (similar in shape to that of a fish). It was not successful. They released it from the starting gate but it would move neither forward nor backward. The team gave up but said they would be back in two years.

Dowfin II used an oscillating fin mounted horizontally. It was one of the few submarines that used elliptical gears for the drive system. It did not qualify but was impressive to watch.

The SubDUDE from the University of California was in my opinion the most impressive non-propeller-driven craft at the race this year. It used two horizontal oscillating foils, one on each side of the submarine (figure 3). The foils were mounted on arms that came from near the center of the submarine. It was impressive because it moved very smoothly through the water. It kept a consistent pace and, unlike the oscillating-tail designs, it didn't lose power due to up-and-down movement. Its smooth pace also helped reduce the drag since drag is increased if the speed oscillates.

Design considerations: occupant positioning

The goal is to position the occupants in such a manner as to reduce the wetted surface area but still retain a practical shape. It is important the ergonomics in a submerged environment be considered. It is also helpful if the designers know ahead of time who the stoker and pilot will be.

Many of the submarine stokers were jammed into the bottom or the back of the submarines and some experienced claustrophobia which can lead to panic. At least one stoker had no intention of getting back inside his submarine for the oval course.

The feeling of claustrophobia can be overcome without changing the hull size or internal layout by adding windows, adding mirrors so that the occupant can see out existing windows, painting the interior of the submarine in a light color, and adding a communication system so that the stoker doesn't feel all alone. These ideas may sound trivial but they can make a substantial difference in the stoker's performance.

One of the advantages of having both occupants in the prone position is that they can both see out the front window. It is also the most natural position for people underwater (you don't see many people swimming in the recumbent position).

It is important to consider two things other than minimizing the required area when positioning the stoker. These are the quantity of air the stoker will consume in a given position, and the effect of the position on the power output. The air consumption and the amount of work required to attain air is at a minimum when the regulator is in line with or just below the centroid of the lungs (when there is no pressure differential). In the Navy's research they found that the most efficient positioning for both power output and air consumption in an underwater environment was to have the stoker lying on his back in such a manner that the regulator is just below the centroid of the lungs. The prone position was found to be almost as efficient.

Power output

Within the next couple of years rotary pedalling systems will, I believe, no longer be competitive. I believe that the linear drive system is going to become a necessity in competitive underwater racing. There are many ways to build a linear drive system. One of the two we made is shown in figure 4.

The advantage of a linear drive system is the reduction in the amount of area the leg must sweep out per power

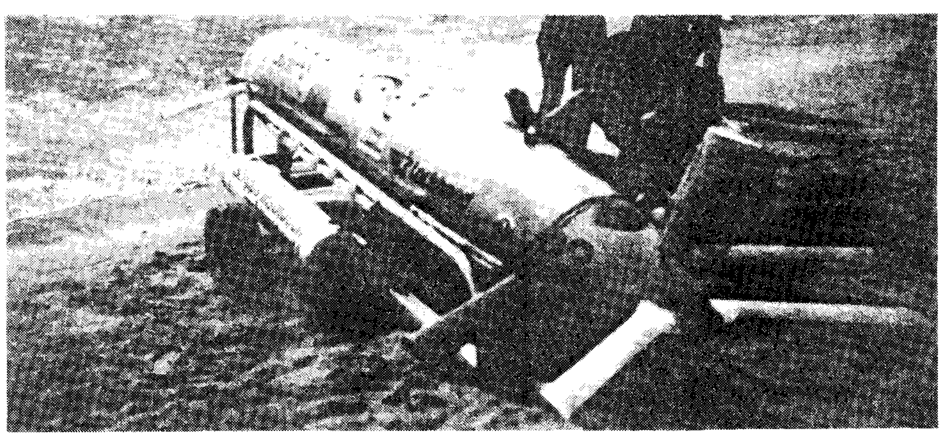

Figure 3 The SubDUDE, Univ. of California, with horizontal oscillating foils

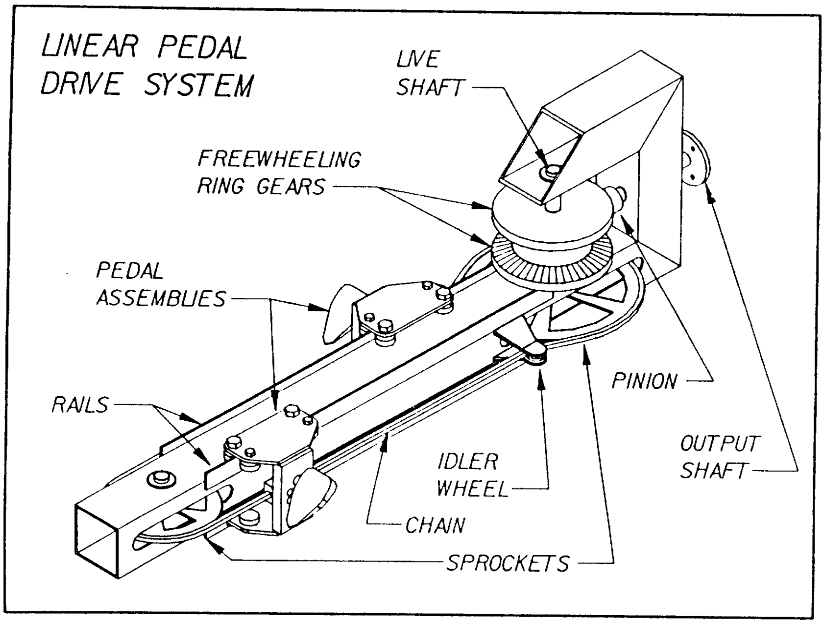

Figure 4 Linear pedal-drive system

stroke and the reduction in the amount of room required inside of the submarine. When using a linear system the leg sweeps out 30 percent less water than with a rotary system. Also the ideal cadence for a linear system is approximately 40 strokes per minute while the ideal is approximately 60 strokes per minute for a rotary system. Thus a person moves about twice the amount of water with a rotary drive system than with a linear system: this results in wasted energy.

The disadvantages are that they are harder to make as mechanically efficient, and parts are harder to attain in most designs.

Stroke length is also important. Many of the teams had stroke lengths of 150-200 mm (six to eight inches). So small a stroke length is very tiring underwater (or above water). It is beneficial to have a setup such that the stoker can choose the desired stroke length while racing. This is possible with a well-designed linear drive system.

According to one of the Navy people a study on human performance underwater showed that an above-average athlete can sustain 370 watts (0.5 hp) for a period of ten minutes. The propeller should therefore be designed for that power input (ours was designed using a previous study that recommended 260 watts (0.35 hp).

Lastly, we extensively researched both the counter-rotating propeller and a ducted propeller and decided to use neither. Although the duct would be nice as a means of protection for the propeller, the increase in efficiency was offset by the increased drag. Having an open-water propeller is also much easier from a manufacturing standpoint. The counter-rotating propeller did increase the overall propeller efficiency but in our opinion it was not enough to overcome the bearing and mechanical losses or the increased complexity and reduced reliability.

Maneuverability

Many entries had the dive planes on the front of the submarine and the rudder on the rear. Some entries adjusted their propeller pitch to steer, others angled their propeller. A couple of teams used hydraulics instead of a direct linkage. One consideration when choosing a steering system is its effectiveness when the submarine is not moving or is moving very slowly.

Life support, trim and ballast

Adjusting the ballast during the race is not a major concern. An 800-meter race will last less than ten minutes for a competitive boat. In that time the team should not need to make major buoyancy changes. We used a single ballast tank in conjunction with a sliding weight system (to adjust the trim). This worked well.

There were many different life-support systems. Some had as little as 4.5 cu.m. (160 cu.ft.) and some had over 14 cu.m. (500 cu.ft.). There were advantages to both options. The less air in the submarine the less room was taken up by the SCUBA tanks and the smaller the submarine could be. But the submarines with excess air could stay in the water longer and thereby increase their in-water time for testing. Since the tanks will become lighter as the air is used it may be worth considering placing the SCUBA tanks at the center of buoyancy of the submarine.

Although not yet approved for use, rebreathers are available. These provide more than enough air and take up much less volume than the traditional SCUBA systems. However, they are extremely expensive.

Hull shape

Designing a low-drag hull is not as easy as it may seem. Most fluid-dynamics courses cover the coefficient of drag over simple two- and three-dimensional shapes. In order to successfully find a low-drag three-dimensional shape (within a reasonable time) one must either rely on the work of others or use computational fluid dynamics (CFD) to model different alternatives.

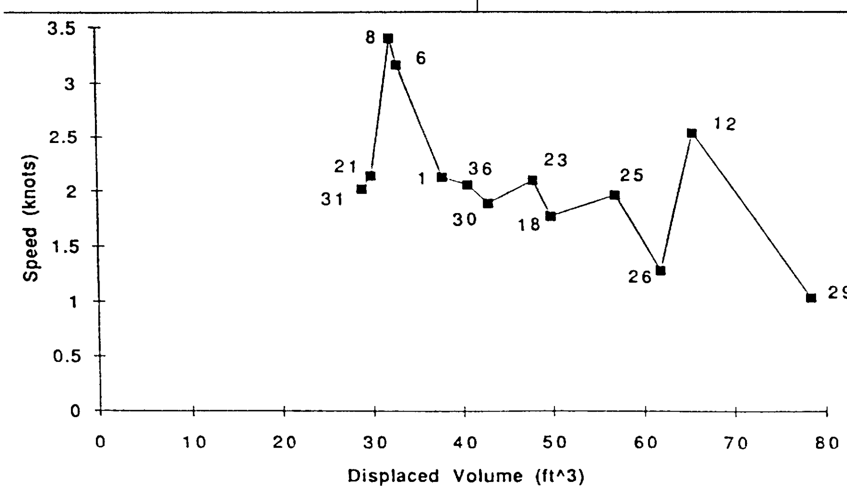

Figure 5 Relationship between displaced volume and average speed

We used CFD to model our submarine. We started by using a rotated cross section of different proven low-drag cable fairings as a basis. Different packaging arrangements of the occupants and gear were evaluated using Intergraph (a computer drafting program) and a simple adjustable plywood mock-up. After a few iterations of modifying the internal layout and the hull shape (using a program called GEODES) we arrived at our present shape. When it was done we had a low-drag, space-efficient, and somewhat cramped submarine.

Figure 5 shows how the displaced volume affected the speed of the submarine. The plotted speed of the SeaDAWG (number 21) does not reflect the actual speed it could have run the course. A competitor's surface buoy became tangled around the prop shaft at the beginning of the race and the boat proceeded to tow both buoys around the remainder of the course. The actual top speed would have been well over a half knot faster (probably about 0.5-0.6 m/s - 1 to 1.2 knots - faster).

Hull construction

Most teams used fiberglass. Some used polycarbonate and Lexan, one used Kevlar, and we used carbon fiber. Our goal was to minimize the thickness but still retain the strength. Carbon fiber fulfills this goal very well. It is also almost as easy to work with as fiberglass.

The majority of the boats were constructed by first making a plug (or male mold). From the plug a female mold was made. Then two splashes (or parts) were made using the female mold. These two halves were joined to form the submarine hull. The advantage of using a female mold is that one can attain a good surface finish on what will become the outside of the submarine.

The choice of material will affect the buoyancy and the ease of testing the submarine. One of the key advantages of carbon fiber is its high strength-to-weight ratio. This enabled us to have a hull that was about two-millimeters thick in most areas. It was very light (two people could carry it comfortably), extremely rugged (we survived a head-on crash into a piling at over two knots with no damage), and the hull was close to being neutrally buoyant (hence we didn't need a lot of lead or foam as did many of our competitors). The reduced thickness also meant less wetted surface area and less frontal area for the same internal volume.

Advice to future competitors

Once again all the teams that participated learned a lot. Most of the teams were saying they would be back in two years with even smaller submarines. I plan to assemble a team to compete in two years.

Testing is crucial. The teams with the most in-water testing time performed better in Florida. This is the predominant lesson.

Reliability is also very important. Of the 34 teams that made it to the competition, eleven did not qualify for the elimination races. This was usually due to a lack of testing and poor reliability.

The pilots can't race around a course they can't see, so make sure the pilot has enough windows. Many of the entries had a hard time seeing the starting lights which meant that the other team got ahead at the start. It is important that the pilot be able to see in front, side to side, and down. It is also important that the rescue diver can see at least one of the occupants.

I strongly recommend a communication system between the support crew and the submarine occupants, even if it is only a one-way system. This is especially important if you are testing in an area with low visibility. One option when testing is to use an underwater speaker.

Use a linear drive system if it is within your budget and you have the mechanical aptitude.

Invest a fair amount of time picking an arrangement that minimizes the volume, and spend some time choosing a low-drag shape.

Lastly I recommend a launch and recovery system that can either be raised and lowered in the water or can raise the submarine out of the water. The ideal launch and recovery system will have these features and will have steerable wheels.

Summary

This article is meant to provide some insight into what happened at this year's race and what must be done to make a competitive submarine for the next race in two years. I am open to questions and insight into human-powered submarine component design.

Questions about future races should be directed to the H.A. Perry Foundation or Florida Atlantic University.

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Cory Brandt is a recent graduate of the University of Washington where he received a B.S.M.E. degree. He presently works at the Boeing Company.

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FIETS HPV PRIZE

The Dutch bicycling magazing *Fiets* is offering a prize of 25,000 Dutch guilders for an HPV that is superior to a regular bicycle and that can be ridden 365 days of the year. Specifically mentioned are rain at 3C and a wind of force 7. It must have a large carrying capacity (minimum 80 litres and 15 kg) and require little or no maintenance. The minimum average speed is 35 kph. Entries are open until January 31, 1993, and judging, including trials of the vehicle, will take place in Holland in February 1993.

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Alternatively, send a stamped self-addressed envelope plus an additional 29-cent stamp to Dave Wilson, MIT rm 3-455 Cambridge MA 02139 and I will ask Carolyn Stitson to send you a copy.

PUBLISHING IN HUMAN POWER

HUMAN POWER depends on inputs from you, our readers. We welcome your letters, articles, reviews of books and papers, technical notes and the like. Here are some notes aimed at helping you help me. (After the extraordinary amount of time that I have spent getting this issue together I need all the help I can get. I have a newly increased respect for the good people who have put previous issues into a coherent whole after I have sent edited separate components. It is a forbidding amount of rather frustrating toil).

FORM. Letters may be sent written or typed. I am happy to enter them into my word-processor. Everything longer than a letter should be sent on a diskette. I use Lotus Ami Pro on a PC: it can accept any of the popular DOS-based word processors. I can usually get Macintosh disks converted.

EQUATIONS. These take a great deal of my time to rewrite: please supply high-quality hard copy (ie on paper) of your equations in a size that will fit this column. *Ami Pro* is supposed to accept equations written in *TeX*, and if you have them in this form in your text in addition to the hard copy it would, I hope, be useful.

UNITS. These must be given in S.I. units, and, if you wish, other units as well. Lengths are km, m, and mm; forces are N; masses are g and kg; speeds are m/s; stresses are Pa or N/m^2.

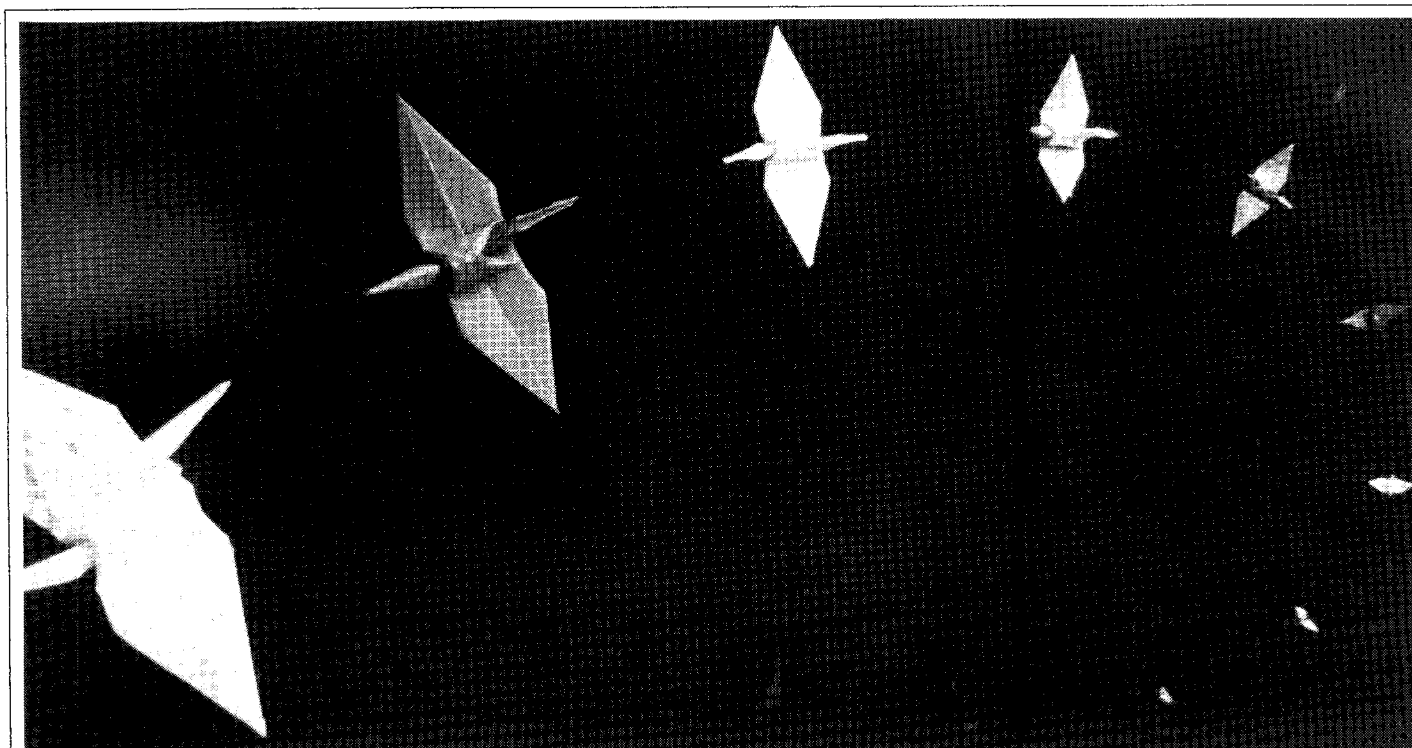
ILLUSTRATIONS. Glossy black-and-white or color photos, or high-quality original or near-original line drawings, graphs, etc are needed. The output of standard copiers is not good enough. (I have been accepting some poor stuff in the past, and even redrawing many line illustrations. We must upgrade *Human Power* in all respects, and this is a good place to start). Each illustration should have a short, informative title. Authors must have copyright to their material. Do not send anything taken from someone else's work unless you have written permission.

ORIGINALITY. We prefer to have completely original material. However, if you have previously published in some arcane journal that allows you to have the paper reprinted elsewhere, we will usually be happy to bring it into *Human Power* in its original or shortened form. (You should do the negotiation on rights). Please do not send me other people's papers and suggest that I run them here. That is plagiarism. A review of other work is, however, scholarly and welcome. I would prefer that you did the review if you have found the material. (You might ask me before doing so because perhaps someone else might be reviewing the same piece).

BIOGRAPHICAL NOTE. It is helpful to readers to know the background of authors of longer pieces. Please add a sentence or two along the lines of those in this issue. Also give your address and possibly your phone number so that readers can communicate with you directly. I have no staff here to send things on.

GRAMMAR GUIDELINES. Write to me for fuller guidelines on submitting materials, including Wilson's guide to grammar (and lots of other aspects to writing). Thank you!

Dave Wilson



"Parade of cranes" a display of micro-origami sent by Akira Naito of Nihon University, author of the lead paper (on HP helicopters) in the last issue of Human Power, and world champion in micro-origami. Here eleven cranes of wingspans ranging from 50 mm on the left to one of just over 0.5 mm mounted on the point of a needle. The display has been accepted with gratitude by The MIT Museum and will be shown in the president's house.

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