Propeller simulation with PropSim

by Theo Schmidt

Abstract

PropSim is an easy-to-use propeller simulation program for evaluating cruising propellers. The basic functions and usefulness are described in a first part, and the way it works in a second, where emphasis is given to explaining propeller physics in simple terms.

INTRODUCTION

Many years ago I needed a propeller for my first human-powered boat. The power-boat propellers available seemed unsuitable, so I wrote to Gene Larrabee, then a professor at MIT, who had designed propellers for Paul MacCready's Gossamer human-powered aircraft and had published various articles on optimal propeller design [1], [2]. Larrabee designed two propellers for me; the experimental models I made from his designs worked very well. However, I really wanted to know more about the topic and to design propellers myself.

Larrabee's minimum-induced-drag design method had two disadvantages. The main one was that I couldn't sufficiently understand the calculus involved! The other was that his method designed an optimum for a specified operating point. This is great for records and racing, where you do have a specific operating point (i.e., power required at a certain speed) and can change propellers for different events. I was more interested in cruising, where wind and waves dictate quite different loads at different times. I wanted a good compromise over a large operating range. The Larrabee designs had high-efficiency peaks of over 90% at their design points, but tended to stall (suddenly lose lift) when overloaded, thus losing efficiency. This is typical for the slender, aeronautical-type blades with high pitch/diameter ratios.

On the other hand, traditional boat or ship propellers don't stall, but don't reach very high efficiencies anywhere in their operating range. They are designed for relatively high loadings in order to minimise the craft's draft, and often for high speeds. Such propellers have wide, sometimes even overlapping blades, resulting in both considerable wetted-surface drag and tip-losses. Typical stall-proof boat propellers also have relatively low pitch/diameter ratios. They must thus turn quite fast, again resulting in much wetted-surface drag. Another consideration important with today's high-powered boats is cavitation, which occurs when the local pressure on the propeller blade's convex surface becomes so low that a cavity occurs, or more accurately, that the water begins to boil even at ambient tempera-

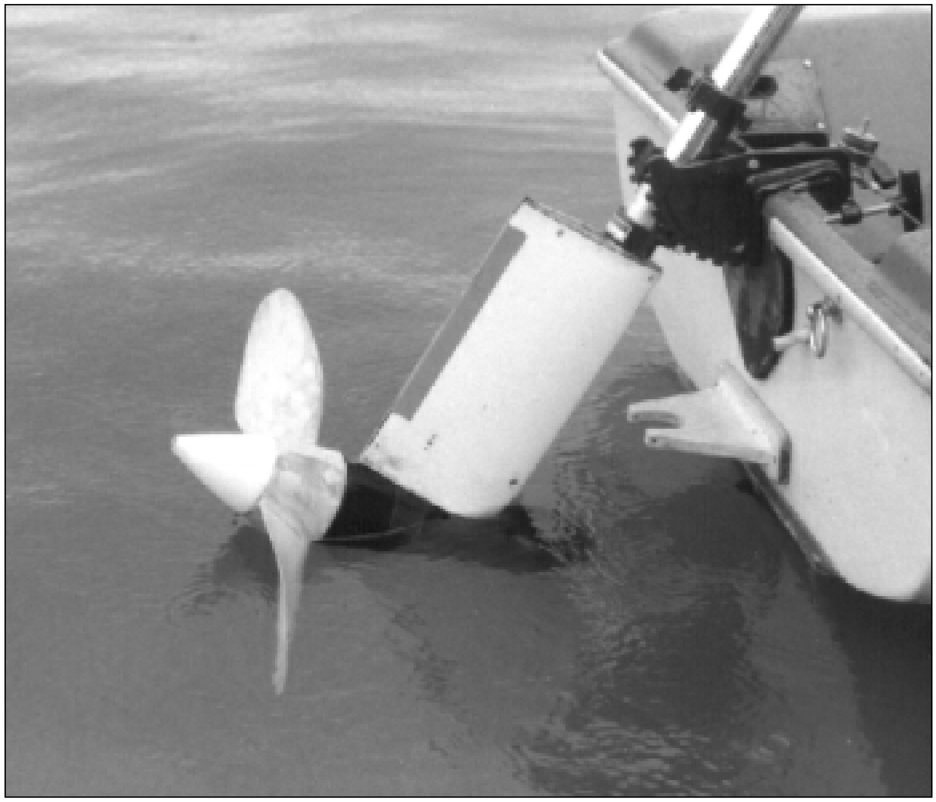

Figure 1. Two-bladed propeller.

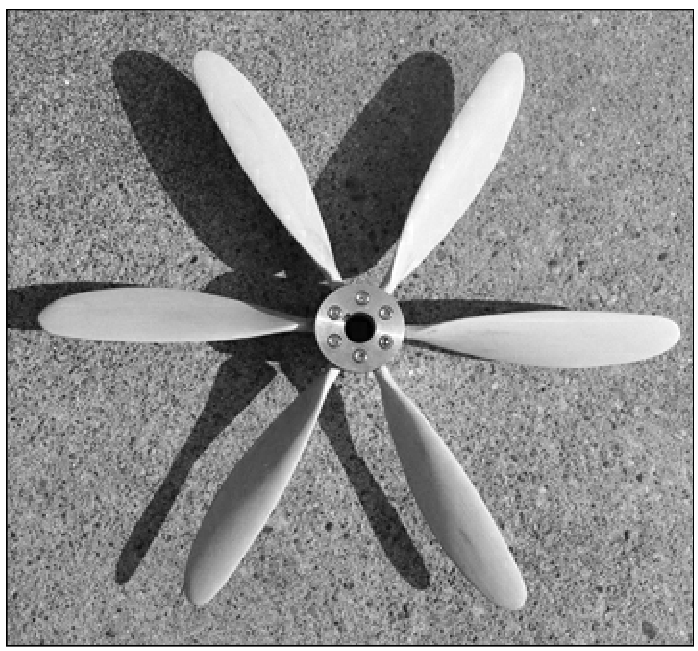

Figure 2. Six-bladed propeller.

The two propellers shown here in two solar-boat applications, were developed for human-powered boats. The two-bladed prop is my standard cruising propeller which has been used for numerous boats powered by one or two persons, and in one case, twelve persons. The six-bladed prop can be pitch-adjusted and also used with fewer blades. Jochen Ewert's flying hydrofoil craft uses a two-bladed version of this propeller. Photos, Theo Schmidt.

ture. With human-powered propellers and hydrofoils this is not a problem so far.

It is plausible that good all-round cruising propellers for low-powered boats are somewhere between the aeronautical-type and the ship-type propellers. In order to evaluate designs suitable for cruising I really needed a simulation rather than a design program. With nothing available to me to run on my "toy" computer, I wrote my own program PropSim in the BASIC programming language and published the first version in *Human Power* [3], along with a specification for a good cruising propeller which has since been made about 50 times. Quite a few people inquired and got copies of the program. Some, like Christian Meyer, expanded and improved it. Many people weren't able to use the program because their computer's understanding of BASIC was different to mine: there are quite a few dialects about. Therefore I've rewritten the program in a new version with some improvements and am making it available as a stand-alone application, at present only for the Macintosh PowerPC, free to *Human Power* subscribers.

PART 1: WHAT CAN YOU DO WITH IT?

PropSim is suitable for studying the behaviour of air or water propellers used for human-powered craft. It can also be used for power applications as long as reasonable speeds and blade loadings are not exceeded. Although a simulation program, PropSim does calculate and output suitable chord and twist-angle values of the blades when given the maximum chord (i.e., blade width), propeller diameter, and pitch. You further specify the boat speed, medium (fresh water, sea water, or air), and number of blades.

The following (fig. 3) is a PropSim input/output page with data corresponding nearly to the propeller in fig. 1.

You thus get a table of output values (e.g., power and efficiency) for a suitable range of propeller speeds starting at that speed at which the propeller freewheels, i.e., produces no thrust. If your input values are reasonable, one propeller speed (i.e., output line) will correspond to the values of a particular craft and situation. The better you know the thrust required for your boat at a particular speed, the better you can optimise the propeller by adjusting the input values until you get the efficiency peak where you want it.

For a racing propeller you would then concentrate on varying several values in order to maximise the peak efficiency.

For a cruising propeller, you would examine the behaviour at several boat speeds and come to a compromise which best suits the intended use.

Figure 4 is the graphical output of a spreadsheet program, corresponding to the data in figure 3. A good overall efficiency requires a Froude efficiency (ETA F in figure 3) between 95% and 99%

Input Values:
Diameter = 0.5 m
Vehicle Speed = 2 m/s
Blade Number = 2
Maximum Chord = 0.090 m
Number of Output Lines = 16
Pitch = 0.66 m
Fluid = fw (water, sea water, or air)
Hub/Diameter ratio = 0.10
Chord Distribution is default
Increment = 10 rpm

Basic output values:
Swept Area = 0.1944 sq m
Blade Aspect Ratio = 3.17
Blade Area Ratio = 0.1641
Tip Angle = 22.7 degrees

RADIUS	CHORD [M]	ANGLE [DEGREES]
0.05	0.075	64.54
0.075	0.085	54.47
0.1	0.09	46.4
0.125	0.09	40.04
0.15	0.085	35
0.175	0.076	30.97
0.2	0.067	27.7
0.225	0.054	25.02

PR SPD [RPM]	P IN [W]	P OUT [W]	ETA [%]	ETA F [%]	THRUST [N]	TORQUE [NM]	CL(5)	SLIP
150	12	6	53	100	3	1	0.01	0.002
160	36	29	82	99	15	2	0.11	0.009
170	64	55	86	98	27	4	0.21	0.017
180	96	83	86	97	41	5	0.3	0.026
190	132	113	85	97	57	7	0.39	0.035
200	173	146	84	96	73	8	0.46	0.045
210	218	181	83	95	90	10	0.54	0.055
220	269	218	81	94	109	12	0.6	0.066
230	324	258	80	93	129	13	0.67	0.077
240	385	301	78	92	150	15	0.72	0.089
250	451	346	77	91	173	17	0.78	0.101
260	523	393	75	90	197	19	0.83	0.114
270	601	443	74	89	222	21	0.88	0.126
280	685	495	72	88	248	23	0.92	0.14
290	776	550	71	87	275	26	0.96	0.153
300	874	607	70	86	304	28	1	0.167

Press <RETURN> for new run of PropSim 4/99

Figure 3. Input/output page from PropSim.

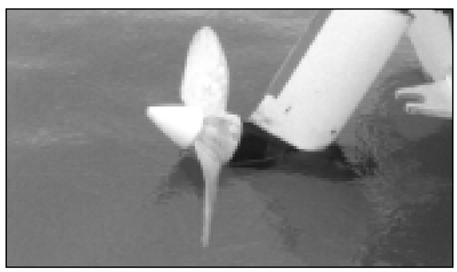

Figure 1 (smaller version from page 3). Two-bladed propeller.

ASSUMPTIONS AND LIMITATIONS

- PropSim assumes and outputs unshrouded straight blades with correct twist for light loading. Things like simple flat plates or variable-pitch props used off the design point cannot presently be modelled, nor can highly skewed or bent blades ("weedless" designs) or props used in rings or tubes (e.g., bow thrusters, Kort nozzles).

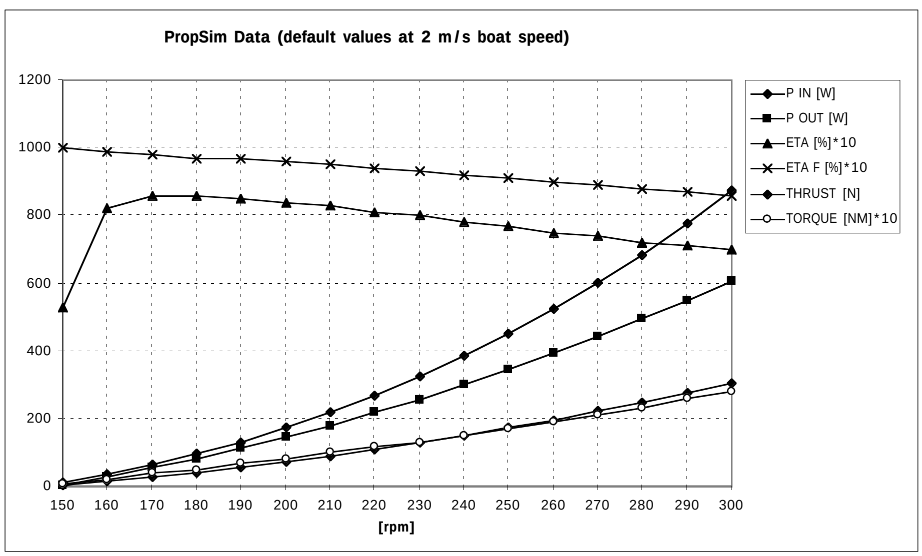

Figure 4. This is the graphical output of PropSim via a spreadsheet program, corresponding approximately to the two-bladed Prop in Fig. 1. A good overall efficiency requires a Froude efficiency (ETA F in figure 3) between 95% and 99%.

- You have a choice of four reasonable blade planforms without knowing which of these (if any) is the optimal one. Yet the program assumes an optimal planform, so in a general case the output values will be slightly optimistic. (This is the consequence of not using Larrabee's minimum-induced-drag method.)
- The program uses a basic medium-thickness flat-bottomed round-nosed foil section (Clark-Y). Strongly differing sections are not correctly modelled.
- Reverse thrust (braking or turbine modes) is not modelled.
- Overloaded (stalled) blades are only approximately modelled.
- Hubs are modelled, but the larger the hub, the less accurate the result.
- No solid-material properties are assumed. Thus it is possible to design highly efficient propellers which are not buildable in practice (although a little common sense or carbon fiber goes a long way!).
- Present program versions (e.g., 4/99) run only on Power Macintosh computers (probably any type). Sorry Bill Gates!
- Present program versions can print, but do not save files or copy to the clipboard. To draw diagrams, you would have to enter the data into an appropriate program manually or with an OCR program. The program remembers your input values only as long as it is kept running.
- The only unit system presently supported is metric SI with propeller speed in revolutions per minute and angles in degrees.

WHAT GOOD IS IT?

With all these limitations you might wonder what good the whole thing is. It turns out that most of the limitations are not very important unless you are after extreme achievements, where only the very best is good enough. For most practical purposes it is the overall performance which counts, and this is highly dependent on the basic geometry: diameter, pitch, and blade area. Planforms and sections are then of secondary importance. Using the program, you can for example determine a geometry which "feels" good at low speeds, which may result in a more popular product than some, or indeed avoid really poor mismatches sometimes proposed even by large companies or knowledgable people. The program is now easy to use and runs quite fast, so the missing graphical and filing capabilities are not catastrophic.

VALIDATION

Although there is good agreement [3] between some results from PropSim and those of more sophisticated programs, this is probably a coincidence. As I have never accurately measured any propellers and there are so many influencing factors, it is very difficult to say how accurate the results are. My cruising propellers designed by this method have been very successful and some have even won races, but I think the program is probably not good enough to make propellers suitable for breaking present hydrofoil and aircraft speed and distance records.

WHERE CAN YOU GET IT?

The new versions of PropSim are available free of charge to members of HPV or research organisations for personal use. In order to get PropSim, e-mail me at <tschmidt@ihpva.org>. For those without online access, disks may be made available subject to a postage and handling charge. Programmers interested in improving the program or porting it to other operating systems than Power Macintosh should ask for the BASIC source code.

PART 2: HOW PROPSIM WORKS

As PropSim is not a design program, but rather a simulation program, you have to enter some halfway-sensible parameters to begin with and the program will behave like a virtual test tank. It is mathematically inelegant, using no calculus, but only simple theory and numerical methods to arrive at solutions, a task well suited to fast number-crunching computers. The underlying method used is the *actuator-disc theory*, which describes the behaviour of a "perfect propulsor" acting continuously on a "disc" perpendicular to the direction of fluid flow. One could say it "couples" perfectly to a disc of fluid which is continuously replaced. This theory is valid for any fluid and for our purposes there is no difference between air and water as long as the physical characteristics are correctly modelled. Secondary effects like cavitation or supersonic flow also have no bearing on the type of propulsor we are interested in and are not modelled.

Because there are many misconceptions on the way a propeller (or indeed any propulsor) works, the remainder of this article attempts to explain propulsion physics in simple terms, using PropSim's inner working as an example. The source code is available from the author or the essential parts can be found in [3].

BASICS BEHIND THE ACTUATOR-DISC THEORY

In order to produce any propulsive force on any craft, you must have matter to react against. In the case of land vehicles using wheels (or barges using poles) to push against the ground, this matter is the ground underneath the vehicle, and as the ground is very stiff, you are pushing against the whole earth, a huge mass which moves backward a tiny amount as you move forward. (This is action = reaction, Newton's third law.) As the earth has very much more mass than have you and your vehicle, you move forward almost the full amount defined by your wheel rotation and the earth moves back only an imperceptible amount. Discounting the small amount of tire slip, you have a propulsive efficiency of practically 100%.

Instead of reacting against the earth by turning the wheels with pedal cranks, you could instead throw bricks out the back and propel your vehicle this way. This is the principle by which rockets move but it is really the same thing: you are reacting against the mass of the brick as you throw it, producing a propulsive force equal to its mass times its acceleration (i.e., the applied speed increase), Newton's second law. The faster you can throw the brick, the lighter it can be for the same effect, and the more bricks you can carry (space-propulsion systems emitting ions at nearly the speed of light can operate for years while expending very little mass). In order that you don't run out of bricks, you could previously lay them out to pick up on the way; this would then be the principle by which jets or indeed propellers operate: they intercept the fluid at rest along their path and act on it. To propel a boat or airplane you are thus “picking up” and “throwing” parcels of water or air out the back; it is exactly the same as with bricks and has little to do with the Victorian notion that a propeller pulls its way through a medium like a screw through a block of wood, although the geometrical concept of “pitch” (distance between two screw threads) is useful in the special case where there is no “slip”: at each turn the screw advances by the distance equal to the pitch.

Now you can produce the required force either by intercepting a large parcel of fluid with a large propeller and speeding this up only slightly, or by using a small propeller or even a ducted impeller in order to speed up a small parcel a greater amount, right up to a high-speed jet. The propulsive force is created at the point where the fluid is accelerated (impeller and nozzle) and not because the jet pushes against the water or air, as many people think. Thus the jets of many motorised water craft actually exit above the water line. Now these small units would be really neat except for one thing: each parcel of of fluid also carries a kinetic energy equal to 1/2 times its mass times its velocity squared, energy which is lost to the propulsive system. Doubling the jet speed you need only half the mass, but you get twice the energy loss, i.e., the inherent loss of a propulsive system is a linear function of the jet velocity.

Therefore it is clear that we must strive towards a small velocity increase and a large mass. The mass available per second is equal to the fluid density times the volume acted upon by the actuator per second. This is equal to the distance travelled per second times the actuator area (perpendicular to the direction of motion). A high propulsive efficiency thus requires either a high vehicle speed or a large actuator disc, whether this is a propeller, oar, or paddle wheel. Boats with relatively small propellers or narrow high-speed jets have very poor propulsive efficiencies at low speeds. At high speeds, the situation improves, as more parcels of water are presented to the propeller or jet drive and thus must be accelerated only slightly in order to achieve the high mass-per-second throughput desired. Thus high-speed craft can use smaller propellers or even jets somewhat efficiently when planing or hydrofoiling, whereas slow craft or heavily loaded craft need the largest propellers that are practically possible.

The state of affairs above is described in simple equations by the actuator-disc theory. The efficiency of an ideal propulsor worked out this way is called the *Froude efficiency* and is a natural limit which cannot be exeeded by any device, no matter how good it is. Any propulsor which has virtually zero slip in the water, whether this is a very large propeller or a huge drag device, approaches 100% Froude efficiency. The essence of the actuator-disc theory is that if the slip is defined as the ratio of fluid velocity increase to vehicle velocity, the Froude efficiency is 1/(slip + 1).

BLADE FORCES

The second component needed to calculate propellers is simple foil theory applied to propeller blades. A blade or wing moved through a fluid generates a force by the very act of accelerating and redirecting fluid as described above. This force can be resolved into components which are perpendicular or parallel to the blade movement, called lift and drag, respectively, or into another pair of components perpendicular or parallel to the direction of vehicle motion, called torque (when multiplied by the local radius) and thrust, in the case of a screw propeller. This is very similar to a wing except that the blade is twisted, so that the blade must be devided into several segments which are treated separately.

Using the propeller diameter, pitch, and rotational speed and also the boat speed, PropSim first works out the angles of ten segments corresponding to an *ideal helix* which would slide through the water with no disturbance at all if rotated at exactly the specified speed. A thin foil shape corresponding to this helix would generate no lift and no thrust at the propeller speed which corresponds to one revolution in the time it advances a length equal to its pitch, i.e., the pitch per time unit must equal the boat speed, giving a zero angle of incidence on the blades. When the propeller is turned faster, this angle increases and propeller theory predicts a lift force increasing in proportion. At angles under 10 degrees this is the same for all usual wing shapes and agrees closely with what is measured in practice. Other values affecting lift are the surface area and the aspect ratio of the complete three-dimensional blade: short fat blades have considerable pressure loss around the tips whereas long narrow blades are less affected this way. (This is where the first propeller designers erred: thinking in terms of the wood-screw model they thought they would get minimal slip with wood-screw-like propellers. However these have tremendous pressure losses around the edges and were thus particularly bad, until one day one got broken accidently and performed much better, leading the way to modern propellers!)

Now PropSim must determine the drag force of each blade segment. At this point, propeller theory becomes very complicated or unknown and we must make use of values measured in tanks or wind tunnels, which are available as tables or diagrams for a great variety of different wing sections. Sets of measurements are always similar if the so-called *Reynolds number* is the same, no matter what the size or speed of the blade or whether the fluid is water or air. All that is needed are tabular data at various Reynold’s numbers and the size, speed, and angle of the blade. PropSim looks up the drag data in a table as a function of lift and Reynolds number, using data for the Clark-Y foil section, which is similar to the Eppler 193g.u. and Eppler 205 profiles, and is relatively easy to define and make because of the flat bottom surface. The segment forces are resolved into thrust and torque components and added up. A further correction is also applied in order to compensate for the tip losses mentioned above. This is called induced drag. In calculating this, PropSim deducts only the theoretical minimum loss, i.e., it assumes that the blade’s planform is optimal. This corresponds to an elliptical lift distribution of an untwisted blade. In the case of a screw propeller, Larrabee has shown that the requirement for minimum induced drag is a uniform wash velocity, i.e., the same local slip values for all segments [1]. It is therefore planned to add a numerical optimisation routine into PropSim to adjust the segments’ chord dimension in order to arrive at this condition.

Until this is implemented, PropSim simulations will be slightly optimistic for blade planforms which do not happen to be exactly correct.

NUMERICAL SOLVING

Now we must marry the two sets of calculations described above. The propeller blades sweep out a virtual disc in the fluid: this is our actuator disc. Initially we assumed no slip for the force calculations although physically there must be some if the prescribed force is to be generated. Using the first results, we can work out the slip or stream velocity required to produce the same forces in the actuator disc. The force calculations are now repeated using the new slip value, and they will be seen to have changed a bit. PropSim keeps doing this until the values no longer change. These calculations almost always quickly converge towards a solution unless wild, nonsense, values are used as inputs. The result is thus a numerical solution for the velocity of the slip stream and all corresponding forces, whence total power and efficiency values can be derived. Once this solution has been found, all desired values are printed, giving a single line of output corresponding to a single operating point.

The propeller speed is now increased by a specified increment and everything repeated until we have a table of propeller values as a function of propeller speed, which is shown on the screen or printed out, as shown above in Part 1. Now the boat speed could be increased and the whole procedure repeated, so the end result is a set of tables describing the propeller behaviour over a wide operating range. It is important to develop a feeling for the physical parameters and not to go outside sensible boundaries. I hope that future versions of PropSim will draw fancy diagrams or at least prepare files suitable for drawing diagrams in other programs. Far-future versions may even have some optimisation routines, but I would be delighted if some of you gentle readers accomplish these improvements before I do!

ACKNOWLEDGEMENTS

Thanks to Gene Larrabee for having started it all, and Dave Wilson, Bob Stuart and Michael Lampi for reviewing this article and giving suggestions.

REFERENCES

[1] Larrabee, E. Five Years' Experience with Minimum-Induced-Loss Propellers. SAE Technical Papers #840026 and #840027, February 1984.
[2] Larrabee, E. Propellers for human-powered vehicles. *Human Power* Vol. 3 No. 2 (1984).
[3] Schmidt, T. A Simple Program for Propeller-Performance Prediction. *Human Power* Vol. 7 No. 2, (1988).
[4] Schmidt, T. Basic Propeller Performance Prediction. Amateur Yacht Reseach Society Publication 109, October 1991.
[5] Poole, P.K. Propeller Design. *Human Power* Vol. 9 No. 1 (1991).

Theodor B. Schmidt, 44, has lived in the USA, Wales, England and now in Switzerland, married, in an old farmhouse full of HPV and boat components (but few actually functioning vehicles!). Degree: BSc (Wales) in Physical Oceanography and Electronic Engineering. Occupations have included domestic solar installation, kite-sail, solar hydrogen, vehicle safety, and Stirling-engine research (with the Center of Appropriate Technology in Langenbruck, Switzerland), and now mainly human- and solar-boat consulting. HPVs and boats are a vocation, as is lobbying for and trying to live in, a car-free healthy environment. Vehicles built and owned include several solar/human-powered tricycles and electric bicycles, scooters, and boats powered by just about everything except internal-combustion engines. Theo is current chairman of the IHPVA.

LETTER