The Aerodynamics of Human-powered Land Vehicles

A bicycle and its rider are strongly impeded by their resistance to the flow of air. Aerodynamic stratagems have brought vehicles that can go 60 miles per hour on a level road without assistance

by Albert C. Gross, Chester R. Kyle and Douglas J. Malewicki

For decades the principles of aerodynamics have been applied with great success to improving the speed and efficiency of aircraft, automobiles, motorcycles and even competitive skiers and skaters. Vehicles powered by human energy, however, were virtually ignored until quite recently, which is strange in view of the fact that air resistance is by far the major retarding force affecting them. With a bicycle, for example, it accounts for more than 80 percent of the total force acting to slow the vehicle at speeds higher than 18 miles per hour. Here we undertake to explain this neglect and to show what attention to aerodynamics is beginning to do for the performance of human-powered land vehicles.

Looking first at the bicycle, one sees that it has remained almost the same in form for nearly a century. The Rover Safety Cycle, which was introduced in England in 1884, could easily pass for a modern bicycle; it lacks only a seat brace, which would have formed the modern diamond frame, and a few components such as brakes and multiple gears. Almost from the beginning the designers and users of bicycles recognized the importance of aerodynamics, but artificial constraints on design largely prevented the application of the necessary technology. It was as obvious then as it is now that wind forces at the bicycle-racing speed of from 20 to 30 m.p.h. are enormous.

Before 1900 the crouched posture of the bicycle racer had become common as a means of reducing air resistance. Another practice adopted before 1900 was to put a multiple-rider bicycle ahead of a single racer to shield him from the wind. In 1895 the Welsh wheelman Jimmy Michael rode 28.6 miles in one hour behind a four-man lead bicycle. In 1899 Charles ("Mile-a-Minute") Murphy of the U.S. gained international fame by pedaling one mile at 63.24 m.p.h. on a bicycle traveling behind a train of the Long Island Rail Road on a board path built for the occasion.

In 1912 Étienne Bunau-Varilla of France patented a streamlined enclosure for a bicycle and its rider that was inspired by the shape of the first dirigible balloons. Versions of this bicycle and its descendants set speed records in Europe from 1912 to 1933. In 1933 Marcel Berthet of France covered 31.06 miles in one hour riding a streamlined rig named the Vélodyne; his pace was more than 3 m.p.h. faster than anyone riding a standard bicycle had gone for one hour.

In the same year the French inventor Charles Mochet built a supine recumbent bicycle (with the rider pedaling while lying on his back) that he later streamlined. With a professional racer, François Faure, this "Vélocar" set a number of speed records between 1933 and 1938. Mochet and Faure hoped the records would be recognized by the Union Cycliste Internationale, the world governing body for bicycle racing. They were not.

Indeed, in 1938 the Union banned the use of aerodynamic devices and recumbent bicycles in racing; the rule is still in force. The ban has been a serious deterrent to the development of high-speed bicycles and is one of two major reasons the bicycle has remained nearly unchanged for so long. (The other reason is that in the developed countries the shift to the automobile has made the bicycle less important for transportation than it once was.)

By its ruling the Union essentially classified improvements in the aerodynamics of bicycles and other technological changes as "cheating." (It is perhaps fortunate that the Union was not active when a Scotch-Irish veterinary surgeon, John Boyd Dunlop, developed the pneumatic tire for bicycles in 1887, otherwise people might now be riding bicycles ar possibly automobiles with solid ste wheels.) To its credit, however, the U ion has gradually begun to relax its r strictions on changes in aerodynamic although recumbents are still forbi den. Since 1976 skintight one-piece su have become common in internatio al bicycle racing. Streamlined helme teardrop cross sections for frame tu ing, streamlined brake levers and oth aerodynamically improved componen have been allowed. In fact, technolog cal change in all forms of human-po ered vehicle is flourishing at a rate u matched since the heyday of the bicyc in the 19th century.

This rapid change can be partly attri uted to a series of events in Californi In 1973 one of us (Kyle) and Jack I Lambie, a consultant in aerodynami who was working independently, bu and tested the first two streamlined bic cles in the U.S. Unlike their predece sors, Kyle and Lambie actually me sured the reduction in drag achieved b streamlining. They did so by conductin numerous coast-down tests, in which a unpowered vehicle is allowed to dece erate on a level surface. In this conditio the deceleration of the vehicle is pr portional to the total retarding forc acting on it; instruments measure eith the speed or the deceleration. Kyle an Lambie, publishing their results ind pendently, both concluded that the tot drag forces on a bicycle could be r duced by more than 60 percent with vertical, wing-shaped fairing that com pletely encloses the bicycle and the ri er. (It was not until some two years la er that either Kyle or Lambie learne that similar vehicles had been built ea lier in Europe.)

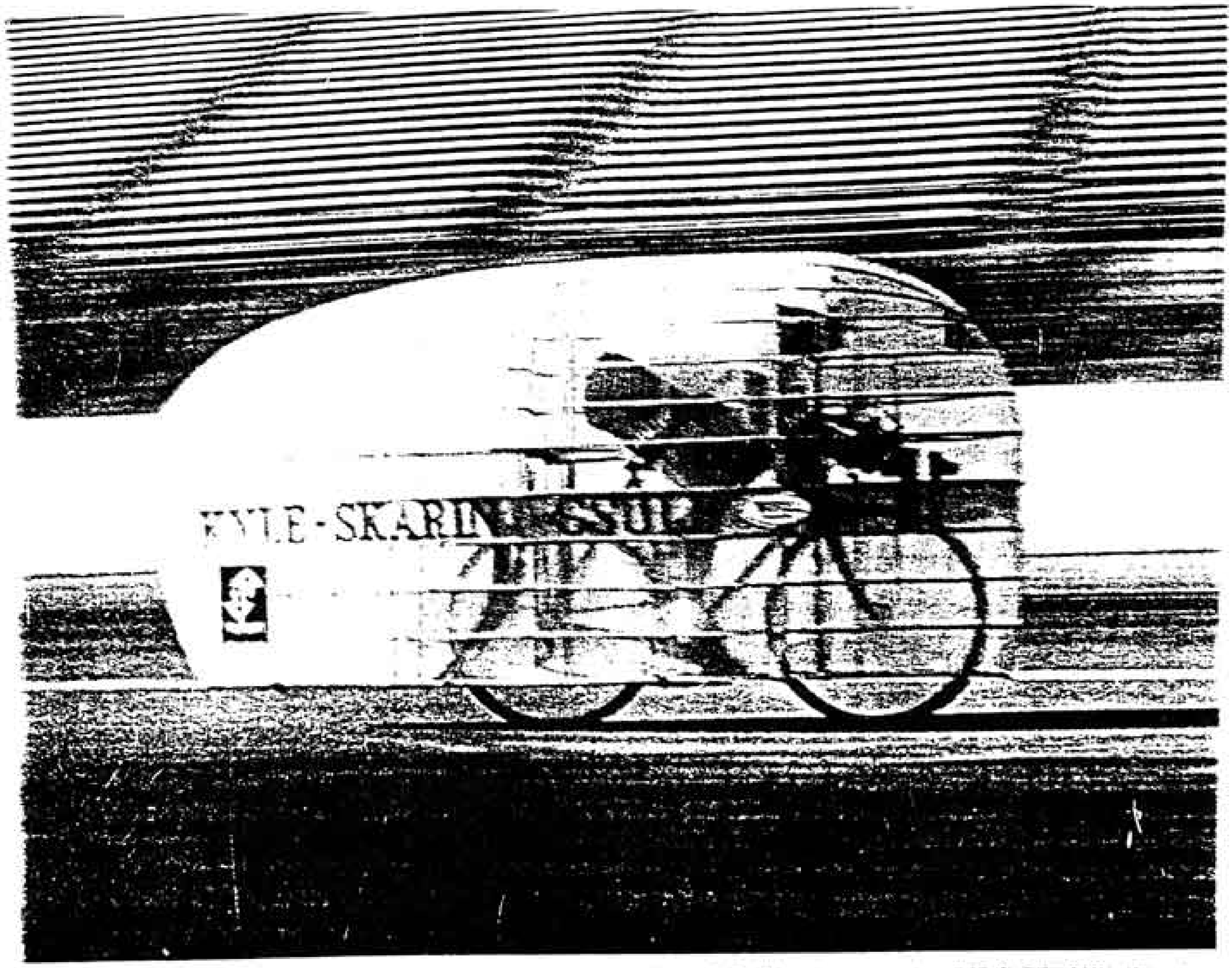
In 1974 Ronald P. Skarin, an Olympi cyclist for the U.S., set five world spee records riding the Kyle streamlined bi cycle at the Los Alamitos Naval Air Sta tion. Because of this success, Kyle an ambie decided to organize a race for nrestricted human-powered vehicles.)n April 5, 1975, at Irwindale, Calif., 14 listinctive vehicles competed in this hisoric first race. Many of them were reumbents, some with the rider pedaling upine (face up) and some with the rider rone (face down). Some were propelled y both hand and foot power. The winer at 44.87 m.p.h. was a streamlined andem bicycle designed by Philip Noron, a high school teacher in Edgewood, 'alif. The pedalers were Norton and hristopher Deaton, who is a skilled acing cyclist but not a world-class cometitor. (The fastest an unaided standard cing bicycle has been ridden is 43.45 p.h., a record set in 1982 by Sergei opylov of the U.S.S.R., a cyclist of orld class.)

Faced with the policy of the Union ycliste Internationale against streamning, the competitors in this race unded the International Human Powed Vehicle Association in 1976. Its purpose was to sanction competitions in which human-powered vehicles would be under no restrictions of design. Since then in dozens of races held in many countries the machines have become much more sophisticated and speeds have risen steadily. Four vehicles have broken the U.S. automobile speed limit of 55 m.p.h. (Each one received an honorary speeding ticket from the California Highway Patrol.) Among them is a third-generation streamlined quadricycle designed by Norton.

At present the world's fastest human-powered vehicle is the Vector Tandem, a gracefully streamlined two-person recumbent. It was built by a team headed by Allan A. Voigt, an engineer who as president of Versatron Research, Inc., primarily designs aerospace servomotors. (The pedalers ride supine and facing in opposite directions.) In 1980, with a flying start of about one mile of acceleration, it covered 200 meters along the track of the Ontario Motor Speedway in California at 62.92 m.p.h. Later that year the Vector Tandem averaged 50.5 m.p.h. for 40 miles on Interstate Route 5 between Stockton and Sacramento.

These extraordinary speeds are almost entirely the result of attention to aerodynamics. A cyclist traveling at 20 m.p.h. typically displaces approximately 1,000 pounds of air per minute. When the machine and the rider are not streamlined, they leave a substantial wake and exact a high cost in human energy.

Two types of aerodynamic drag affect the performance of a bicycle: pressure (or form) drag and skin-friction drag. Pressure drag results when the flow of air fails to follow the contours of the moving body. The separation changes the distribution of the air pressure on the body. If the separation takes place toward the rear of the body, the air pressure there becomes lower than it is on the forward surface, causing drag.

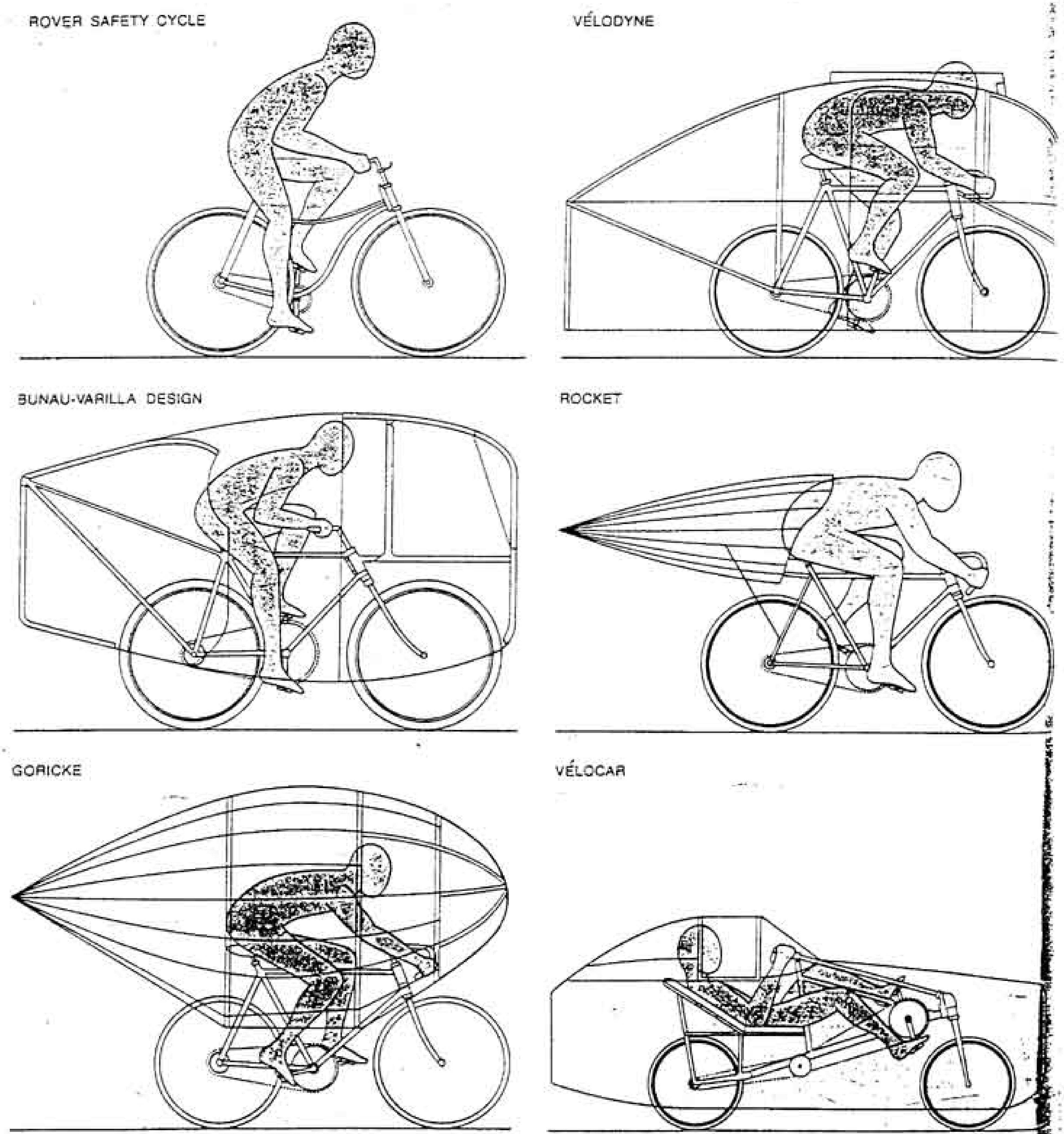


EAMLINED RACING BICYCLE designed by one of the aurs (Kyle) and ridden by Ronald P. Skarin, an Olympic cyclist for U.S., is shown setting the world record of 31.88 miles per hour for hour of pedaling from a standing start. The key to the performance was the streamlined fairing that reduced the aerodynamic resistance of the rider and the bicycle. Skarin established the new speed record in 1979 at the Ontario Motor Speedway in Ontario, Calif. Except for the fairing the vehicle was basically a standard racing bicycle.

Skin-friction drag results from the viscosity of the air. It is caused by the shearing forces generated in the boundary layer: the layer of air immediately next to the surface of the body.

Blunt configurations such as the cylinders, spheres and other shapes found on a bicycle are aerodynamically inefficient because the airflow separates from the surfaces. Low-pressure regions form behind the objects, resulting in pressure drag hundreds of times greater than skin-friction drag. In contrast, air flows smoothly around a streamlined shape. The air closes in behind as the body passes. Pressure drag is greatly reduced and skin-friction drag becomes more important.

For the highest efficiency a vehi should be designed to minimize t transfer of unrecoverable energy to t air by the two types of drag. At the pr ent level of technology aerodynam drag absorbs from 40 to 50 percent the fuel energy consumed by an au mobile or a truck at 55 m.p.h. Since t bicycle has lower power, weight a



EARLY IMPROVEMENTS in human-powered land vehicles resulted in the introduction of the Rover Safety Cycle in England in 1884. In 1912 and 1913 Étienne Bunau-Varilla of France obtained patents for a streamlined design; similar bicycles set many speed records. The Goricke was developed in Germany in 1914. The Vélodyne was ridden 31.06 miles in one hour (a new record) by Marcel Berth of France in 1933. From the same year is the Rocket, designed by Oscar Egg. Another French vehicle, the Vélocar, set several spe records between 1933 and 1938. Most of the drawings are based o data from the Wolfgang Gronen Archive at Binningen in Switzerla

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A term employed to describe the erodynamic efficiency of a shape is e drag coefficient. An inefficient shape uch as a sphere will have a drag coeffiient of, say, 1.3, whereas a streamlined hape such as a teardrop will have one f less than .1. Hence an object of teardrop shape can move with less than a enth of the loss of energy incurred by n object of cylindrical shape.

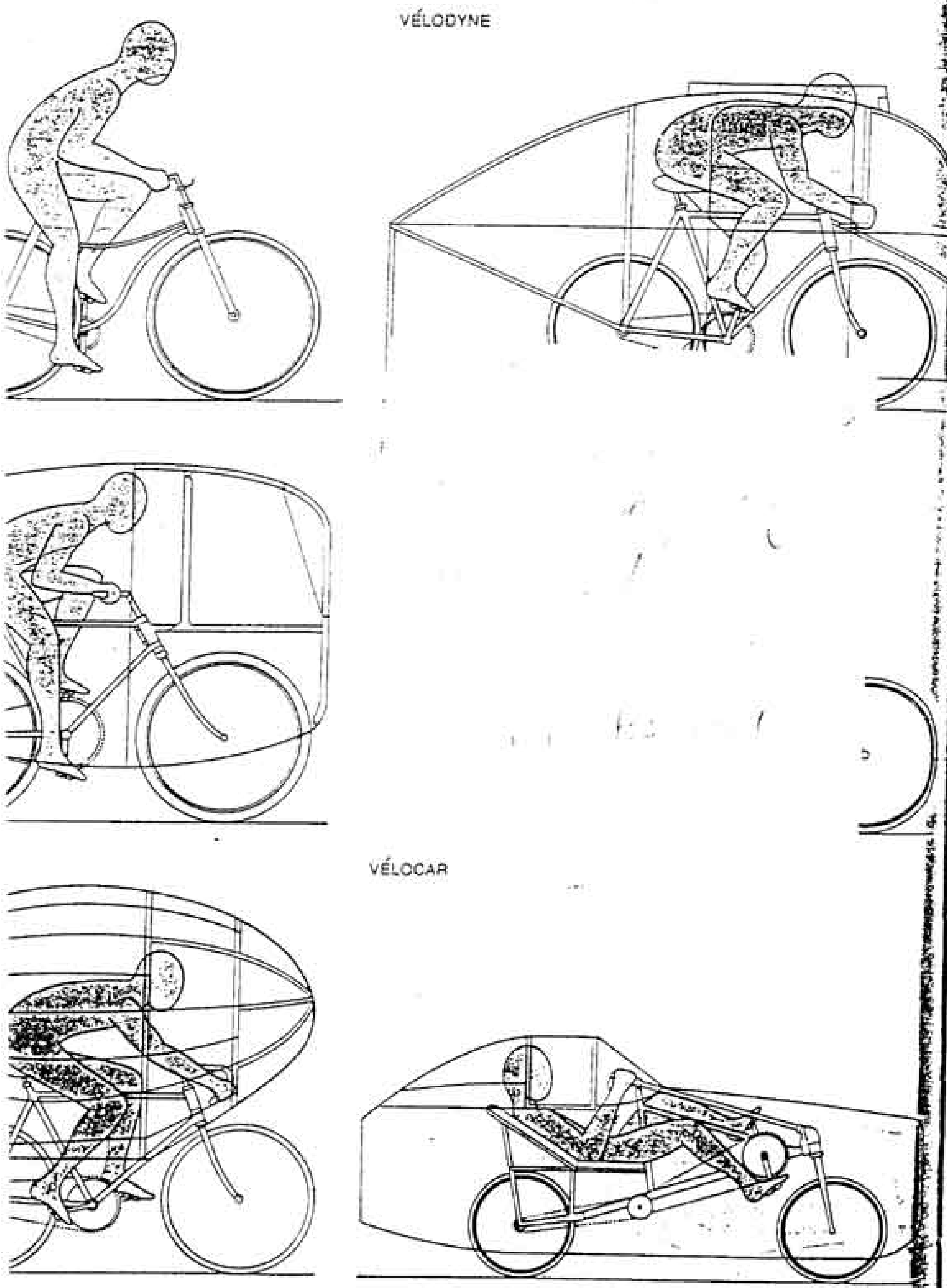
For land-transportation vehicles the erodynamic resistance is almost directy proportional to the product of the frontal area and the drag coefficient. For convenience we call the product the effective frontal area. In discussing which of two vehicles has less aerodynamic drag it is not sufficient to compare drag coefficients; the size of the vehicle must also be taken into account. That is done n the concept of the effective frontal area. An ordinary bicycle and its rider will have an effective frontal area of from 3.4 to six square feet, whereas a streamlined human-powered vehicle can have one of less than .5 square foot.

The force of aerodynamic drag increases as the square of the velocity. Power is proportional to the product of drag force and velocity, so that the power necessary to drive an object through the air increases as the cube of the velocity. Hence a modest increase in speed requires an enormous increase in power. A cyclist who suddenly doubles his output of power when he is traveling at 20 m.p.h. will increase his speed to only about 26 m.p.h.

Conversely, reductions in aerodynamic drag affect speed less than one might think. If the air drag is cut in half at 20 m.p.h., a cyclist who does not change his power output will speed up to about 24.4 m.p.h. The reason is that the rolling resistance remains constant. If that resistance could be ignored, doubling the horsepower or reducing the effective frontal area by half would again get the speed up to about 26 m.p.h.

In sum, high speeds require extremely high aerodynamic efficiency. The Vector Tandem, receiving an input of slightly more than one horsepower from each of its two riders, attained a speed of 62.92 m.p.h. For a standard bicycle to achieve that speed would require more than 6 h.p. That level of power from a human rider is clearly impossible.

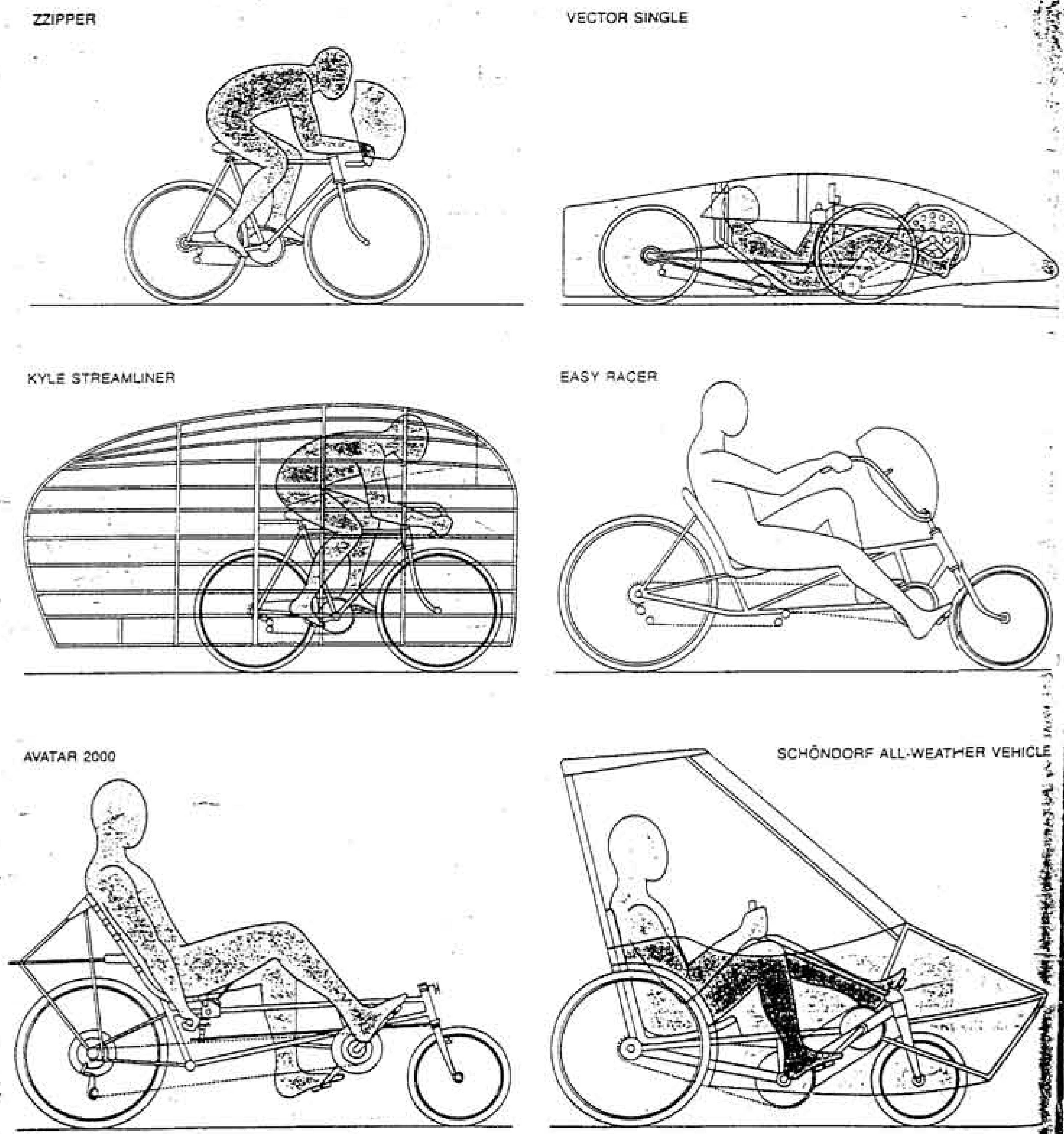
Designers and riders can reduce the aerodynamic drag on human-powered vehicles in three major ways. First, they can cut down the amount of energy wasted by the vehicle's interaction with the air. They do it by streamlining (reshaping the front and rear of blunt objects to minimize the pressure drag) and



ı human-powered land vehicles re- e Rover Safety Cycle in England in e Bunau-Varilla of France obtained : similar bicycles set many speed rec- d in Germany in 1914. The Vélodyne was ridden 31.06 miles in one hour (a new record) by Marcel Berth of France in 1933. From the same year is the Rocket, designed by Oscar Egg. Another French vehicle, the Vélocar, set several speed records between 1933 and 1938. Most of the drawings are based on data from the Wolfgang Gronen Archive at Binningen in Switzerlan

by smoothing rough surfaces to minimize skin-friction drag. Second, the amount of air encountered during each second of forward travel can be reduced. This is done by lowering the effective frontal area of the vehicle-rider combination. The same effect can be achieved by riding at higher altitudes. Third, the rider can find air moving in such a way that it provides a tail wind. Here the most effective approach is drafting, that is, riding closely in the wake of another vehicle.

At high altitudes the atmosphere is less dense and bicyclists encounter less air. In Mexico City (elevation 7,414 feet, where the air is only 80 percent as dense as it is at sea level) cycling records are from 3 to 5 percent faster than records made at lower altitudes. At La Paz, Bolivia (elevation 12,000 feet), sea-level



MODERN HUMAN-POWERED VEHICLES make intensive use of streamlining to reduce the aerodynamic drag of the vehicle-rider combination. The simplest is the Zzipper, which is a partial fairing mounted in front of the rider. The Kyle Streamliner dates from 1973. A design that is meant for touring and commuting rather than for racing is the Avatar 2000; it utilizes the advantages of a recumbent position for the rider. The Vector Single, which has a full fairing, is theoretically capable of reaching almost 62 m.p.h. with an input of one horsepower from the rider. The Easy Racer is a recumbent designed mainly for touring or commuting, but it has also been raced. The last vehicle is one of the all-weather recumbents designed by Paul Schöndorf in Germany for elderly and handicapped people.

records could theoretically be improved by 14 percent. On the moon, where there is no atmosphere and only one-sixth the gravitational attraction, a suitably equipped bicyclist could theoretically ride at 238 m.p.h. with a very modest input of .1 h.p.

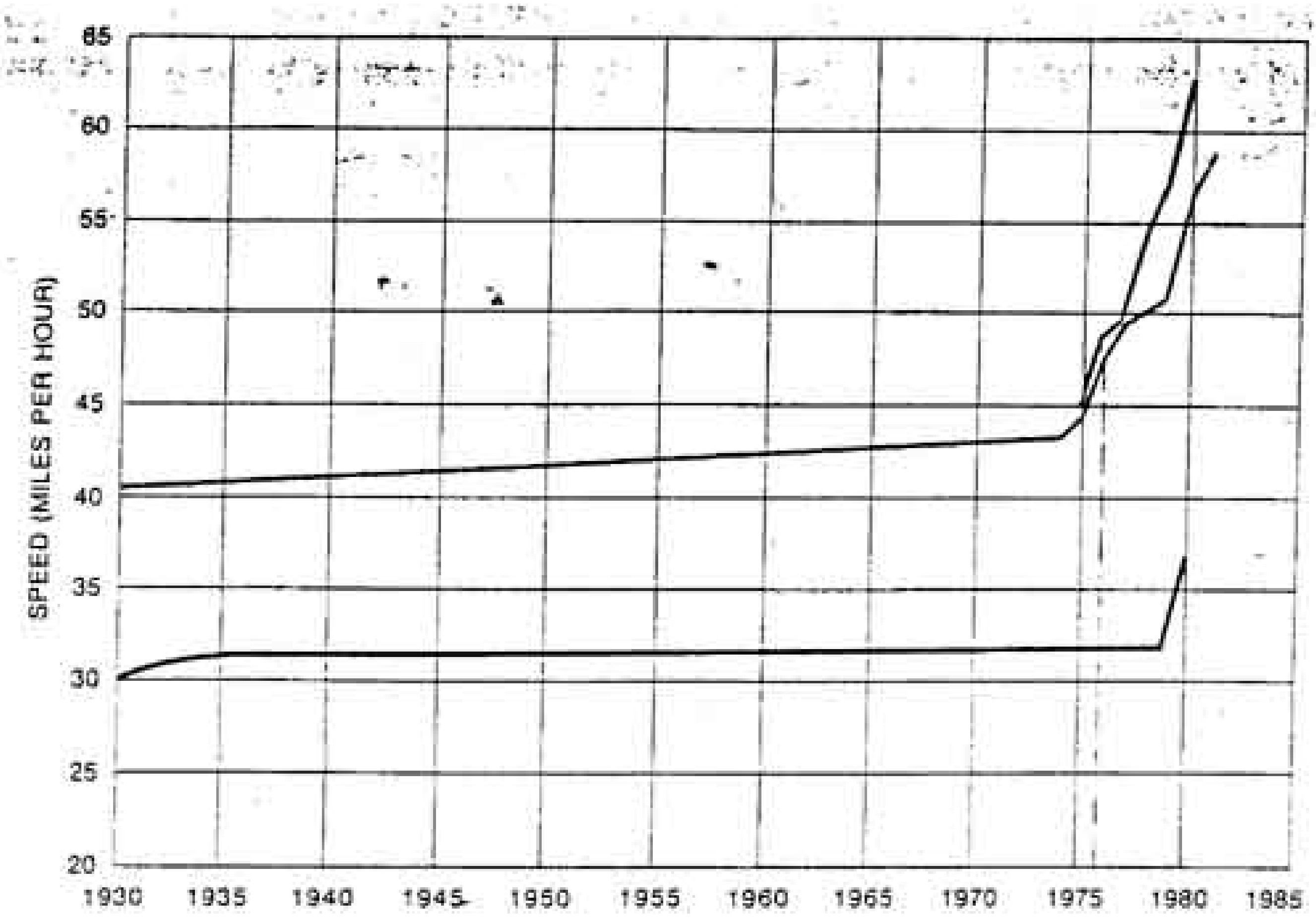
Analyzing the relation in which 80 percent of the power generated by a cyclist traveling on level ground at 18 m.p.h. goes to overcome air resistance, one finds that about 70 percent of the power consumption is due to the air's resistance to the rider and 30 percent to the air's resistance to the bicycle. This finding leads to the conclusion that to improve the performance of the standard bicycle one must first improve the aerodynamics of the rider.

For riders who race, the restrictions of the Union Cycliste Internationale leave little room for improvements beyond what has already been done in adopting the crouched position, the streamlined helmet, the skintight suit and the streamlining of components of the bicycle. As Voigt has calculated, even with a "perfect" bicycle (no aerodynamic drag on the machine at any speed and tires with no rolling resistance) the aerodynamic drag on the rider alone would severely hamper improvements in performance. According to Voigt, a crouched rider on a conventional racing bicycle could reach a maximum velocity of about 34 m.p.h. with a power input of 1 h.p. On a perfect bicycle the same rider making the same effort could achieve 38 m.p.h.

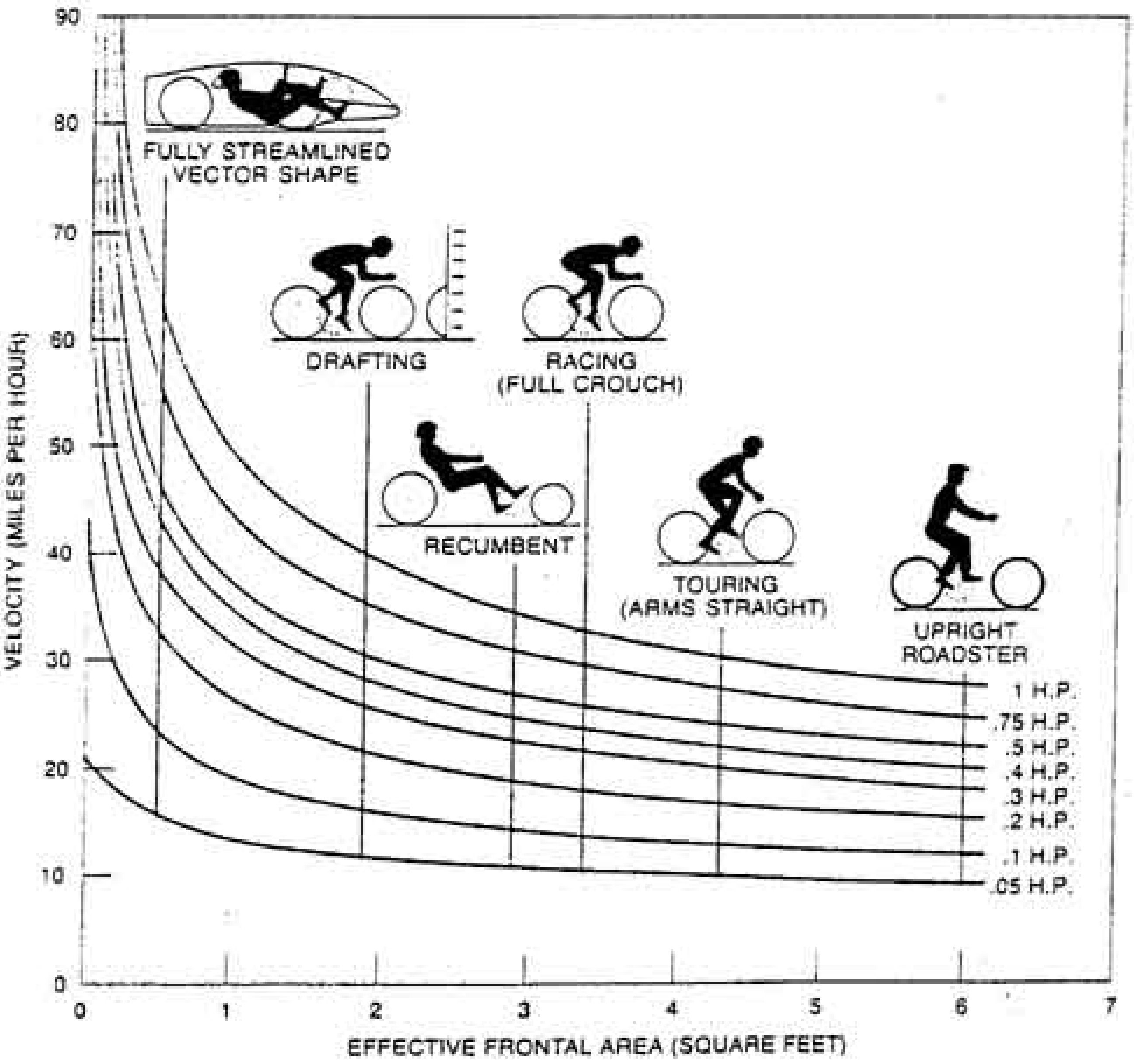
For the millions of noncompetitive cyclists who simply want a more efficient ride, several aerodynamic improvements are possible. They can be ranked in order of cost, beginning with the cheapest: a partial fairing such as the Zzipper, developed and manufactured by Glen Brown of Santa Cruz, Calif. It is a small, transparent, streamlined shield mounted in front of the rider. For about $60 a rider can lower the aerodynamic drag by about 20 percent, achieving a speed increase of some 2.5 m.p.h. for a 1-h.p. input.

Another effective way of reducing aerodynamic drag is to ride a recumbent bicycle. (The machine would cost several hundred dollars more than a basic touring bicycle.) The pioneers in this field are Gardner Martin of Freedom, Calif., designer of the Easy Racer, and David Gordon Wilson of the Massachusetts Institute of Technology, designer of the Avatar 2000. Because of the smaller frontal area presented by the recumbent rider, wind resistance decreases by 15 to 20 percent, resulting in about the same speed increase as is achieved by the Zzipper fairing.

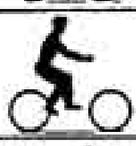
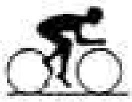
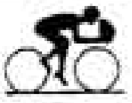
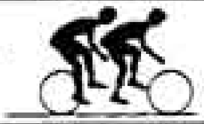
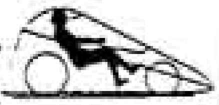
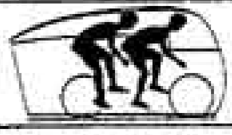
The recumbent bicycle offers other advantages. It is more comfortable to ride than a standard bicycle. In acci-



SPEED RECORDS of human-powered land vehicles have risen rapidly since the formation in 1976 of the International Human Powered Vehicle Association, which puts no restrictions on design. The time of the founding is indicated by the broken line. For many years before then the rules of the Union Cycliste Internationale, which banned streamlined vehicles from sanctioned bicycle competition, had kept speed records virtually unchanged. The curves represent records for multiple riders for 200 meters with a flying start (*color*), single riders under the same conditions (*gray*) and riders who pedaled for one hour at the maximum effort (*black*).



EFFECT OF STREAMLINING is to improve the performance of human-powered vehicles at all levels of power input. The upright roadster is the least streamlined vehicle, the Vector shape the most streamlined. Drafting means to follow closely behind another vehicle, here a bicycle. A good athlete can produce 1 h.p. for about 30 seconds, a healthy nonathlete for about 12 seconds. They can sustain an output of .4 and .1 h.p. respectively for about eight hours. The effective frontal area is the product of the drag coefficient and the projected frontal area.

	DESCRIPTION			FORCES AT 20 M.P.H. (POUNDS)	AERODYNAMIC DATA			ROLLING RESISTAN COEFFICIE
					DRAG COEFFICIENT	FRONTAL AREA (SQUARE FEET)	EFFECTIVE FRONTAL AREA (SQUARE FEET)	
STANDARD BICYCLES	BMX (YOUTH OFF-ROAD RACER)	30-LB. BIKE, 120-LB. RIDER, KNOBBY TIRES, 20-IN. DIA., 40 P.S.I.		5.52 2.10	1.1	4.9	5.4	.014
	EUROPEAN UPRIGHT COMMUTER	40-LB. BIKE, 160-LB. RIDER, TIRES 27-IN. DIA., 40 P.S.I.		6.14 1.20	1.1	5.5	6	.006
	TOURING (ARMS STRAIGHT)	25-LB. BIKE, 160-LB. RIDER, CLINCHER TIRES, 27-IN. DIA., 90 P.S.I.		4.40 .83	1	4.3	4.3	.0045
	RACING (FULLY CROUCHED)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN., DIA., 105 P.S.I.		3.48 .54	.88	3.9	3.4	.003
IMPROVED MODELS	AERODYNAMIC COMPONENTS (FULLY CROUCHED)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.		3.27 .54	.83	3.9	3.2	.003
	PARTIAL FAIRING (ZZIPPER, CROUCHED)	21-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.		2.97 .54	.70	4.1	2.9	.003
	RECUMBENT (EASY RACER)	27-LB. BIKE, 160-LB. RIDER, CLINCHER TIRES, 20-IN. FRONT, 27-IN. REAR, 90 P.S.I.		2.97 .94	.77	3.8	2.9	.005
	TANDEM	42-LB. BIKE, TWO 160-LB. RIDERS, CLINCHER TIRES, 27-IN. DIA., 90 P.S.I.		5.32 2.66 1.62 .81	1	5.2	5.2	.0045
	DRAFTING (CLOSELY FOLLOWING ANOTHER BICYCLE)	20-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 27-IN. DIA., 105 P.S.I.		1.94 .54	.50	3.9	1.9	.003
RECORD HOLDERS	BLUE BELL (TWO WHEELS, ONE RIDER)	40-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 20-IN. FRONT, 27-IN. REAR, 105 P.S.I.		.61 .8	.12	5	.6	.004
	KYLE (TWO WHEELS, TWO RIDERS)	52-LB. BIKE, TWO 160-LB. RIDERS, SEWUP TIRES 105 P.S.I.		1.44 .72 1.12 .56	.2	7	1.4	.003
	VECTOR SINGLE (THREE WHEELS)	68-LB. BIKE, 160-LB. RIDER, SEWUP TIRES, 24-IN. FRONT, 27-IN. REAR		.51 1.02	.11	4.56	.5	.0045
	VECTOR TANDEM (THREE WHEELS)	75-LB. BIKE, TWO 160 LB. RIDERS, SEWUP TIRES, 24 IN. DIA.		.62 .31 1.78 .89	.13	4.7	.6	.0045
THEORETICAL LIMITS	PERFECT BIKE	NO ROLLING RESISTANCE, NO DRAG ON BIKE		3.07 0	.8	3.8	3	0
	DRAGLESS RIDER	ROLLING RESISTANCE INCLUDES RIDER'S WEIGHT		1.33 .81	1.1	1.2	1.3	.0045
	PERFECT RECUMBENT	DRAG ON RIDER ONLY		.72 0	.6	1.2	.7	0
	PERFECT PRONE BIKE	DRAG ON SMALL BUT STRONG RIDER		.51 0	.6	.8	.5	0
	PERFECT PRONE STREAMLINER			.07 0	.05	1.4	.07	0
	MOTOR PACING	42-LB., BIKE, 160-LB. RIDER, MOTORCYCLE ROAD-RACING TIRES, 70 P.S.I.		0 1.21			VARIES WITH SPEED	.006
	MOON BIKE	25-LB. BIKE, 160-LB. RIDER, 15-LB. SPACE SUIT		0 .15			0	.0045

...ND, NO WIND			EFFECT OF HILLS	
HORSEPOWER REQUIRED (PERCENT)	ALL-DAY TOURING	MAXIMUM SPEED	STEADY SPEED UP	STEADY-SPEED COASTING
146	10.1	27.8	12.2	19.8
140	11.3	27.6	10.9	24
100	13.1	31.1	12.2	27.7
77	14.7	33.9	13	31.2
73	15	34.6	13	32.2
67	15.4	35.7	13.1	33.9
75	14.4	35.2	12.5	33.7
66	15.2	36.6	13	35.2
47	17.5	41	13.6	41.7
27	22.5	58.6	12.9	77.4
24	23.3	56.6	14	69.9
29	21.8	61.2	11.3	90.1
23	25.6	72.5	13	108.4
59	16.7	35.9	13.4	34.7
41	18.4	45.8	13.3	50.3
14	27.1	58.3	16.8	66.9
[illegible]	30.4	65.3	23.2	65.3
[illegible]	58.3	125.9	25.6	174.5
[illegible]	29.4	294	12.6	?
[illegible]	37.5	2,375	78.4	?

dents that do not involve an encounter with an automobile it is much safer, since the rider is closer to the ground (making falls less serious) and the feet are forward (making a head injury less likely in a fall). A problem is that a recumbent is hard to see on a road and so is perhaps more vulnerable to automobiles; the problem can be relieved somewhat by mounting on the vehicle a long, thin pole with a flag.

At the top of the expense ladder is a bicycle with a full fairing. The Vector Single, a one-rider version of the Vector Tandem, is the best example of a fully faired, enclosed, pedal-powered vehicle. (It is the machine portrayed on the cover of this issue of *Scientific American*.) According to Voigt, the vehicle is theoretically capable of reaching 61.7 m.p.h. with a 1-h.p. input, an increase of 28.2 m.p.h. over what has been done with a standard racing bicycle. A Vector Single costs about as much as a first-class racing bicycle.

In going up or down a hill a fully streamlined vehicle retains its advantage over a conventional bicycle. Although the Vector Single weighs about 80 pounds, compared with about 25 pounds for a standard bicycle, it can climb moderate hills as fast as or faster than the bicycle. With an input of .4 h.p. a bicycle can climb a 2.5 percent grade at about 16 m.p.h. and a 6 percent grade at about 11 m.p.h. With the same input the Vector can climb the two grades at 20.5 and 11 m.p.h. respectively.

Downhill the difference between the two machines is remarkable. The bicycle can descend a 2.5 percent grade at 29.5 m.p.h., the Vector at 54. On a 6 percent grade the bicycle can reach a speed of 39 m.p.h. and the Vector can exceed 100. Such potential speeds mean that if streamlined human-powered vehicles become common, careful attention must be given to the design of brakes and suspension and to the stability of the vehicle.

Since the aerodynamic drag force is proportional to the square of the relative velocity, head winds, tail winds and even crosswinds can drastically change both aerodynamic drag and the power requirements. For example, a bicyclist going at 18 m.p.h. in still air must increase his power output by 100 percent to maintain that speed against a head wind of 10 m.p.h. Usually a bicyclist confronting a head wind slows down and tries to maintain his customary leg force and pedaling cadence by shifting gears. This is one reason bicycles with multiple gears are desirable even for level country.

A tail wind makes the bicyclist go faster with his customary input of power. In general moving air will speed up or slow down a bicycle by about half the wind speed. When one bicyclist rides in the wake of another, the power requirements of the drafting rider are reduced by about 30 percent. The forward bicyclist creates an artificial tail wind.

The closer the rear bicycle follows the leader, the more pronounced the drafting effect is. One can think of the rear rider on a tandem bicycle as drafting extremely closely. Tandem riders use 20 percent less power per rider than two separate cyclists.

When the riders in a line of drafting bicyclists take turns in the lead position, the entire group can travel much faster than a single rider. In a pursuit race of 4,000 meters (almost 2.5 miles) a four-rider team can go about 4 m.p.h. faster than a single bicyclist. Typically a group of bicycle tourists of equal ability can travel from 1 m.p.h. to 3 m.p.h. faster than any rider alone. The larger the group is, the faster it should be able to travel (up to, say, a dozen riders).

Artificial winds created by passing automotive traffic can increase a bicyclist's speed from 1 m.p.h. to 3 m.p.h. for periods of about seven seconds. The larger the passing vehicle, the more substantial the effect. A steady stream of traffic can enable a bicyclist to sustain a speed from 3 m.p.h. to 6 m.p.h. higher than would otherwise be possible for a given energy input.

When a bicyclist rides directly in the wake of a motor vehicle, quite remarkable speeds can be attained. The practice is called motor pacing. On August 25, 1973, Allan V. Abbott, a physician in California, achieved a record of 138.674 m.p.h. motor pacing along a measured mile at the Bonneville Salt Flats in Utah. John Howard, a U.S. Olympic cyclist, is attempting to break Abbott's record and to achieve a motor-pacing speed in excess of 150 m.p.h.

Although the findings we have described are significant in their own right, one wonders if they will have any practical application beyond their effect on speed records. For a large fraction of the world's bicycle riders it seems unlikely that the work will have much immediate utility. For example, in the

PERFORMANCE OF HUMAN-POWERED VEHICLES is summarized. The numbers listed under forces for each vehicle represent air resistance and rolling resistance respectively. The five columns at the far right represent respectively the horsepower required at 20 m.p.h. as a percentage of the touring rider's performance; the all-day touring speed in miles per hour at an output of .1 h.p.; the maximum speed at an output of 1 h.p.; the steady speed in miles per hour up a 5 percent grade at an output of .4 h.p., and the coasting speed down the same grade.

many developing countries where the bicycle is the chief means of transportation most riders travel at about 7 m.p.h., often with a substantial load; aerodynamic drag becomes more important than other impediments to bicycle motion only at speeds above 10 m.p.h. Even here the work on aerodynamics makes a contribution. Without it designers would not know why they should largely ignore aerodynamics for slow-moving human-powered vehicles.

For bicycles intended for slow but sure progress it makes sense to decrease rolling resistance by improving tires and by paving roads. Designers should also reduce the bicycle's weight to facilitate climbing hills. The recent introduction of "mountain bikes" in the U.S. is a step in the direction of making lightweight bicycles durable enough for rugged or unpaved roads.

In several ways the knowledge gained by the recent research on the aerodynamics of human-powered vehicles can be directly useful. Although the standard bicycle is likely to be the predominant representative of the class for many more years because of its public acceptance, low cost, simplicity and mechanical reliability, it offers plenty of scope for innovation. For example, a light, simple and inexpensive front fairing will substantially improve the performance of the standard bicycle. The recumbent bicycle may come into greater use by commuters and tourists because of its efficiency and comfort.

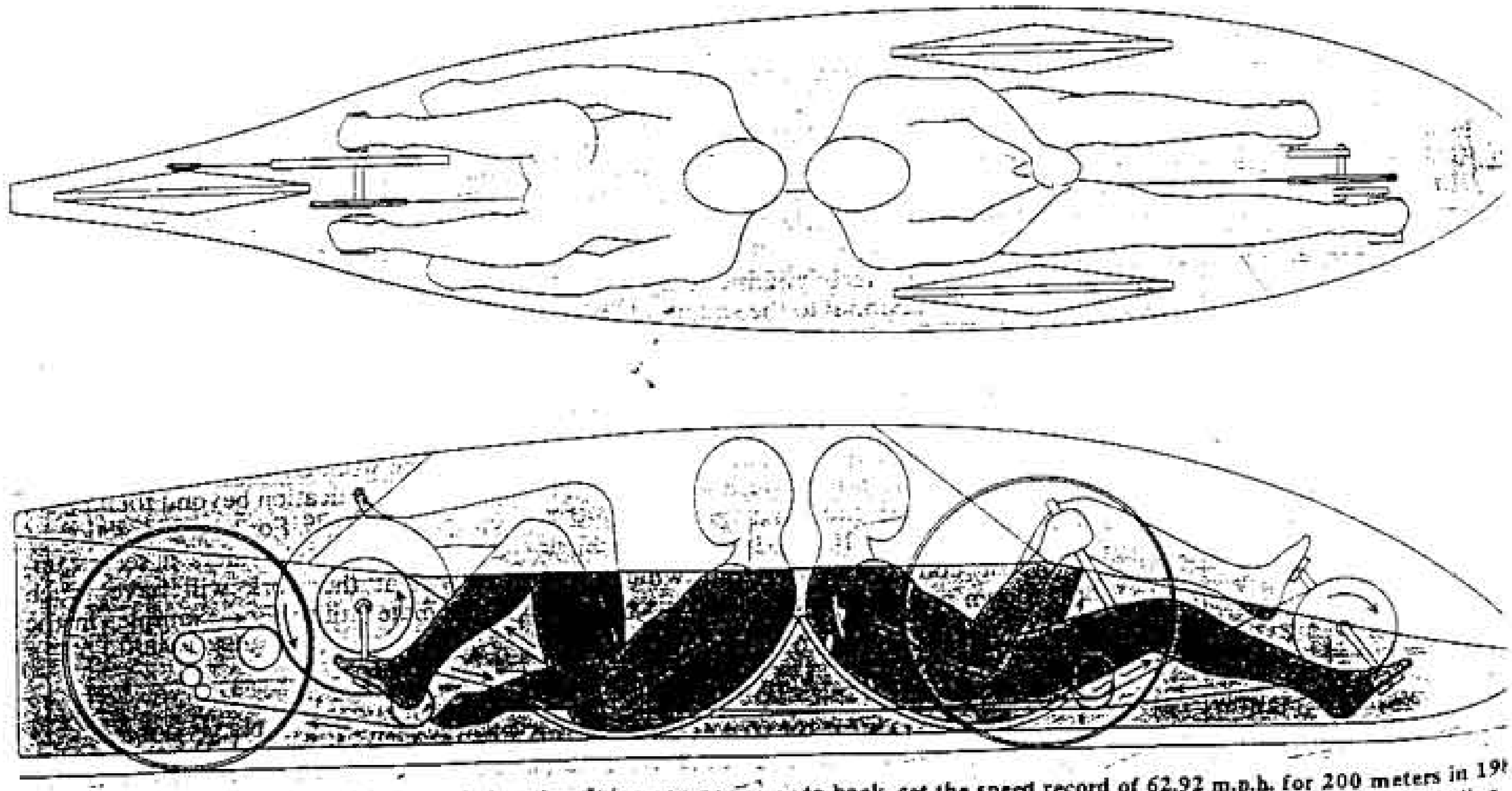
A further application of the technology would be to fit a recumbent with a small, lightweight motor of low horsepower. The motor would serve mainly as an aid in accelerating from a stop and in climbing hills. Fitted also with as much streamlining as would be consistent with the need for ventilation and stability, the machine would be a true moped. (The machines now sold under that name are not really motor-pedal vehicles but merely underpowered motorcycles.)

The recent research has inspired inventors to develop several special-purpose human-powered vehicles. Paul Schöndorf, a professor of engineering at the Fachhochschule in Cologne, has built a series of easily pedaled, all-weather recumbent tricycles for the elderly and the handicapped. Similar vehicles would serve well in retirement communities. Douglas Schwandt of the Veterans Administration's Rehabilitation Engineering Research and Development Center at Palo Alto, Calif., has built hand-cranked tricycles and bicycles for paraplegics. William Warner, a paraplegic who once held the record for hand-powered vehicles in the races sponsored by the International Human Powered Vehicle Association, says a disabled person can propel such a vehicle much faster than a standard wheelchair and thereby can gain a new sense of freedom and mobility. (The present record of 25.09 m.p.h. was set in 1981 by Ascher Williams of the Palo Alto rehabilitation center.)

In principle a fully enclosed, streamlined human-powered vehicle could be quite useful in transportation. A rider could travel at speeds of from 20 to 3 m.p.h. in all kinds of weather. As su vehicles are now designed, howeve they would not serve on the open roa They lack adequate ventilation, visib ity, maneuverability and such safe features as lights and windshield wi ers. Most of them are not easy to g into or out of.

To produce a practical vehicle of th kind would require an investment an an engineering effort comparable to th made in producing a new automobil Even then the pedaled vehicle would n be safe in traffic that included a lar number of motor vehicles. One mu conclude that a fully enclosed huma powered vehicle will not be a practic form of transportation until fuel shor ages remove most motorized vehicl from the roads or until special roadw are built for pedaled machines.

Far likelier is the development lighter and more fuel-efficient autom biles employing much of the technolo we have described. One of us (Ma wicki) has already built such a ve cle, a single-passenger machine weig ing 230 pounds. It holds records for fu economy at the freeway speed of m.p.h. with a gasoline engine (15 miles per gallon) and with a diesel e gine (156.3 m.p.g.). The diesel reco was set on a trip from Los Angeles Las Vegas, during which the avera speed was 56.3 m.p.h. A trend towa such vehicles could help to extend fu resources and ironically might postpo the time when the human-powered ve cle will have come fully into its own.



VECTOR TANDEM is shown in plan and elevation. It is a companion vehicle to the Vector Single portrayed on the cover of this issue of SCIENTIFIC AMERICAN. The Tandem, receiving an input of a bit more than 1 h.p. from each of its two riders, who are positioned back to back, set the speed record of 62.92 m.p.h. for 200 meters in 19 (The riders had a flying start of more than one mile.) Traveling an interstate highway in California later that year the Vector T dem managed an average speed of 50.5 m.p.h. on a trip of 40 mil