

# HUMAN POWER

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## HUMAN POWER

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## CONTENTS

### Design and development of a human-powered machine for the manufacture of bricks

J. D. Modak and S. D. Moghe demonstrate two important characteristics in this report on brick-making in India. One is that human power can be used for tasks that take, for a short time, far more power than one person can produce. It can be done through energy storage, in this case a fly-wheel. The second is that human-powered brick production is economically viable and socially desirable.

### Tip-over and skid limits of three- and four-wheeled vehicles

Dietrich Fellenz first analyzes the conditions for tip-over and skid limits for multi-track vehicles, and then produces two useful charts that can be used for vehicle or roadway design.

### Energy and equity and human power: Ivan Illich reviewed

An admirer of Ivan Illich, John Snyder, summarizes a 1973 essay he wrote, and relates it to conditions a quarter-century on, particularly with respect to the future of human power. Theo Schmidt adds observations about the viability of an automobile-centered culture.

### The stiffness of tubes of various configurations and materials

"Mr. Z" - John Zabriskie - discusses this topic, of great interest to builders of HPVs, dispassionately and in places provocatively. He shows us that sometimes what seems obvious is not necessarily true.

### Aerodynamic drag components

Goro Tamai gives us a primer on the drag of ultra-streamlined vehicles. Surface area rather than frontal area becomes dominant, something overlooked by many designers of HPV "streamliners".

## TECHNICAL NOTES

### Oxygen uptake, recumbent vs. upright

Mark Dreila reminds us of work that showed that there is no difference in power produced by athletes pedalling in the upright or recumbent positions.

What is amazing to this editor is the range of efficiencies among athletes: a range of 18% to 33.7% was found. A similar wide range was measured for the percentage of the maximum oxygen uptake that could be tolerated before lactate built up, shutting off further power production. Some athletes could tolerate 90%, others only 60%.

### Dynamic model of a rear suspension

Jobst Brandt tries to discourage people from making simple models of systems as complex as riders on a bicycle with suspension.

### Maximum human power vs. duration of effort

Your editor has been plotting people's performances in pedalling and rowing and has updated the curves of steady power output vs. duration.

### Transmission efficiency

Your editor discusses a report that chain transmissions have efficiencies over 99%.

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Your editor reviews HPV-related papers from volumes 28-30 of the *Journal of Biomechanics*.

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An analogy between the campaign for nonsmokers' rights and a campaign we would like to have for HPV rights; safety considerations for drivers of motor-vehicles and of HPVs; and the launch of a mainstream recumbent magazine.

## CONTRIBUTIONS TO HUMAN POWER

The editor and associate editors (you may choose with whom to correspond) welcome contributions to *Human Power*. They should be of long-term technical interest (notices and reports of meetings, results of races and record attempts, and articles in the style of "The building of my HPV" should be sent to HPV News). Contributions should also be understandable by any English-speaker in any part of the world: units should be in S.I. (with local units optional), and the use of local expressions such as "two-by-fours" should be either avoided or explained. Ask the editor for the contributor's guide. Many contributions are sent out for review by specialists. Alas! We are poor and cannot pay for contributions. They are, however, extremely valuable for the growth of the human-power movement. Contributions include papers, articles, reviews and letters. We welcome all types of contributions, from IHPVA members and nonmembers.

# DESIGN AND DEVELOPMENT OF A HUMAN-POWERED MACHINE FOR THE MANUFACTURE OF LIME-FLYASH-SAND BRICKS

by J.P.Modak and S.D.Moghe

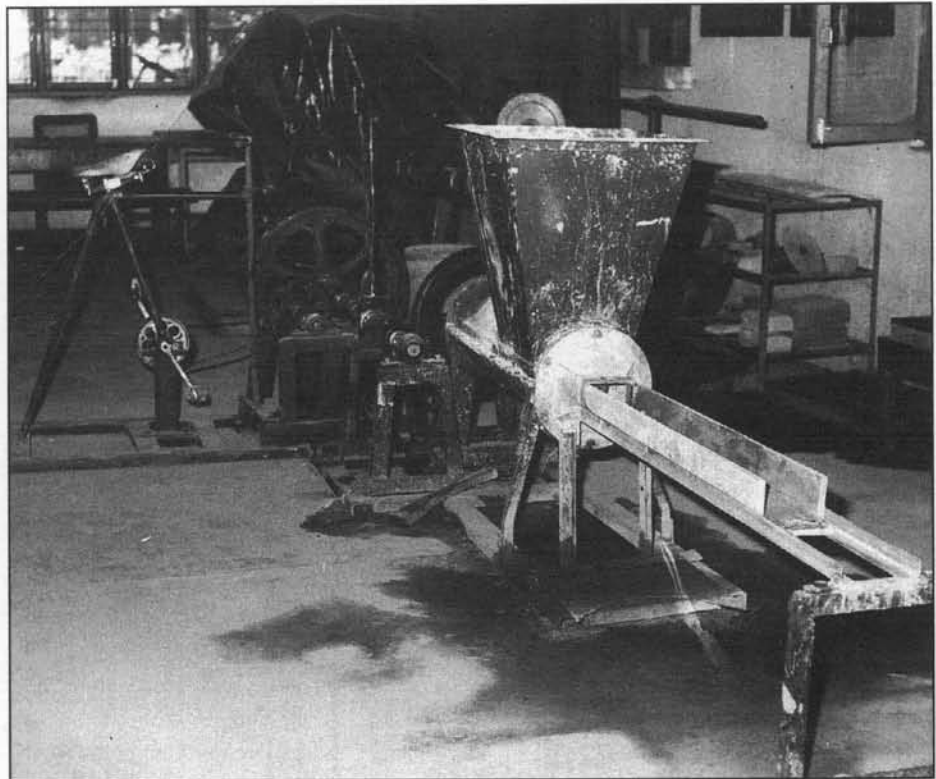
*A human-powered brick-making machine has been designed and developed. The machine uses the human-powered flywheel motor as an energy source, consisting of a bicycle mechanism, a pair of speed-increasing gears and a flywheel. This kind of intermediate mechanism is helpful in driving various rural operations utilising unskilled workers. The design and working details of the brick-making machine are described. The machine is economically viable.*

*This machine concept can be adopted for human-powered process units needing more than 2kW short-term power and which could have intermittent operation without affecting the end product. Water-lifting, wood-turning, wood-cutting, potter's wheel and algae formation processes have been energised using such a machine concept.*

## A NEED FOR A HUMAN-POWERED BRICK-MAKING MACHINE

The housing needs of under-developed countries in general and India in particular are growing at a fast rate. The shift of population from rural to urban areas has further aggravated the problem. In order to solve this housing shortage there is a need for innovations not only in building technology but also in materials to be used. The quantity of material required is of such magnitude that unless positive efforts are made for finding resources to match the requirement, no worthwhile purpose will be served. Thus the gap between houses required and the houses available will continue to increase.

The skilled workers required for meeting the shortage of housing in India and other under-developed countries in general itself is of such magnitude that the problem of getting the required number of masons and skilled workers is impossible to tackle, even if all available skilled manpower in the building trades were transferred to meet the shortage in housing. The problem is still exacerbated by the emigration of skilled workers to middle-east countries. There is a need on the other hand for utilising the unemployed and unskilled population of the under-developed countries in solving this housing problem, especially when we consider the



Brick-making machine

non-agriculture part of the year when unskilled workers in sufficient number could be available for construction purposes.

Similar observations also hold good for slum clearance in the cities. The major component of construction in conventional technology is brick. A good quality of earth for making bricks is available only in the river beds: this material is auctioned by revenue departments every year, and the cost is increasing continually. Even then the quality of bricks that is available is not always satisfactory.

Moreover, the manufacture of bricks requires a considerable amount of coal: it is estimated that for every 100,000 bricks that are made about 16 tons of coal are required. As far as India is concerned the problem of brick-making is more complicated since the workers for making these bricks is available from particular areas and they are available only after the harvesting of crops. Other workers are not used for this purpose since their productivity is low and the wages to be

paid are high. Due to the floating population of workers involved in brick-making, all brick manufacturers are very reluctant to make major investments in brick-making machinery that will need manning year 'round and attract all provisions of the labour laws.

In view of the foregoing discussion, there is a need for intermediate mechanisation in brick-making to get consistently good-quality bricks that are within a tolerable limit of sizes, utilising as far as possible unskilled workers available in plenty everywhere, by making them work with machines that require only physical effort. To reduce the power consumed in brick-making as well as in brick-burning, the machine should preferably be human-powered and require little maintenance.

With the above points in view, a bicycle-operated machine was designed and developed 1979-82 (Modak) that energised a flywheel to extrude a long-enough brick column to yield an average four to five bricks in one energisation of the flywheel. This paper details the design and

development of this machine. Further attempts have been made to produce bricks without using soil. This has been possible by utilising a mixture of lime, flyash and sand, or only lime and flyash, for the production of bricks. This solution is beneficial because the present brick manufacture spoils the landscape by producing soil deposits and creating pits wherever brick fields are in operation. This process, by contrast, converts a harmful by-product of thermal power stations, namely flyash, into useful building material.

### BASIC CONCEPT OF THE MACHINE

On average, the power produced by a man is approximately 75W (0.10 hp) (Alexandrov, 1981), if he works continuously. Therefore human power may be used for a process if the power requirement is a maximum of 75W. If process power requirement is more than 75W and if the process can be of an intermittent nature without affecting the end product, a machine-system can be developed that stores energy. Figure 1 describes the schematic arrangement of the proposed machine.

Essentially, the machine consists of three sub-systems: (1) the energy unit, (2) appropriate transmission, and (3) the process unit. The energy unit consists of a conventional bicycle mechanism, a pair of speed-increasing gears  $G'$  having a speed-rise ratio  $G'=2.4$  and a flywheel. The transmission consists of a single-jaw spiral clutch (William, 1953) and the torque-amplification gear pair  $G$  having torque-

amplification ratio  $G=4$ . For brick manufacturing, a process unit PU consists of an auger, and a cone and die, conventionally used for motorised brick-extruders for the manufacture of clay bricks (Searl, 1955).

The suggested machine system uses human energy achieved by pedalling and stores this energy in a flywheel at an energy-input rate convenient to the pedaller. After storing the maximum possible energy in the flywheel (pedalling time could be 1–2 minutes) the same can be made available for the actuation of any process unit by making available the energy stored in the flywheel through a suitable clutch and torque-amplification if needed. Thus the flywheel will decelerate depending on the actual resisting torque offered by the process. It implies that the pedaller does not pedal while the flywheel is supplying energy to the process-unit.

### AVAILABILITY OF DESIGN DATA FOR THE PROPOSED MACHINE

The literature search we made did not produce data regarding what should be the numerical value of  $G'$  and the moment of inertia of the flywheel so that this man-machine system could store maximum energy in the flywheel for the shortest possible pedalling time. Obviously we wanted the most compatible system with the minimum possible internal human-energy loss. Thus no design data were available for the energy unit. We called this unit a "Human-Powered Flywheel Motor" (Modak & Bapat, 1987).

Upon engagement of the clutch there is a rapid transfer of momentum and kinetic energy between the energy unit and the process unit. The process unit input shaft is thus instantaneously accelerated and, after reaching the maximum speed, is subjected to deceleration. This deceleration is induced by the resistance offered on account of extrusion of lime-flyash-sand paste contained in the extruder. Thus the process unit input shaft is in a transient state of motion (rigid-body angular velocity of the auger is changing). The literature available as far as design of an extruder is concerned pertains only to the manufacture of clay bricks using a motorised machine wherein an auger shaft is always in a steady state of motion. The literature search did not provide any information regarding horse-power requirement, optimum auger speed, details of geometry of blade, cone and die for such an extruder for manufacturing lime-flyash-sand, or only lime-flyash, bricks. Thus no design-data was available for the process unit nor for a single-jaw spiral clutch and torque-amplification gears. (Here the emphasis is on severity of initial mechanical shock and its associated severe adverse effects such as excessive stressing of the system under severe impact, random vibrations and rapid wear).

In view of the foregoing the main parameters and dimensioning of the components were decided essentially based on intuition and general past mechanical design experience. Accordingly the machine is designed and is described in figure 2. A photograph of this machine is given on page 3.

### MECHANICAL DESIGN OF THE MACHINE

The machine has a die (1; see figure 2) that is bolted to the conveyor drum (2). The die has a variable cross-section, convergent near the conveyor-drum end to compact the material and to prevent rotation in the die, while a subsequent uniform section gives the desired shape to the column. The material is fed through the hopper (3).

The detachable mould (4), lined from inside by acrylic material to minimise friction, is kept level and in contact with a die on the mould stand. (5). The mould can be lifted or pulled from the stand.

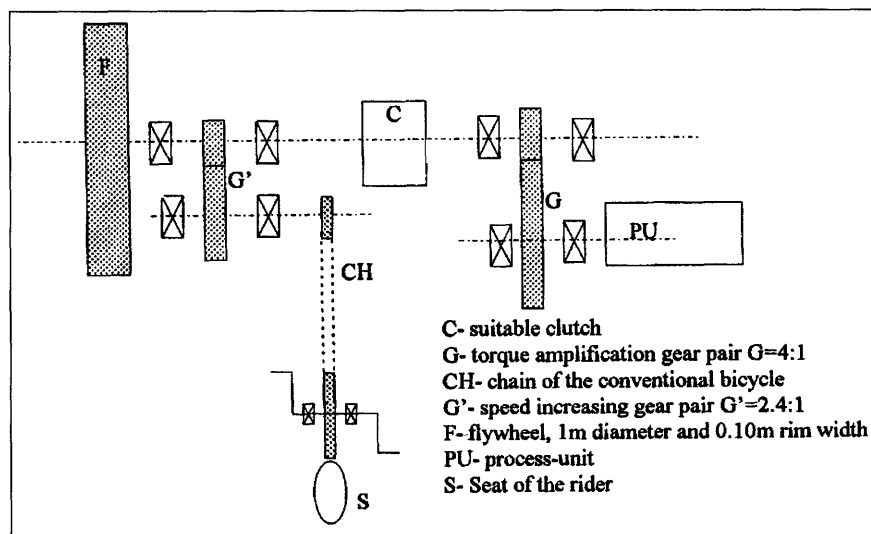
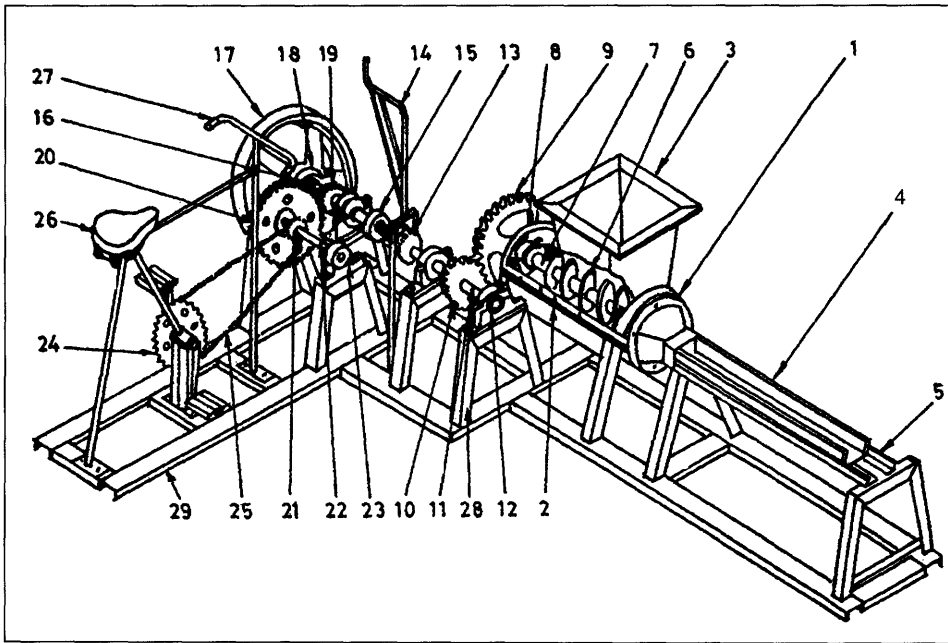


Figure 1. Plan view of the schematic arrangement of the machine



**Figure 2. Mechanical parts of the machine**

1. Die 2. Conveyor drum 3. Hopper 4. Wooden mould 5. Mould stand 6. Screw conveyor
7. Conveyor shaft 8. Bearing 9. Gear I 10. Pinion 11. Pinion shaft 12. Bearing 13. Movable jaw of clutch 14. Clutch lever 15. Fixed jaw of clutch 16. Flywheel shaft 17. Flywheel 18. Bearing 19. Pinion II 20. Gear II 21. Free wheel 22. Intermediate shaft 23. Bearing 24. Chain wheel
5. Roller chain 26. Driver's seat 27. Handle 28. Bracket 29. Frame

The screw-conveyor (6) is mounted on a conveyor shaft (7). The shaft is supported by two bearings (8) outside the conveyor drum. Gear I (9) is mounted on the conveyor shaft between two bearings. Pinion I (10) which meshes with gear I is mounted on a pinion shaft (11), between two bearings (12). The left overhang of the pinion shaft is splined and takes the movable half of the clutch (13). Axial movement of clutch is possible using the lever (14).

The fixed half of the clutch (15) is keyed to the flywheel shaft (16) which is supported by two bearings (18). The flywheel (17) was readily available in a market of old machine parts. This flywheel is mounted on the shaft at the extreme left. Gear pair II (19 and 20) is mounted between the flywheel shaft and an intermediate shaft on which the rear sprocket (21) of the bicycle chain drive is mounted. Thus, the total speed-rise ratio between the bicycle driving crank and the flywheel is kept at 6.24. Out of this, the chain drive provides a speed-rise ratio of 2.6 and the remainder is provided by gear pair II (same as G' described in figure 1). The crank, chain wheel and pedal assembly

is identical to the one used for the bicycle. An existing bicycle frame is used to provide seat and handle support. Specifications of the major machine parts are described in table 1.

A spiral jaw clutch is used because it is expected that this type of clutch is likely to consume less energy for its own operation as compared to the friction clutch (Chavan, Shukla & Kamble, 1983). In order to ensure that the energy does not flow from the flywheel to the driving pedals after the clutch is engaged, it is necessary to have a one-way clutch between the driving pedals and the flywheel.

### MANUFACTURING PROCESS

The complete process of manufacturing bricks has two stages:

- (1) manufacture of columns of the paste of brick ingredients with water, and
- (2) conversion of these columns into bricks. The proposed machine manufactures the columns.

### Working of the machine

A properly prepared mixture of dry ingredients with water is poured through hopper (3) into the conveyor drum (2) of the screw conveyor. The water content may be 25–30% by weight of dry mixture.

A person pedals the mechanism for about a minute with the clutch in the disengaged position. In this time the flywheel of about 1m diameter and 0.1m rim width can be accelerated from rest to about 700–800 rpm. During pedalling he has to overcome only the inertia of the flywheel. The operator pedals for about one and a half hours before wishing to have a change of activity or some food or drink. (He gets a rest period of 6–10 seconds between two consecutive extrusion operations.)

After attaining the pre decided maximum flywheel speed pedalling is stopped. The clutch is immediately engaged and the energy stored in the flywheel is made available to the process unit through the clutch and the torque amplification gears G. The clay extrusion immediately commences upon the clutch engagement and it continues for 6–10 seconds, until such time as the flywheel comes to rest. A clay column about 1.3m

**Table 1. Specifications of major machine parts**

No.	Name of component	Major dimensions (mm)	Material
1.	Intermediate shaft	Length=740, max. diam=52	SAE 1030 mild steel
2.	Flywheel shaft	Length=740, max. diam=72	SAE 1030 mild steel
3.	Conveyor shaft	Length=1030, max. diam=68	SAE 1030 mild steel
4.	Flywheel	Outer diam=1000, rim width=100, No. of arms=6, hub diam=100, wgt=50kg	Cast iron
5.	Pinion I	PCD=190, face width=50, No. of teeth=24	Cast iron
6.	Gear I	PCD=455, face width=50, No. of teeth=91	Cast iron
7.	Pinion II	PCD=130, face width=55, No. of teeth=24	Cast iron
8.	Floating gear	PCD=533.5, face width=55, No. of teeth=97	Cast iron
9.	Clutch	Length of one-half=118, mean diam=67	Cast steel
10.	Conveyor screw	Outer diam=180, pitch=160, Helix angle=23°	Mild steel
11.	Bearings	Intermediate shaft flywheel shaft conveyor shaft	6008 6409 6312



**Table 2. Performance of human-powered brick-making machine for different mixes and their composition**

Sr. No.	Composition by weight	Cross section mm x mm	Max speed of flywheel (RPM)	Column length (m)	Extrusion time (sec)	Strength without baking, kgr/mm <sup>2</sup>	MN/m <sup>2</sup> MPa	Horse-power (hp)	KW
1.	River clay + sand (1:1)	90 x 90	750	0.70	10	0.27	2.65	1.95	1.45
2.	Black cotton soil+flyash+sand (1:2:1)	90 x 90	750	1.04	5	0.205	2.01	3.90	2.91
			650	0.72	7.5			9.95	1.45
			550	0.70	10			1.05	0.783
3.	black cotton soil+flyash+sand (1:1:2)	90 x 90	750	0.53	10	0.205	2.01	1.95	1.45
			650	0.30	15			0.98	0.73
			550	0.25	30			0.35	0.26
4.	Lime+flyash+sand (1:2:4)	90 x 90	750	0.90	7	0.70	6.9	2.79	2.08
		90 x 90	450	1.00	13	0.42	4.1	0.54	0.40
5.	Lime+flyash+sand (1:2:4)		750	0.75	7	-	-	2.79	2.08
6.	Lime+flyash (1:1)	90 x 90							
			450	0.90	15	0.40	3.9	0.47	0.35
			450	0.90	15	0.20	2.0	0.47	0.35
			450	0.90	15	0.15	1.5	0.47	0.35

long is obtained at the end of the extrusion. The extrusion time depends on the type of clay, the flywheel terminal speed, and the size and shape of the cross sections of the die. The machine has been tried for extrusion of various clays, various die cross sections and various flywheel terminal speeds at the end of the pedalling. Table 2 provides information about these trials.

**Conversion of brick column into bricks**

Sometimes the extruded column might have a bulge, which must be removed by pressure from a flat plate before the column is detached from the mixture in the die. The mold is then taken manually to a column-curing platform and demoulded. Immediately after demoulding, a column is not enough stiff to be cut. After about one hour, however, it becomes stiff enough to be cut into bricks of standard length of 200mm. On an average in one cycle of operation of the machine (total cycle time being maximum 70 seconds), 6-7 bricks are manufactured.

These bricks are cured by sprinkling water on them or by covering them with a damp cloth for 28 days. During the process of curing they undergo a low-temperature cementing reaction which imparts fairly high strength and water-absorption resistance to these bricks. Therefore it is necessary to provide a storage facility for 30x1500 (= 45,000) bricks before they are fully prepared for sale. Additional land or proper storage racks for vertical storing of these bricks may also be needed. Fifty columns can be accommodated on one curing platform 6m long and 1m wide.

A team of five unskilled workers is required for performing various manual operations of this kind of brick making. Out of these five, one pedals the flywheel, two remove the bulge from the column, detach the mould, lift the mould from the stand and carry the mould to the curing platform on which moulds are demoulded. The remaining two bring the prepared mixture to the machine hopper.

**ECONOMIC VIABILITY**

This machine was operated for one month by a team of five workers on an eight-hour shift. The actual time of machine operation was five and one-half hours a day. The team was required to perform several other supporting operations such as preparation of the mixture for the next day, curing of bricks manufactured earlier, shifting of one-day-old bricks from the curing platform to the storing stack, maintenance of the machine, and maintenance of the factory (i.e.,

premises, housing, machine and other accessories described earlier). These operations needed two and one-half hours per shift. During the first week of machine operation, the number of bricks manufactured were 400 per day; this output increased steadily to 1000 bricks per day in the last week of machine operation. This steady increase in production level was on account of proper synchronization of various human activities which a team of five workers is required to perform every day. There was a learning process about the manufacturing activity as the teammates continued to work together on the process. The production level would increase with experience. The machine capacity is about 2000 bricks per day, so that a further increase in production level with experience would be expected.

A machine site can therefore be considered to be a small factory comprising a machine, enough vertical brick storing racks, curing platforms, enough space for storage of raw material, etc.

The cost of manufacturing of lime flyash sand bricks was calculated for various locations in Vidarbha (a region in Maharashtra state of India). These locations were comprised of (1) a state industrial development corporation of a very big town like Nagpur, (2) a state industrial development corporation of district places like Bhandara, and locations near raw materials like Rajura (near the lime quarries), Chandrapur (near 1200-MW thermal power station producing an abundance of flyash) and on the bed of river Kanhan (nearness of sand). A detailed breakdown of cost is given in table 3, based on a production of 1000 bricks per day.

The current selling price is Rs.1.15 per

**Table 3. Total cost of manufacture of lime-flyash-sand brick**

Plant location	Cost of material per brick (NP)				Labour charges (NP)	Depreciation (NP)	Recovery of investment w/ interest (NP)	Total manufacturing cost (NP)	Remarks
	Lime	Flyash	Sand	Total material					
Nagpur M.I.D.C.	34.00	5.00	8.00	47.00	7.00	1.00	5.00	60.00	
Bhandara M.I.D.C.	35.00	6.00	4.00	45.00	7.00	1.00	4.00	57.00	
Chandrapur M.I.D.C.	34.00	18.00	4.00	56.00	6.00	1.00	4.00	67.00	*After getting flyash locally
		*2.50		*40.50				*50.00	
Rajura	30.00	19.00	4.00	53.00	6.00	1.00	4.00	64.00	*After getting flyash at Chandrapur
		*5.00		*39.00				*50.00	
Koradi	34.00	2.50	4.00	40.50	6.00	1.00	4.50	52.00	
Kanhan	35.00	6.00	1.00	42.00	6.00	1.00	6.00	53.00	

brick. This implies that on an average the monthly earning of the entrepreneur of this small-scale factory manufacturing lime fly-ash sand bricks or lime flyash bricks is at least Rs.10,000/month. The average earning of a middle-class person in the nearby locality is around Rs.7000 per month. This establishes the economic viability of the proposal for human-powered brick manufacture. Further, this also justifies the development of a human-powered process machine needing a power requirement far in excess of human capacity in continuous operation in general and of a human-powered brick-making machine in particular.

### OTHER APPLICATIONS

After establishing the functional feasibility and economic viability of this first attempt at developing a human-powered machine for brick manufacture (1979–82), several other rural applications of this kind of flywheel motor as an energy unit have been tried for water lifting (Bapat, 1992), wood turning (Modak & Bapat, 1993), wood cutting (Modak et al, 1993), potter's wheel (Dhakate et al 1995), and algae manufacturing (Katpatal et al, 1994). For each of these applications an intuition-based design of a process unit was used. These applications also proved to be functionally feasible and economically viable.

### FURTHER DEVELOPMENT

After developing this first human-powered machine (1979–82) for the manufacture of lime-flyash-sand bricks, Modak and his associates worked on further development of this concept of the use of human-powered energy source for feeding power to various applications needing power far in excess of human continuous capacity.

These developments are towards (1) generating design data for human-powered flywheel motors (Modak & Bapat, 1994), (2) generating design data for clay extruders for lime-flyash-sand bricks (Modak & Askhedkar, 1994), (3) generating design data for development of a torsionally flexible positive clutch subjected to frequent on/off cycles (Modak et al 1990; Modak & Pattiwar 1997; Modak & Gupta 1997; Modak et al 1997; Modak & Deshmukh, submitted). (It is envisaged that this type of clutch will permit gradual energy

transfer from the flywheel to the process unit avoiding frequent breakdowns of the presently-used spiral jaw clutch), (4) development of cranking arrangement (Moghe 1993; Modak & Moghe 1997), and (5) establishing the manufacturing feasibility and economic viability of keyed brick (Sohoni et al).

It is also necessary to generate design data for various applications such as (1) water lifting, (2) wood turning, (3) wood cutting, (4) potter's wheels, and (5) algae manufacturing.

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## TIP-OVER AND SKID LIMITS OF THREE- AND FOUR-WHEELED VEHICLES

by **Dietrich W. Fellenz**

### ABSTRACT

Knowing the safe performance envelope of one's vehicle is a pre-condition for successful riding. This paper analyses the forces acting on a vehicle in a steady turn, and determines the minimum turning radius for skidding and the effect of CG-location on tip-over. The equations are developed for the general four-wheeler, which includes the three-wheeler. The vehicles are described in terms of wheel configuration, front and rear track and wheelbase, as well as CG-height and setback. Vehicle tip-over and skid limits are determined and presented in non-dimensional form for application to any sized vehicle.

### SYMBOLS AND DEFINITIONS

- tf, tr tracks of front and rear axles, resp., [m]
- b wheelbase, [m]
- x<sub>cg</sub> CG setback from reference axle, [m]
- h<sub>cg</sub> CG height over road, [m]
- d lateral CG offset, normal from outside tire contact line, [m]
- V driving speed, [m/s]
- μ tire friction coefficient, [/]
- r radius of turn, [m]
- φ angle between tire contact line and vehicle center line, [deg]
- m vehicle mass, [kg]
- g acceleration of gravity, 9.80665 [m/s<sup>2</sup>]
- W vehicle weight, [N]
- F tire friction force, [N]
- C centrifugal force, [N]

### VEHICLE CONFIGURATIONS

The general vehicle layout is shown in fig. 1. It includes all conceivable three- and four-wheeled configurations.

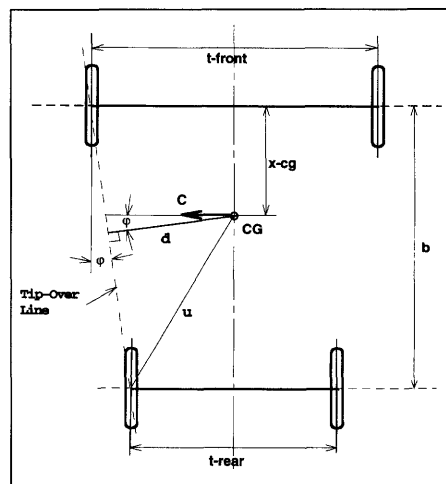


Figure 1. General four-wheel geometry

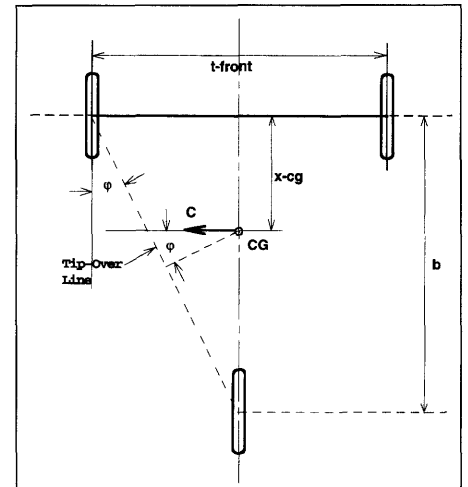


Figure 2. Wheel geometry

The marked reduction in tip-over stability of three-wheeled compared to four-wheeled vehicles is apparent from fig. 2, when one compares the distances between the CG and the tire-contact line.

The forces that must be balanced with respect to vehicle tip-over are shown in fig. 3, in a plane normal to the tire-contact line.

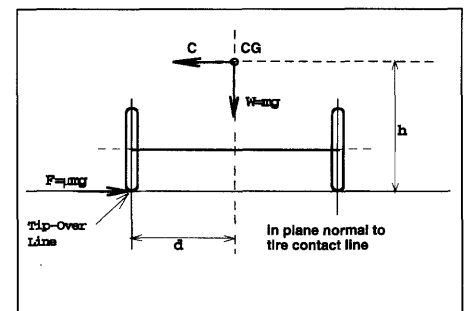


Figure 3. Forces determining tip-over

### ANALYSIS

When a vehicle makes a turn, the centrifugal force, pointing outwards in the direction of the turning radius vector, acts at the center of gravity (CG), and creates a overturning moment, with its height above the road being the lever arm.<sup>1</sup> To prevent tip-over, the overturning moment must be counteracted by the restoring moment of the vehicle weight, with the horizontal distance from the tip-over line being the lever arm. The tip-over line is defined by the tire/road contact points of the outside wheels.



The skid-limited turning radius is derived as:

$$F = C \implies r = \frac{v^2}{\mu g}$$

The tire-friction force is assumed to be proportional to the tire load. This assumption may lead to some illusions regarding skidding behavior that will be discussed later.

The tip-over-limited height of the CG is derived as:

$$Wd = Fh \implies h_{CG} = \frac{d}{\mu}$$

Of course, a tip-over moment exists only to the extent that the centrifugal force is reacted by tire friction.

The tip-over lever arm  $d$  is determined by the vehicle geometry:

$$d = \frac{\left(1 - \frac{x_{CG}}{b}\right)\left(1 - \frac{t_r}{t_f}\right) + \frac{t_r}{t_f}}{\sqrt{4\left(\frac{b}{t_f}\right)^2 + \left(1 - \frac{t_r}{t_f}\right)^2}}$$

It is apparent from the drawing that if the rear wheels are placed closer together than the front wheels, or if there is only a single wheel in the center, the lateral distance to the tip-over line gets smaller as the CG is moved back. The CG setback must therefore be chosen just as judiciously as its height. In the special case where front and rear axles are equal, a variation of CG setback has no effect on tip-over.

The tip-over and skidding behavior are independent of the driving direction. Therefore, three-wheelers with the single wheel either fore or aft are covered. (The CG-“setback” is measured from the two-wheel axle.)

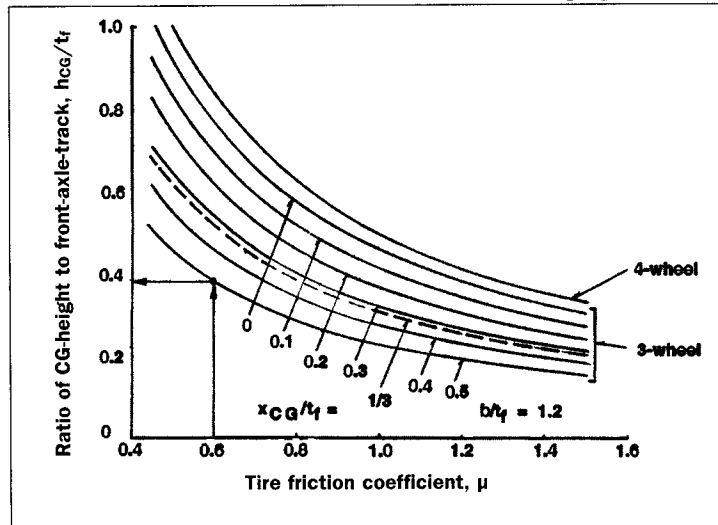


Figure 4. Tip-over conditions

## RESULTS

The minimum turning radius for a given friction coefficient and driving speed, the skid-limit, is shown in fig. 4. For smaller turn- radii the vehicle will skid. (See footnote 2 about the construction of the graph.)

Figure 5 shows the tip-over limit in terms of the maximum allowable CG height. The curves are for four- and three-wheelers and cover a variety of the CG heights and setbacks. All dimensions are normalized, so that the results can be applied to any size vehicle.

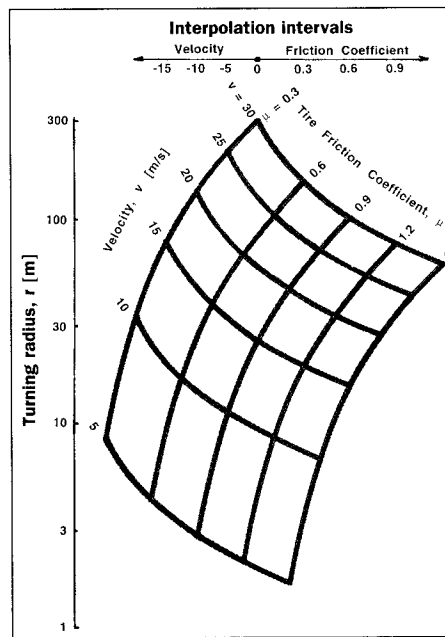


Fig. 5. Skid-limited turning radius

## TIRE-FRICTION MODELS

The assumption that the tire-friction force is proportional to wheel load is a

convenient old standby quoted in all automotive textbooks. The model “works” as long as the friction coefficient covers the aggregate effects of what is really happening. It does not, however, contribute to the understanding of the friction process. Strictly

taken, if the load-proportional model were true, the location of the CG would have no effect on the skidding characteristics, since both the friction force and the centrifugal forces would be directly proportional to mass as it is distributed, meaning that the same ratio of centrifugal and friction forces would exist at each wheel.

From this would follow that the vehicle would start and stop skidding on all wheels simultaneously, and also skid perfectly parallel. The wheel configuration would be of no consequence. This, of course, is not realistic.

If one looks at the tires of sports cars or, in the extreme, drag racers one knows that the contact area must be an essential parameter in an up-to-date tire-friction model besides wheel load. Bicyclists know to let some air out of their tires when confronted with winter conditions to increase the contact area and tire friction.

For HPVs where minimum rolling resistance is essential, relatively high tire pressures are used that result in small but not negligible contact areas. Contact area becomes important in a skid, and it is for this reason that vehicles need to be balanced to bring the CG near the center of all contact areas. As an approximation, the CG of the four-wheeler should be near one-half of the wheel base, and for the three-wheeler it should be at about one-third of the wheelbase.

With three-wheelers there might be the temptation to move the CG up front, almost between the steering wheels, in order to get good tip-over stability. A consequence of that, other than strange skidding behavior, would be the tendency for the rear wheel to leave the ground during braking with attendant loss of directional control.

## SUMMARY

The analytical relationships governing vehicle skidding and tip-over have been presented. Working diagrams are provided for three- and four-wheel vehicles covering a range of tire-friction coefficients and center-of-gravity locations. Non-dimensional parameters are used to make the results applicable to any vehicle size.

In my limited search of the tire literature I have not been able to find a more realistic tire-friction model. If you should come across something interesting,

or have any other comments or questions, please contact:  
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#### FOOTNOTES

- 1 The purist will point out that forces on the vehicle have to supply a radially inward force to produce the inward acceleration required in a turn. This force is equivalent to the popular "centrifugal force." —*ed.*
- 2 The graph in fig. 3 is constructed as a carpet plot. Here the dependent variable is plotted on the vertical scale, while both independent parameters are plotted against horizontal, linear-interpolation scales, creating a network of evenly spaced nodes. Interpolation is done in the horizontal direction, as indicated by the scales shown at the top node. Using the grid of the graph paper, very accurate interpolations can be made in all independent parameters.

*Dietrich Fellenz is a retired aerospace scientist who participated in the conceptual design phase of the space shuttle. He was first drawn to HPVs by the clever decision to design the Gossamer Condor to be flown at max. lift rather than max L/D, as all the competitors were doing. He has enjoyed following land-, water- and air-HPV developments ever since.*

#### From Sheldon Brown's collection of quotations; used with permission.

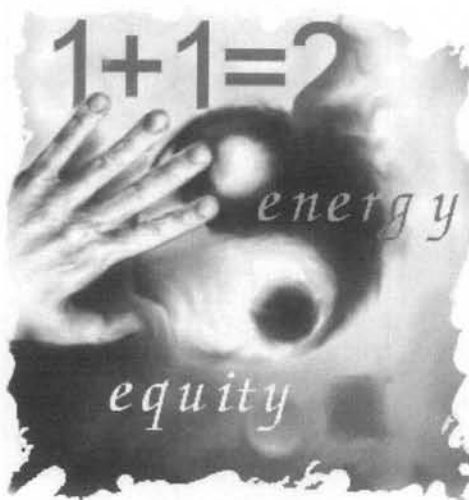
"When anyone asks me how I can best describe my experience in nearly 40 years at sea, I merely say, 'uneventful.' Of course, there have been many gales and storms and fog and the like. But in all my experience, I have never been in any accident of any sort worth speaking about. I have never seen but one vessel in distress in all my years at sea. I never saw a wreck and never have been wrecked, nor was I ever in any predicament that threatened to end in disaster of any sort."

—*E. J. Smith, Captain, RMS Titanic, before the first and final voyage*

## ENERGY AND EQUITY AND HUMAN POWER: IVAN ILLICH REVIEWED

by John Snyder

It's an interesting assignment to write about philosophy for a technical publication. Philosophy can be imprecise, subject to a myriad of interpretations, whereas science-and-technology is clean and uncluttered in its quest towards the unveiling of absolute truth. Science-and-technology provides a comfortable, reproducible way of viewing the world. Philosophy appears fuzzy and multicolored. The two, philosophy and science-and-technology, form a union as inseparable as form is to function, as Yin is to Yang. Ignore one, the other will never be fully understood.



People of rational minds will not likely engage in fist fights to determine the sum of one-plus-one. One-plus-one equals two. No question. The best shape for a rolling bicycle wheel is round, not square. No debate.

But, when we dare to ask questions of a different nature (such as: is it proper to design a nuclear bomb? Or is a bicyclist who rides in motorized traffic merely pushing against the tide of progress?) the answers remain open to personal and cultural interpretation.

Philosophy, or more clearly stated, a system of values, determines how we will use, or not use, a given technology. In an interesting twist, the introduction or abandonment of a given technology in turn determines the system of values practiced

by a group of people. This relationship between values and technology as they relate to transportation was explored by Ivan Illich in a 12,200 word essay, "Energy and Equity", first published in 1973.

Currently out of print, this thought-provoking essay, whose message remains fresh and up to date, may be available through interlibrary loan or from used or second-hand bookstores. For readers with Internet access, "Energy and equity" may be downloaded from the following website: [http://www.cogsci.ed.ac.uk/~ira/illich/texts/energy\\_and\\_equity/](http://www.cogsci.ed.ac.uk/~ira/illich/texts/energy_and_equity/)

Comprehension of the material does not come quickly. Having grown up in the automobile-centric culture of the United States, there are many concepts I've held to be self-evident truths. In the same way as a bicycle wheel must be round, I believed without question that high-speed travel was desirable. Faster is better, right? Illich dared to question that particular assumption as well as many other "truths". His essay is to be read slowly and savored with an open mind.

A few select points from the material follow along with my own interpretation.

According to Illich, any energy crisis, such as occurred in the early 1970s, is a falsehood. The illusion of energy as a limited commodity serves only to perpetuate the idea that mankind needs machinery. "According to this [false —*ed*] notion, man is born into perpetual dependence on slaves which he must painfully learn to master. If he does not employ prisoners, then he needs machines to do most of his work." This perceived dependency implies that the well-being of a society (or individual) can be measured by the number of energy slaves it has to command. Illich asked rhetorically: do free men need them?

He states that energy policies of governments can follow three paths:

- high levels of per-capita energy use with high levels of efficiency,
- the least possible use of mechanical energy by the elite or, a seldom-regarded option,
- least possible per-capita energy use

which would promote social equality [e.g., bicycling].

From the vantage point of nearly twenty-five years later we've witnessed the implementation of the first two paths. In the West energy use continues to grow along with the assumption that somehow cleaner transport systems and factories make up for more transport systems and more factories. Regarding the second: the most efficient motorized vehicles and other energy-consuming devices have proved the most capital intensive, thus being an option for only a select few.

Social equality and the wattage used in a society, Illich argues, can grow together for only a short while. As energy affluence increases, a threshold is crossed whereby equity disappears. The rich get richer while the poor get poorer because of centralization and control of the distribution of energy sources.

When we talk about energy, we often also mean power. It is no coincidence that we can equate physical with political power. Other mechanisms which amplify the divide between poor and rich are compound interest and the legality of individuals owning vast amounts of land. Anyone who has played the game monopoly knows that eventually all power and property is transferred to very few players who have absolute control over the rest. This process continues until the game is reset, i.e., a poor loser dashes the playing board to the floor or, in real life, a revolution or war occurs.

*Note by Theo Schmidt, Assoc. Editor*

Thus I will suggest, in accord with Dr. Illich's statements, the institution of slavery, commonly believed to be dead, remains alive within modern culture as evidenced by how we use and modify our tools. This in turn influences how we interact with others.

A way to demonstrate the above assertion begins with regarding power-assistance. On a bicycle, power-assist refers to the addition of an auxiliary motor to supplement the effort of a rider. Such devices first appeared in the 19<sup>th</sup> century, conceived as a way to make life easier, a way to lessen the burden of pedaling a bicycle.

From the vantage point of a century

ago, the future—our present—was a bright place filled with material riches and leisure. In the past these goals were satisfied by forcibly reallocating the time and energies of others for the benefit of an elite class. Idealists of the time stressed finding the means to promote the dissolution of elitism while developing a way to elevate the standing of all humans. Machines were to be one of the means of removing other humans and to some extent domestic animals from the bondage of physical labor, deemed an undesirable condition by civilized societies.

During the late 1600s, Thomas Hobbes characterized "automata", that is machinery with motors, as a form of artificial life [Leviathan]. Machines function as mankind's slaves whose labor would create benefit without the element of exploitation. Our current word "Robot" used to convey a related concept and comes from the Slavic "robota" meaning forced labor.

In a highly simplistic way, human-powered bicycles of the 1890s, when married to a slave motor, gave birth to the motorcycle, whose progeny in turn became the horseless carriage. The modern automobile represents but one ripened fruit of values born in the 19<sup>th</sup> Century: acquisition of power, a feeling of control, luxury, leisure, convenience, and dominion without the guilt. The institution of slavery and its underlying value system remain with us. The servants' faces have changed. The masters' hearts have not. Instead of a submissive beast-of-burden pulling a cart or several man-servants shouldering a resplendent houdah, the master calls upon a mindless, uncomplaining automaton to transport him effortlessly from place to place.

But, any master-slave relationship is one of mutual imprisonment. A master depends on the slave's production. In a culture dependent on automobiles for transport, individuals are compelled to use monopolized support systems. Paved roads, gasoline, car, a myriad of regulations, insurance, dealerships, financial lending—all provide closely controlled fodder needed to keep the slave/automobile alive. The master/driver becomes a prisoner to compulsory consumption. In some instances an inability or unwillingness to consume all of the requirements of automobile ownership, such as failure to purchase mandated insurance, results in

literal imprisonment.

What starts out as a simple and relatively benign tool, the bicycle, when modified to express the value of greater power unwittingly corrupts into a way to deny power. In Dr. Illich's words, "...the impact of industrially packaged quanta of energy on the social environment tends to degrading, exhausting, and enslaving, and these effects come into play even before those which threaten the pollution of the physical environment and the extinction of the race. The crucial point at which these effects can be reversed is not, however, a matter of deduction, but of decision."

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"Energy and equity." In *Tools for Conviviality*, Harper & Row, 1973.  
Readers might also want to see...  
Newton, Edgar. "A convivial life". (lead-in: "The bicycle world needs its visionaries. Edgar Newton examines the life and thinking of Ivan Illich.") *Bike Culture* 14, Dec 1997, pp 14-15.

*John Snyder is an artist and cyclist from Great Falls, Montana.*

## A concluding comment by Theo Schmidt

If we are to believe Illich and other similar observers, a worthwhile civilisation can survive only if it knows what not to do. At which level does vehicular power threaten civilisation? The Amish people in the USA still use only simple carts and horses out of choice and live happy, fulfilled lives. They are probably below the sustainable threshold. A planetfull of today's automobiles at the northern/western level is clearly not possible and above the sustainable threshold. Although humanity will always want and need a whole spectrum of vehicle types to use where appropriate, it is high time that we design and make vehicle types which satisfy the needs of the greatest number of people without endangering civilisation. HPVs, including bicycles, clearly go a long way in this but cannot satisfy all needs. Assisted power may be a way towards universal sustainable transportation, or it might be a poor compromise making things worse. Only time will tell.

# THE STIFFNESS OF TUBES OF VARIOUS CONFIGURATIONS AND MATERIALS

by John Zabriskie

## ABSTRACT

*Tubing stiffness is a function of both shape and material composition. This article discusses the contribution of both characteristics to the overall stiffness. Specific material aspects are discussed. Geometric aspects relating to the moment of inertia are analyzed via examples. Some formulas are given for use in analysis. A method for directly comparing alternatives involving both different materials and differing geometries is demonstrated in the form of a test case. Other configurations are analyzed by example.*

## INTRODUCTION

Structural stiffness is important: we rely on it every day. The chair you're sitting in, the building you're in, your vehicle for transportation all require appropriate stiffness to function well. For the scope of this article, we'll narrow our focus to tubing stiffness. This is especially important to constructors who are designing or redesigning frames for human-powered vehicles. A frame with poor stiffness can contribute to pedaling inefficiency, odd handling quirks and other unpleasant behavior.

The Alan was an Italian road-racing frame of the early 70s that featured aluminum tubes glued and screwed into investment-cast lugs. It used tubing of the same outside diameter as a Reynolds 531 frameset. This contributed to its noticeable lack of stiffness. If you came up to a stop sign with both brakes on, stopped and released only the rear brake, the frame would unwind and the rear tire would roll back 30 or 40 mm. A further reason to avoid these frames was energy dissipation. Trying to sprint by standing on the cranks was an exercise in futility. The frame absorbed pedaling effort through deflection, diverting vast amounts of energy from driving the tire. On rough roads however, the ride was very, very plush.

Additionally, we'll further restrict the scope of this article to consider only the cross-section of a tube or beam, ignoring joining and end effects. We'll examine the simple view of tubes. Our first consideration is the material the tube is made of.

## MATERIAL ASPECTS

Engineers call the stiffness of a material its modulus. The stiffer a material is, the more it resists deforming. The modulus of elasticity, denoted by the symbol E, relates the applied stress (force applied to an area) on a material to the strain (or distortion) experienced due to that stress. E is used in all our bending and stiffness calculations. It represents the material contribution to stiffness.

In order to rate materials and to compare their performance, engineers often attempt to normalize characteristics. This allows equivalency among the various cases. If we divide a material's modulus by its density, the result is the specific modulus, or modulus normalized to mass. Some moduli and densities of various structural metals (from MIL-HANDBK-5C) are listed in Table 1.

From observation, then, we see that steel is about three times stiffer than aluminum. Steel's density is slightly less than 3 times that of aluminum, so it appears to be close to an even tradeoff. Looking at the specific modulus, you'll notice that steel is just a little bit better than aluminum, which is just a little bit better than titanium. Is the specific modulus useful? By itself—not very. The only strong conclusion we can draw is that beryllium is amazingly stiff for its weight.

Some of you may ask, "What about those amazing aircraft alloys like 7075-T6? Don't the trace elements and heat treating make these alloys stiffer than unalloyed 1100 aluminum?"

No, alloys are not significantly stiffer, since stiffness is a basic material property and is affected only slightly by alloying elements. [A large percentage of another material *will* affect the stiffness however, as in the law of mixtures.] However, alloys are normally stronger, having much higher tensile strengths. That's what makes them so useful. The disadvantage is that the combination of all those alloying elements, solution and heat treating tend to make the alloys\* more brittle. The basic trade-off is loss of ductility for higher strength.

Table 1. Various structural materials

Tube material	Modulus E [Gpa]	Density, $\rho$ [Mg/m <sup>3</sup> ]	Specific modulus [E/ $\rho$ ]
Carbon steel	207.0	7.80	26.5
Aluminum	71.0	2.71	26.2
Stainless steel	190.0	7.75	24.5
Magnesium	44.8	1.79	25.0
Titanium	110.3	4.57	24.1
Beryllium	292.9	1.86	157.5

## GEOMETRY ASPECTS: ...THE FUN STUFF

Consider two tubes of the same material and identical wall thicknesses. The only thing that differs is their shape: one is round and the other is square. These are depicted in the figure below: where:

- A cross-sectional area
- I area moment of inertia
- J torsional moment of inertia
- D outer diameter or dimension
- t wall thickness
- d inner diameter or dimension

[Please note: Weight is a directly proportional function of the cross sectional area, length and material mass. Since length and material are the same, areas will be compared for relative performance.]

In this example, the outer diameter is 2 units and the wall thickness is 0.125 units. The units of measure don't really matter, as long as you're consistent.

Several conclusions can be drawn from figure 1.

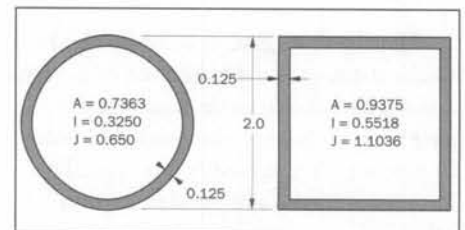


Figure 1

equations for round tubing

$$d = D - (2 \times t)$$

$$A = \left(\frac{\pi}{4}\right) \times (D^2 - d^2)$$

$$I = \left(\frac{\pi}{64}\right) \times (D^4 - d^4)$$

$$J = I \times 2$$

equations for square tubing

$$d = D - (2 \times t)$$

$$A = (D^2 - d^2)$$

$$I = \frac{1}{12} \times (D^4 - d^4)$$

$$J = I \times 2$$



- a. The round tube of the same dimension, D, will be lighter. (78.5% of the square tube, in this case.)
- b. The square tube is stiffer – 170% in both bending and torsion.
- c. Specific bending stiffness:
  - round – (.325 / .7363) = 0.4414
  - square – (.5518 / .9375) = 0.5886
 square is 133% stiffer than round
  - Specific torsional stiffness:
    - round – (.650 / .7363) = 0.8828
    - square – (1.1036 / .9375) = 1.1772
 square is again 133% stiffer than round

For these symmetrical cross sections the torsional moment, J, is simply twice the area moment.

[Specific stiffness is found by dividing the area moment of inertia (or torsional moment) by the weight (or area in this case). This value is a normalized measure of stiffness efficiency.]

By now some of you are asking, “What about round and square cross sections of the same area (or weight)?” Consider two more cases – one with the same outer diameter but thicker wall and the other with the same wall thickness but larger outer diameter. Again the results are depicted in table 2 (the previous two cases are also shown for completeness).

**Table 2**

Tube type	round	square	thick round	big round
Dimension	2	2	2	2.5123
Wall thickness	0.125	0.125	0.1624	0.125
Area, A	0.7363	0.9375	0.9375	0.9375
% weight of sq tube	78.50%	100.00%	100.00%	100.00%
Moment, I	0.325	0.5518	0.3988	0.6697
I % of sq tube	58.90%	100.00%	72.30%	121.40%
Normalized I	0.4414	0.5885	0.4254	0.7144
Norm I % of sq tube	75.00%	100.00%	72.30%	121.40%

Notice that:

- a. Normalizing the stiffness doesn't matter since the areas are the same.
- b. Although the thick round tube is stiffer than the original round tube of thinner wall thickness, the normalized stiffness is less.
- c. The big round tube of the same wall thickness as the square tube has over 20% greater stiffness for the same weight. Bigger is better.

Some of you undoubtedly have jumped ahead to the next obvious point. “What about a round tube that has the same

stiffness as the square tube?” This exercise is best left to the reader and her/his favorite spreadsheet. I know this is a cop-out, but seriously, you *can* do this yourself. Extrapolating from the preceding examples, we can infer that for the same stiffness, the round tube would: (a) have a somewhat larger diameter. (b) thinner wall thickness and (c) would be lighter.

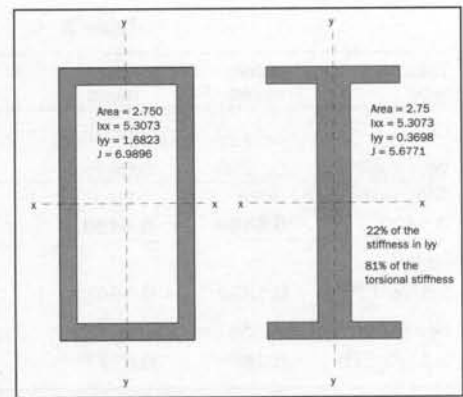
If this argument is taken to the extreme, the result would be a really huge tube that would be paper thin – very stiff and extremely lightweight. Yes, but... the specter of local buckling hovers nearby. Local buckling occurs when the wall thickness is not great enough to transfer the applied stress without distorting some – it dimples or starts to wrinkle. For our tube to function as an integral part of a structural frame it must stay tubular and not distort. Local buckling is not allowed.

For example, stand on an empty beer or soda-pop can as carefully as possible. You should be able to support your full weight on it if you apply the weight gradually. Now bend over and poke the side of the can with a pencil. You will collapse the can. Your poking has caused local buckling and resulted in catastrophic failure of the can as a structural member.

While analyzing local buckling is beyond the scope of this article, an easy rule to go by is, “If you can distort the tube wall by pushing on it with your finger, it's way too thin.”

I recall reading of someone in Europe who had created a frame out of old hair spray cans joined together or some other rather thin-walled but large-diameter tubing. To counteract this local buckling phenomenon, he had pressurized the tubes to keep them stiff. Apparently the frame was uncomfortably stiff, but it did not buckle.

The next example examines rectangular-cross-section tubes and I-beams. Here we have a box beam and an I-beam of the same overall dimensions. The web of the I-beam is twice as thick as the wall of the box beam to keep the cross sectional areas the same. The beams in figure 2 are the same weight. In this case: b = 2, h = 4, t = .25

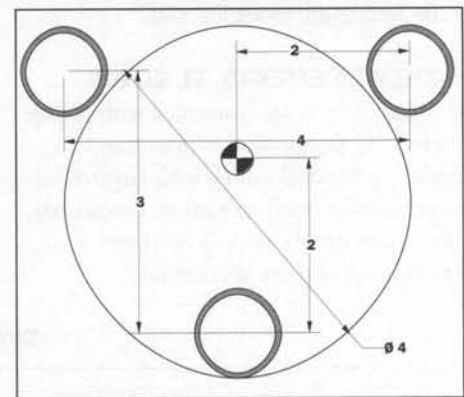


**Figure 2. Box beam and I-beam**

**CONCLUSIONS HERE**

- a. Both the box beam and I-beam have the same resistance to bending about the short axis (x-x).
- b. Due to the lack of material outboard, the I-beam suffers in bending about the long axis (y-y) with only 22% of the stiffness.
- c. Torsional stiffness is also reduced, by almost 20%.

Another example to keep you awake at night. Suppose you have three tubes spaced as shown in the figure below. This would make a fairly stiff, lightweight beam.



**Figure 3**

The tube diameters are 1 unit OD with a 0.062 unit wall thickness. The spacing and centroid are as shown in the figure. The combined area is 0.55 sq units. The resulting moments of inertia are 1.158 about the horizontal axis and 1.523 about the vertical axis. (This means that the example is 30% stiffer in side-to-side bending.)

Since a four-unit round tube is approximately the largest that will fit within the three-tube envelope, what wall thickness will give the same stiffness? The answer is 0.064 units. The weight penalty is a little less than 1.5 times the weight (1.43 actually). If we were to try to keep the weight the same, the resultant wall

Table 3

Tube type	thick round	big round	big & thin	big & thinnest
OD	1.5230	2.8585	4.0000	4.0000
Wall thickness	0.1250	0.0625	0.0636	0.0442
Three-tube area	area	area	area	area
0.5490	<b>0.5490</b>	<b>0.5490</b>	0.7861	<b>0.5491</b>
lxx/lyy				
1.158/1.523	0.1352	0.5367	<b>1.5231</b>	1.0741
Specific lxx/lyy	specific l	specific l	specific l	specific l
2.11/2.776	0.2463	0.9777	1.9374	1.9563

thickness would be 0.044 units. The stiffness would be reduced to 70.5% of the 3-tube design. This is shown in table 3.

The first column is the three-tube design. The other cases are either comparisons with the same area, columns 2, 3, and 5 or, in the case of column 4, the actual vertical axis moment is the same (the **bold** numbers are the same). For this example, the single tube is not better than the three-tube design. Even in the case where the stiffness is the same, the single-tube design is heavier. In the cases where the designs have the same areas, implying that the weights are the same, the single tube designs are much less stiff.

#### COMBINED EFFECTS: EI, EI, OH!

Many of you are concerned with taking an existing design of some frame and replacing the steel tubing with larger-sized aluminum or titanium tubing. Fortunately, there is a simple method for direct comparison of these alternatives.

product E\*I is measure of the relative stiffness of a tube taking into account both material and geometry contributions. It's quite useful when directly comparing alternative candidates having different materials and configurations to a reference case, as we'll demonstrate.

Suppose we have a frame of two-unit-OD steel tubing of 0.035 unit wall. This will be the base case. Consider two alternative frame materials: (2) 6061-T6 aluminum and (3) Ti-6Al-4V titanium. We'll consider three geometric variations: (a) thicker, (b) bigger and (c) huge. For each of these six test cases, we'll vary the wall thickness in the spreadsheet to adjust the E\*I product as close to the base case as possible. We'll then look at the % of the original weight (see table 4).

Obvious conclusions are that bigger, but thinner, is better. Notice that there is not a significant difference between titanium and aluminum in our example. For the same stiffness, aluminum is only slightly lighter

Table 4

tubing comparison	original	case 1a (thicker)	case 2a (bigger)	case 3a (huge)	case 1b (thicker)	case 2b (bigger)	case 3b (huge)
OD	2	2	2.5	3	2	2.5	3
wall thickness	0.035	0.10836	0.0528	0.03005	0.06489	0.03227	0.01848
material	4340 steel	6061-T6	6061-T6	6061-T6	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
area	0.1090	0.3312	0.2052	0.1409	0.2006	0.1259	0.0868
I	0.0536	0.1569	0.1569	0.1569	0.0971	0.0971	0.0971
E	2.90E+07	9.90E+06	9.90E+06	9.90E+06	1.60E+07	1.60E+07	1.60E+07
density	0.283	0.098	0.098	0.098	0.16	0.16	0.16
E x I	1552993	1553026	1553592	1553612	1553196	1553643	1553104
E x I % (original)	n/a	100.00%	100.04%	100.04%	100.01%	100.04%	100.01%
weight / in	0.0308	0.0325	0.0201	0.0138	0.0321	0.0201	0.0139
weight % (original)	n/a	105.23%	65.18%	44.77%	104.03%	65.31%	45.03%

In beam bending and deflection formulas, the product, E\*I, is a common term throughout. E, as you'll remember, is the material component of stiffness, where I is the geometry component. The

than titanium. In a practical sense, though, available tubing wall thicknesses will constrain any design.

#### SUMMARY

To maximize the stiffness of a tube:

1. make the outer dimensions or diameter as large as practical;
2. make the wall thickness as thin as possible without causing the problem of local buckling;
3. choose a material with a high modulus; and
4. possibly split the load-carrying duties among several smaller tubes spaced a reasonable distance apart.

#### EPILOGUE: WHY ARE THE TUBES IN A CANNONDALE OR KLEIN FRAMESET SO LARGE?

To get the same stiffness as a steel frameset, framemakers using aluminum tubing must increase the tubing diameters to compensate for the loss of stiffness from the modulus difference. Remember the E\*I term? Aluminum's modulus [E] is about 1/3 than of steel, so aluminum tubes should have about 3 times the moment [I] of steel tubes to have the same stiffness.

#### IN SEARCH OF FURTHER ENLIGHTENMENT?

Check out almost any text on design of machine elements or machine design. My personal favorites are:

Beer, F.P. & Johnston, E.R. 1972. *Vector mechanics for engineers: Statics and dynamics*. NY: McGraw-Hill. (ISBN: 0-07-004292-6)

Brush, D.O. & Almroth, B.O. 1975. *Buckling of bars, plates, and shells*. NY: McGraw-Hill. (ISBN: 0-07-008593-5)

Roark, R.J. & Young, W.C. 1975. *Formulas for stress and strain*. NY: McGraw-Hill. (ISBN: 0-07-053031-9)

Shigley, J.E., 1972. *Mechanical engineering design*. NY: McGraw-Hill. (ISBN: 0-07-056881-2)

Also recommended as just a good read: Gordon, J.E., 1978. *Structures (or Why things don't fall down)* NY: Plenum Press. (ISBN: 0-306-40025-1)

#### ABOUT THE AUTHOR

John Zabriskie

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mrZ's interest in wheeled





transport first surfaced when he was four years old. After mastering balance on roller skates, he migrated to various bikes in the neighborhood until his constantly-pestered parents eventually relented and bought him his own. Although he cannot remember being without a bike or two, he maintains that he has never owned more than six at once. He has been a recumbent rider for over 3 years, commuting to his day job on the prototype for the SWB Linear Sonic. [It's not a bad design, considering its shortcomings and the price was right. The creaking encourages me to be smooth, the pedaling flex encourages high rpm, and the frame flex takes the edge off the rough Idaho roads.] After earning a BS in Mechanical Engineering at Georgia Tech, mrZ moved west. Aside from a short stint at Ford Motor Co., in Dearborn, MI, he has been designing prototypes for over 20 years at the Idaho National Engineering Laboratory (INEL) ranging from high-speed ultralight trains to ceramic heat exchangers to flying windmills to C31 motorhomes and other "stuff we can't talk about". He specializes in the bizarre, or at least the odd and different—"hang a sharp left at ordinary and keep walking, ... until you see something interesting." Although too much of his work life is computer-aided, he'd rather not go back to the old days of slide rules. He lives halfway between Sun Valley, ID and Jackson Hole, WY. It's just about perfect, considering the length of the winter (which is not quite eternal). He will admit to commuting every month for the past two years, even though he considers himself just a fair weather rider. It must be an El Niño effect.

## AERODYNAMIC DRAG COMPONENTS

by Goro Tamai

The total aerodynamic drag acting on a vehicle body is the sum of four aerodynamic drag components. Thus, total aero. drag = pressure drag + viscous friction + induced drag + interference drag. (1)  
 $D_{aero, total} = D_{pres,sep} + (D_{skin} + D_{pres,BL}) + D_{ind} + D_{int}$ . (1.1)

The first term, the pressure drag  $D_{pres,sep}$ , is often the dominant term for passenger automobiles. This bulk of drag arises when the air flow fails to hug the rear of the car body all the way down to the trailing edge (or rear bumper). When the flow "separates" from the surface of the car as shown in figure 1(a), a low-pressure void, or vacuum, is left behind the car, literally sucking the car backwards. There is also a significant amount of energy expended in generating the vigorous vortices behind the body. A shape that exhibits flow separation is called a "bluff body." For a typical production car, about 50 to 90 % of the total aerodynamic drag is attributable to separation pressure drag (Katz, 1995; Kelly, 1977). The separation pressure drag is also sometimes called the form drag. Though the separation pressure drag is regarded as a separate entity from skin friction, flow separation actually occurs because of the skin friction. The details of this are explained in many aerodynamics text books such as (Anderson, 1991). The separation pressure drag is usually strongly dependent on the vehicle's frontal area.

The second term of equation 1, the viscous friction, is made of two terms:  $D_{skin}$  and  $D_{pres,BL}$ . These terms are lumped together as "viscous friction" because they are both a direct result of the boundary layer. The boundary layer is the thin region of flow near the body surface where the effects of fluid (air) viscosity are significant. We will look at the two components of viscous friction separately. First, the skin friction  $D_{skin}$  is the viscous shearing of the fluid molecules tangential to the body surface. If the flow is "attached" (i.e., not separated) to the body, the  $D_{skin}$  can be the dominant drag component. This is essentially the same friction phenomenon that can be felt when running a knife through honey.

Though in many engineering applications, the viscosity of air may be neglected, this is surely not the case with sleek tapered bodies where, the designer hopes, the air flow remains attached to the body from nose to tail. In applications where low drag is vital, the body should be shaped to resemble more of an airplane wing (airfoil) rather than a blunt-reared passenger vehicle. When a car body's tail is extended so that it gradually tapers to a knife-edge as shown in figure 1(b), the air flow can manage to stay attached to the tail of the body, and the usually dominant pressure-drag component can be practically eliminated. A shape that exhibits no flow separation is called a "streamlined body."

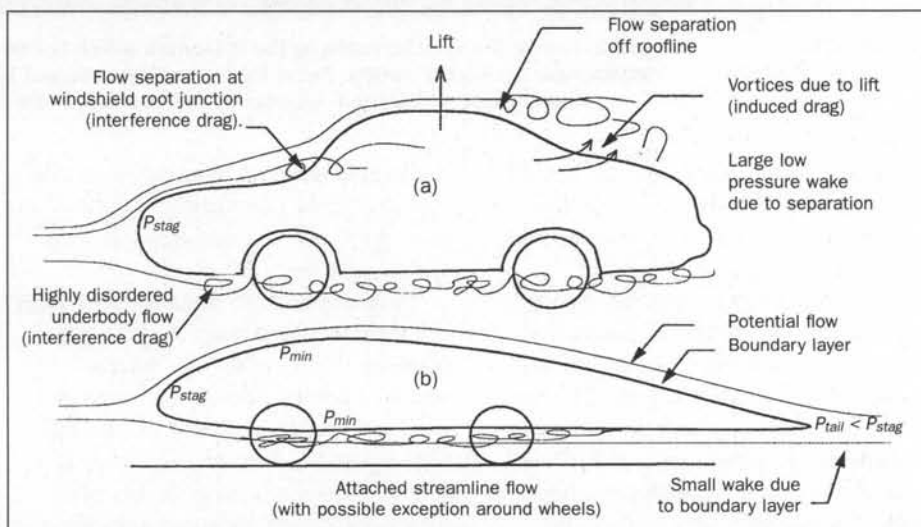


Figure 1. (a) Airflow over a production car exhibiting large-scale separated flow starting near the rear window. (b) Separation-free airflow over a streamlined vehicle body.

**Table 1. The relative sizes of the drag components are summarized and the variable(s) shown to which each is most strongly proportional.**

	Separation pressure drag	Viscous drag (boundary layer)	Induced drag	Interference drag
<b>Proportional to:</b>	Frontal area	Wetted area	Lift (shape, ground effect)	Holes seams, craftsmanship junctions, etc.
Bluff body (e.g., production car)	BIG %	Small %	Medium-Big %	BIG %
Streamliner (e.g., solar car, HPV)	~0%	BIG %	~0%	Small-BIG %

The importance of streamlining a body designed for super low drag can not be emphasized enough. A good piece of data to keep in mind is that a bluff body such as a cylinder has five to ten times the aerodynamic drag of an airfoil of equal frontal area, depending on the speed (Shapiro, 1961; Hoerner, 1965).

Even if a body is fully streamlined, there is still a small

pressure-drag component. This is the second term of the viscous-friction drag of equation 1.1, the pressure drag due to the boundary layer  $D_{pres,BL}$ . The  $D_{pres,BL}$  is usually a small term that is generated by the existence of the boundary layer. The boundary-layer flow starts at the nose at some stagnation pressure. The flow velocity at the stagnation point is zero, and the pressure is

maximum. As the flow progresses "uphill" along the (upper) body surface, the flow accelerates, and the pressure decreases by Bernoulli's principle in the inviscid "potential flow" just outside the boundary layer (Anderson, 1991). The pressure decreases to a minimum near the thickest section (where the local velocity is highest). As the flow progresses back down the rear of the body, the pressure tries to increase back up toward the stagnation pressure. All along, the boundary layer increases in thickness as illustrated in figure 1(b). Due to the presence of the ever-thickening

boundary layer, the outline of the boundary layer can not rejoin to form a rear stagnation point, and thus full pressure recovery is not possible. This inability to form a rear stagnation point is what produces the small wake shown in figure 1(b). The resulting pressure distribution around the body produces a net lower pressure at the rear—that is, the body is effectively being sucked backwards similar to the separated-flow case (but to a much smaller extent). This pressure drag inside the boundary layer is the  $D_{pres,BL}$ . The failure of complete pressure recovery

wanders about with no definite flow direction. However, near the trailing edge of a streamlined body, the tuft can be observed to align cleanly with the air flow sliding off the tail. The sum of both pressure-drag components and the skin friction is called the profile drag. The boundary-layer drag or the profile drag is strongly dependent on the vehicle's wetted surface area.

The fourth term of equation 1.1, the induced drag  $D_{ind}$ , is a result of a body generating lift. When a body in a fluid generates upward (airplane) or downward (Indy race car) lift, the lift is accompanied by an added drag force. A lifting body induces vortices due to the pressure differential between the top and bottom of the body. The kinetic energy of those swirling vortices manifests itself as extra work done by the vehicle's powerplant. For

land vehicles, the lift can be a strong function of the body curvature (particularly in side view) and the ground clearance. An interesting side note is that "lift" can actually be used to reduce the aerodynamic drag force of a vehicle if the airfoil is positioned vertically relative to the ground. In this case, the vehicle is effectively sailing.

Finally, the fifth term of equation 1.1, the

interference drag  $D_{ind}$ , is a result of everything from fabrication limitations, to ventilation passages, to design compromises. Interference drag can be caused by imperfect matching of body panels, stickers or decals on the body, bumps or surface roughness, and holes where the wheels protrude from the body. Also, if a body is an assembly of two or more shapes attached together, the resulting complete-vehicle aerodynamic drag will typically be greater than the sum of the individual bodies. This is the junction drag generated at the corners between the main



**Figure 2: Among the vehicles raced by the author are the championship winning cars: the Manta solar car (right) and the 2-seat EV Aztec. The Aztec was based on the famous Morelli shape which has been used by HPV racers. (Photo: I. Gregoratto)**

can be graphed in a coefficient-of-pressure ( $C_p$ ) plot. If the boundary layer did not exist, the  $C_p$  value at the tail would return to the stagnation value of +1.

Some authors have regarded this  $D_{pres,BL}$  as a small local-separation drag. Strictly speaking, this is not the case since a separated flow by definition has zero skin friction. The skin friction at the trailing-edge region of a separation-free body is very much non-zero since the boundary layer is still dissipating energy through shearing action. This can be observed with yarn-tuft tests. In a separated flow, the tuft

body and the canopy or wheel fairings. In many cases, the interference drag is actually a pressure drag, and can be as much as half the total vehicle drag.

The designer of ultra-streamlined body or fairings should strive to minimize the sum of these five aerodynamic drag components. The separation-pressure-drag term should be first on the "hit list," followed by the induced-drag component (mostly for safety reasons). The interference drag component is very difficult, if not impossible, to eliminate. And finally, if the above three components are minimized, the skin-friction term will be the dominant term. Large reductions in interference drag can be obtained by sealing holes and properly contouring the junctions. An overwhelming (over 90%) fraction of a smooth non-lifting streamlined body with no protrusions is skin friction.

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*Goro Tamai's background in aerodynamics stems from his years as a solar-car designer and racer at the Massachusetts Institute of Technology. He was the team leader of the 1995 MIT team that won Sunrayce 95, the North American solar racing championship. Since graduation, he has been working as an automotive powertrain engineer in Detroit. In his "spare" time, he has written a book on aerodynamics tentatively titled, *The Leading Edge: Aerodynamic Design of Ultra Streamlined Land Vehicles*. *The Leading Edge* was designed to be a how-to manual for the ultralight-vehicle constructor, as well as the ultralight-vehicle enthusiast. Great effort has been made to present the material qualitatively, as well as quantitatively, in as simple and crisp a format as possible. The book will, it is hoped, be released within the next few months. Goro Tamai can be reached at [goro@alum.mit.edu](mailto:goro@alum.mit.edu).*

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## TECH NOTES

### OXYGEN UPTAKE, RECUMBENT VS UPRIGHT

*Editorial note: This letter is reproduced, with permission from Mark Drela of MIT, from some correspondence on the HBS (hardcore bicycling science) mail list. It was in response to someone who stated that athletes can take up ten-percent less oxygen in the recumbent than in the "upright" pedalling positions. —Dave Wilson*

The test data reported in the article below shows that there is no significant difference in oxygen uptake between producing power in the normal "upright" position and in a recumbent position. These tests were performed with a normal saddle and a recumbent seat attached to the same pedal ergometer unit, so there is no issue with equipment variability.

Nadel, R.E & Bussolari, S.R. "The Daedalus Project: Physiological Problems and Solutions." *American Scientist*, July-August 1988.

Jim Papadopoulos put the following questions to the HBS mail list.

1. Is oxygen uptake a predictor of power output? That is, if two people ride stationary bikes for an hour, and one has higher  $\text{VO}_2$ , does it mean that s/he was producing more power?

2. Does  $\text{VO}_2$  max relate quantitatively to maximal steady-state power? [You can't actually work for an hour at that power level. Even the power level you can produce for an hour does not really qualify as steady state. Also, I think that the top racers don't generally have the highest  $\text{VO}_2$  max levels.]

No to both questions. The tests showed a very wide variation in efficiency among different athletes. All were national and Olympic-class. The efficiency was defined as  $d(\text{Power})/d(\text{Kh } \text{VO}_2)$ , where Kh is the heat of glucose oxidation. The derivative in effect removes the resting  $\text{VO}_2$  offset, and is virtually constant up to  $\text{VO}_2$  max. The efficiency numbers ranged from 18.0% to 33.7% (!). The 33% guy might have only half the  $\text{VO}_2$  max of the 18% guy and still be nearly the same-caliber cyclist.

The endurance tests (separate from the  $\text{VO}_2$  max tests) also showed a very big difference in the percentage of  $\text{VO}_2$  max that could be sustained without gradual lactate build-up, which quickly forces the athlete to stop. Some riders conked out at

60%, and others could tolerate 90%. (Nadel told me this—it's not in the paper). This may be related to fast/slow twitch muscle ratios, but I'm just guessing. Mark Drela <[drela@orville.mit.edu](mailto:drela@orville.mit.edu)>

### DYNAMIC MODEL OF A REAR SUSPENSION

This is a comment on a recent letter to the Hardcore Bicycle Science (HBS) mailing list from an engineering student. He writes: "I have recently gone through the academic exercise of developing a computer algorithm that will derive the equations of motion for any planar mechanical system. The only stipulation is that the planar mechanical system must be made up of elements found in a library of modeling components."

This is not the first time someone has come up with a model for the various aspects of a bicycle. However, it is the rider that is not practical to model. If you follow the threads on [wreck.bike](http://wreck.bike) (another mailing list), there are endless discussions why one frame rides better than another. Some of this is pure fantasy but I believe part of it is real. There is great disagreement on whether one bicycle works better than another. The reason is that riders have greatly different techniques.

I had it easy with modeling the bicycle wheel because I didn't use it as a design mechanism, but rather an analysis of what the wheel can support. The wheel got to where it is pragmatically. Ultimately, the bicycle is relegated to do that as well, regardless of people's desires to include its peculiarities in design forecasts. The reason for failures is often not anticipated but the school of trial and error weeds them out.

"Now that the code is done, I am looking for applications with which to use my program. As a demonstration, I would like to develop the equations of motion to predict PEDALING INTERACTIONS in a rear-suspension mountain bike."

I'm not sure the rear suspension has an engineering solution. A springy rear end, and even a front one, interferes with the basic operation of propelling the bicycle. I have had the opportunity to talk with Ritchey and Frischknecht about this and for most races the rigid bike is preferred.

Rock Shox is a sponsor and furnishes needed money for the team; but without anyone directly saying so, it appears that

the suspension is not an advantage. Downhill racing is another matter entirely. For this the best vehicle is a motor-less dirt motorcycle with more than one foot of front and rear travel.

I have been to plenty of bike shows and the suspensions I see offered there are exercises in how complex a linkage one can make to approximate a swing arm without actually having one. There are many theories on where the pivot point must be located, most of which are predicated on countering the adverse effects of suspension while pedaling hard. I have not yet seen one that a racer would use in Paris-Roubaix.

*"I have created a simple model and I would like to invite everyone to comment on my model. As this will be a demonstration of my algorithm, please keep in mind I want to keep the model as simple as possible."*

At this point you have come upon the difficult part. What is the input? As you know, garbage in = garbage out.

—Jobst Brandt <jbrandt@hpl.hp.com>

*(reproduced here from HBS Digest no. VI #324 with the permission of Jobst Brandt and the HBS moderator, Jim Papadopoulos. I excluded the name of the modeller because I have not asked his permission. Dave Wilson)*

## MAXIMUM HUMAN POWER

The purpose of this note is to give some new data on maximum human power output, coming from Tyler Hamilton's record climb of Mt. Washington on August 23, 1997, and the "CRASH-B Sprints", a competition for champion rowers on Concept-II rowing ergometers (power-measuring exercisers), held in the Boston area in the spring each year. First, here is some background.

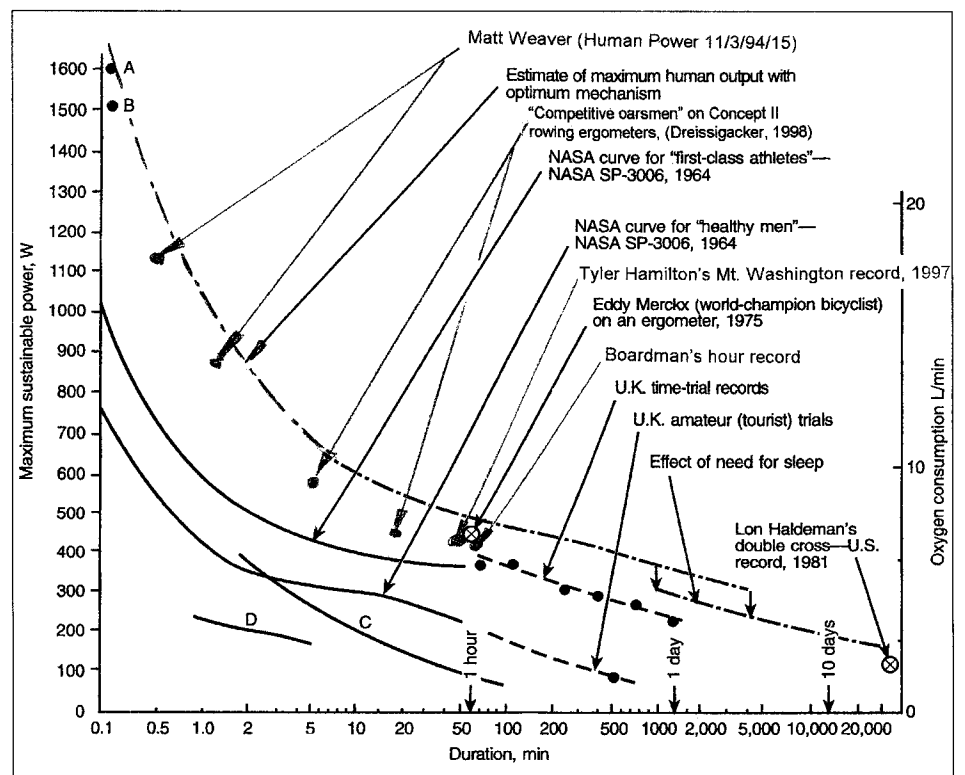
In *Bicycling Science* I included (as figure 2.13) a NASA plot that has two curves showing the duration for which people had been found to be capable of generating power, most often by pedalling. One curve is for "healthy men" and the other is for "first-class athletes", both for a limit of one hour. Frank Whitt extended this time limit by calculating the power output of riders who broke records in bicycling time trials (long-distance races), and of "weekend bicyclists" in so-called "tourist" time trials. When we plotted the "tourist" power levels they were found to be extensions of the

"healthy men" line, while the data from the record times were reasonable extensions of (although higher than) the line for first-class athletes. Since the book was published I have been collecting data whenever possible, and have been interested in different methods of producing human power. It has always intrigued me that J. Y. Harrison found that people produced rather similar amounts of power in pedalling and in rowing, except when on a rowing ergometer that had the stroke defined rather as is done in a piston-crank mechanism in an auto engine (his results are shown in figure 2.6 in *Bicycling Science*). In this case, which he termed "forced rowing" because the rower was no longer free to determine where the stroke should begin and end, the subjects produced significantly more power over the duration of the tests. Unfortunately, the duration was only five minutes. Allan Abbott and I showed an updated version of the NASA plot in *Human-Powered Vehicles* (Human Kinetics, 1995) in figure 3.4, reproduced here; I added a line giving my estimate of the maximum power that would be achieved by the best athletes using some undefined optimum mechanism. (One mechanism that I would like to see tried is John Kingsbury's "K" Drive that takes the foot through an ellipse instead of a circle. I have bought a "K"

Drive to try it out).

The type of rowing that is used for the Concept II indoor rowers, used in the CRASH-B trials, is "free" rowing, giving as close to the feel of real rowing as possible. (CRASH-B stands for Charles River All Star Has-Beens.) Dick Dreissigacker, principal of the company that makes the Concept II, was kind enough to give me two points from the 1997 "Annual World Ranking" that he put in the "very competitive" category: 570 watts for 5 minutes, 40 seconds, and 450 watts for 18 minutes, 30 seconds. I have shown these on the plot: they can be seen to be close to a line that would go through the Boardman-Hamilton points. Dick Dreissigacker may be able to give us an article about this year's trials, or at least more data that could differentiate data by sex and by age, for instances.

Tyler Hamilton's time for the annual bicycle race up the Mt. Washington auto road in August 1997 was 51 minutes, 56 seconds, almost six minutes less than the old record. The distance is 12.23 km (7.6 miles), the vertical rise is 1429 m (4688 ft), the road surface is 40% dirt and the remainder is often quite rough. The mean grade is over 12% and the final grade is over 21%. (When I went up the Mt. Washington road at a small fraction of Tyler Hamilton's speed I found myself



doing unintentional wheelies on my Avatar 2000, so steep were some stretches.) His average speed was 3.93 m/s (8.78 mph). If I guess his weight at 70 kg (154 lb.) and that of the bike (a fairly standard Trek OCLV, according to a report and photo in *The Ride Magazine*, September 1997) 10 kg (22 lb.) the total is 80 kg. Guessing the rolling-resistance coefficient on the rough surface as 0.02, the average rolling-resistance power is 62 watts and the average power lifting his body and the bike is 360 watts. The total is 420 watts, neglecting wind resistance helping or hindering the climb, and neglecting chain and gear friction. This data point is very close to world-champion Eddy Merckx's one-hour feat on an ergometer in 1975, and to Chris Boardman's calculated power output during his one-hour record (thought to be 440 watts, from a note by Wayne Lim). It would give 6 watts per kg of Hamilton's weight, if all these guesses are correct.

What seemed equally amazing to me (besides his performance) was Hamilton's average cadence. The Ride reported stated that he had no special equipment whatsoever, and that his lowest gear was 39x25; "he rode much of the climb, however, in the 23-tooth cog, and made several surges in the 21." If he had 700-mm wheels, as seems likely, his average cadence would have been 63 RPM. This has given me a considerable lift, as it is close to my favorite cadence, and about half the level, I thought, of "real" bicyclists working at full power.

Tyler Hamilton is reported as having been seated for most of the climb, getting up on the pedals only for the very steepest pitches. This is relevant to the question of whether recumbents are slow on hills. It has often been reported that riders of "road" and "mountain" bikes have an advantage over recumbent riders, who cannot get up out of the seat to "dance" on the pedals. Hamilton has shown us that this isn't much of an advantage, even for him and his comparatively high gear on possibly the steepest hill-climb in the world (considerably steeper, according to Wayne Lim, than the Alpe d'Huez in the Tour de France).

—Dave Wilson

## TRANSMISSION EFFICIENCY

In *HP* 13/1/17/1997 I gave a brief review of a paper presented at the Seventh International Cycle-History Conference in Buffalo, NY in 1996 by Ron Shepherd, professor of engineering at Melbourne University, Australia, in which he stated that high-accuracy tests by his students had shown that the power loss in derailleur pulleys is generally considerably less than one percent of that transmitted, and that the overall efficiency of chain transmission is normally over 99%. I wrote to ask if he could write about his tests and results for the readers of *Human Power*, because his data seemed to rate transmission losses as considerably lower than those measured by my co-author, Frank Whitt, and reported in *Bicycling Science*. He courteously declined in a letter from which I am giving, with his permission, some extracts.

"Thank you for your recent invitation to contribute an article to HUMAN POWER. On reflection, however, I don't really have anything to add to the paper I presented at the conference in Buffalo. . . My interest is now more in the history than in the engineering.

"In the past as a touring cyclist I was passionately interested in the most efficient use of my energy, and following the publication of the first edition of BICYCLING SCIENCE I had several years of stimulating correspondence with your co-author, Frank Whitt, until his death.

"For some years Frank Berto and I have been compiling a history of bicycle gearing, with the intention of publishing a book called THE DANCING CHAIN. Frank is covering the 'modern' period post WW2, and I the early times up to WW2. I was struck by the fact that although the two-pulley rear derailleur was manufactured by 1908, the French shied away from it for 40 years for fear of the 'passive resistance' it produced in the chain. Then I was stung by Chet Kyle's assertion in CYCLING SCIENCE in June 1991 that ergometers were accurate only to 5% and the inference that transmission loss, which was considerably less than that, could never be measured.

"I devised an experiment with a 'cascade' of ten derailleurs in series to increase the power loss ten times and thus reach a measurable level. I took the idea to Professor John Williams in the Department

of Mechanical Engineering at the University of Melbourne. He said if we use a differential dynamometer we can measure the power loss directly, and eventually we encouraged graduate students Michael Malone and Dean dell'Oro to do the work. They showed quite elegantly that derailleur power loss was small. I hoped to extend the experiment to compare the power losses with shaft drive, belt drive, hub gearing etc. and applied to Shimano in both Australia and Japan for funding. However, I received no response and without funding the university was unable to continue the work. . ."

We need to have this experiment extended in this way, in addition to finding losses for chain drive in new-but-dirty, worn-but-clean and worn-and-dirty conditions over the range of gear ratios. We hope that someone will be able to find some funding for this valuable work.

I am looking forward to reviewing the Shepherd-Berto book for *HP*.

—Dave Wilson

## REVIEWS

### JOURNAL OF BIOMECHANICS

Elsevier Science publishes this journal in Britain, but it is used by prominent researchers all over the world to record and reference their work in the biomechanics of the production of human power, among many other fields. We have been remiss in not reviewing this journal for *Human Power*. I am attempting to cover below the relevant papers published in the last three-to-four years, even though my qualifications are not truly up to the task. If someone more qualified would volunteer to review earlier and later issues of this journal, I and our readers would be very grateful. —Dave Wilson

### A comparison of muscular mechanical energy expenditure and internal work in cycling

S. A. Kautz, M. L. Hull and R. R. Neptune, *J. Biomechanics* vol. 27 no. 12 pp. 1459-1467, 1994.

Most of the papers of interest to human-power practitioners are co-authored by Maury Hull, professor of mechanical engineering at the University of California, Davis. His co-authors are usually his former graduate students. He has produced



a steady stream of valuable papers on the biomechanics of bicycling.

This study examined the role of the pedaller's "internal work", defined as the sum of the changes of potential and kinetic energy of the components of the body (principally the parts of the lower limbs, with the upper body being considered stationary). The body's total work then consists of the "external work" of the feet on the pedals plus the (positive or negative) internal work. In 1991 Hull et al. reported on the design of a pedalling velocity profile that theoretically reduced internal work by at least 48% for the cadences used by endurance bicyclists. For the present study an oval chain-wheel was designed that approximated this velocity profile. The reduced internal work was produced by setting the long axis of the oval approximately perpendicular to the crank. This was tested, along with a circular chain-wheel, and a similar oval chain-wheel though with the long axis of the oval approximately in line with the crank, giving increased internal work compared with that for a circular chain-wheel.

No differences in power output with reduced and increased internal work were found. "...[I]t appears that designing non-circular chain-rings to limit energy fluctuations is not a sound approach for realizing a chain-ring shape which improves cycling efficiency."

This negative finding is valuable. People have spent a great deal of effort devising elliptical and other non-round shapes of chain-ring. Extravagant claims have frequently been made. It is noteworthy that these non-round chain-rings have never, to my knowledge, been used to win races over any distance.

The only criticism that I could make on the work is that the subjects were allowed to pedal "for 3 minutes to become accustomed to the chain-ring". It may take the body considerably longer to become accustomed to any unusual pedalling action.

#### **The influence of Tendon Young's modulus, dimensions and instantaneous moment arms on the efficiency of human movement**

M. Voigt et al., *J. Biomechanics* vol. 28 no. 3, 1995.

Young's modulus is the springiness or elasticity of a material. The experimental

part of the investigation was carried out using seven male subjects who, a month before the experiments, had been asked to become accustomed to small repetitive jumps by using a skip rope. Measurements of the positions of "anatomical landmarks" during jumping were made using high-speed cameras. A mathematical model of a human being, incorporating variations in tendon modulus and in the moment arms that the distance of the tendon attachment point to the joint provided, was also studied and correlated with the human study. Some measurements of the properties of tendons from cadavers were also made. Considerable differences in Young's modulus were found.

The conclusions were that variations in tendon modulus and in moment arm have a large effect on human output, and "can explain observed inter-individual differences in movement economy."

One is born with the instructions for one's final tendon moment arms, and presumably for the characteristics of one's tendons. There was no indication that exercise or diet could change the tendon properties, although it seems likely.

#### **The effect of rider weight on rider-induced loads during common cycling situations**

Cal Stone and M. L. Hull, *J. Biomechanics* vol. 28 no. 4 pp. 365-375, 1995.

This is the latest in a series of Maury Hull's bicycle-loading studies of increasing sophistication. Early measurements were on seated riders and measured just pedal loads. In this study, five cyclists of varying weights (547 - 894 N), cat. 2 to cat. 4 racers, rode a bicycle on an inclined treadmill, during simulated seated cruising, seated climbing, and standing climbing, during which measurements of loads and moments were taken along all significant axes at the pedals, the handlebars and the seat. (Only seated-cycling results are reported here). Three types of loading were recognized: rider-induced loading from pedalling forces and from the rider's weight; surface-induced loading from traversing surface irregularities; and control-induced loading from braking and steering.

In a study as complex as this it would be foolhardy of this reviewer to try to summarize the results in a paragraph. The obvious was not found: all loads did not increase in proportion to the rider's weight.

Some did, many rather surprisingly did not. Readers will need to examine the paper in detail to profit from the many data plots and tables. We look forward to a future paper on the loads from standing cycling. The authors' conclusions state that the present data should enable analyses to be made for fatigue failure at the bottom bracket, "the region most prone to fatigue failure". I am delighted that data are given for handlebar loads: during my many years of riding upright bicycles I never had a failure near the bottom bracket, but have had three (aluminum-alloy) handlebars fail during use, in addition to several aluminum-alloy and steel cranks. These data should be used by all designers, from those of discount-store "cheapies" to those of the top-rung racing road bikes. And recumbent designers can learn from the data too.

#### **An improved-accuracy six-load-component pedal dynamometer for cycling**

Tom Boyd, M. L. Hull, and D. Wootten. *J. Biomechanics* vol. 29 no. 8, pp. 1105-1110, 1996, Elsevier Science Ltd., UK

This is the latest in a series of pedal dynamometers of increasing capability and accuracy. This used elements called "shear panel elements" or SPEs, flexing elements having compliance in one direction over a hundred times that in the orthogonal directions. A compact arrangement was designed so that the pedal did not feel strange to the subjects. Strain-gauges give readings that convert to loading. The principal purpose of this sophisticated dynamometer is to investigate loads that could contribute to knee-overuse injuries. The paper quotes two reasons for these injuries: overtraining, from riding in too high a gear, or overdoing it too early in the season; and "pathomechanical injuries", resulting from misalignment between the pedal path and the rider's accustomed pedalling action.

The paper gives some details of the design of the dynamometer and some sample results. As with other papers reviewed here, a full list of references is given, with credit given to previous researchers who contributed concepts or techniques.

#### **Pedal and knee loads using a multi-degree-of-freedom pedal platform in cycling**

Thomas F. Boyd, R. R. Neptune, and M. L.



Hull. *J. Biomechanics* vol. 30 no. 5 pp. 505-511, 1997. Elsevier Scientific Ltd., UK.

The hypothesis being tested was that knee-overuse injuries could be alleviated or prevented by the use of pedals that allowed two degrees of rotation of the foot relative to the pedal. Ten male volunteer competitive cyclists rode a conventional bicycle (adjusted to the configuration of each subject's own bicycle) on a Schwinn Velodyne ergometer. They were tested using four pedal platforms: one having zero degree of freedom; one having one degree of freedom, of rotation about an axis along a fore-aft line through the pedal surface; a second one having one degree of freedom, of rotation about a perpendicular axis through the pedal surface; and one having these two degrees of freedom simultaneously. The pedal loads were measured using the pedal dynamometer described in the paper reviewed above, and the knee loads were inferred from video and encoder measurements on the subjects applied to a model of the bicycle and rider as a five-bar system.

The results showed that, indeed, knee loads were reduced more by the two-degree-of-freedom pedals than by either of the one-degree-of-freedom pedals. However, "The benefits of BOTH [the two-DOF pedals] did not manifest fully at the knee. Whereas at least half of the eight quantities describing each of the coupled moments was significantly reduced at the pedal . . . none of the quantities associated with the coupled loads was reduced significantly at the knee. . . . However, all quantities associated with both coupled loads were lower on the average, thus indicating a general nonsignificant reduction."

The results were therefore not as marked as was expected. There was a comment that this may be a function of averaging across the ten subjects.

My own inexpert musing on this points out that individuals vary widely. Some people bicycle all their lives and have few knee problems, while others have to give up biking because of severe difficulties. As the discussion states, "care must be taken in applying the results to each individual." It

may also be that the knee, or some knees, is/are affected by quite small loads in directions other than the predominant.

This and the other papers are written in precise medical/biomechanical terms, difficult for a lay reviewer to interpret precisely, for which I apologize. It is also a warning that the lay reader must be prepared to spend time understanding and/or translating the terms to match her/his vocabulary.

#### **Muscle coordination of maximum-speed pedaling**

Christine C. Raasch et al., *J. Biomechanics* vol. 30 no. 6, pp. 595-602, 1997. Elsevier Scientific Ltd., UK.

Here, "maximum-speed pedaling" means "pedaling to achieve maximum speed on a bicycle or maximum power output on an ergometer", rather than pedaling against no resistance to reach maximum RPM. The work was carried out at the Palo Alto Veterans' Affairs (VA) facility by Stanford mechanical engineers, principally. My review will consist of some quotations.

"Pedaling . . . seems to require complex muscle coordination, as evidenced by recorded electromyographic patterns. . . . Maximum-speed pedaling was chosen because it has a clearly defined goal, which allows us to produce a simulation using optimal control, and because this goal requires transferring as much energy as possible from the muscles to the crank subject to the specific frictional and inertial load encountered at the crank.

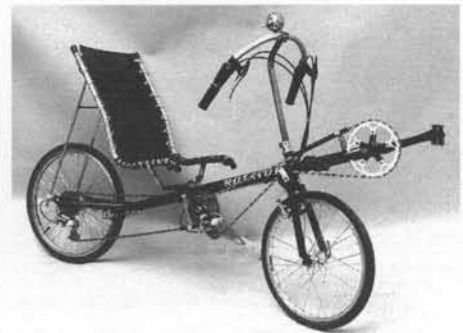
"Over the crank cycle, uniarticular hip and knee extensor muscles provide 55% of the propulsive energy, even though 27% of the amount they produce in the downstroke is absorbed in the upstroke. Only 44% of the energy produced by these muscles during downstroke is delivered to the crank directly. The other 56% is delivered to the limb segments, and then transferred to the crank by the ankle plantarflexors. [These], especially soleus, also prevent knee hyperextension by slowing the knee extension being produced during downstroke by the other muscles, including hamstrings. Hamstrings and rectus femoris make smooth pedaling possible by propelling the crank through the stroke transitions."

—Dave Wilson

## **LETTERS**

### **A BEGINNING RIDER'S COMPARISON OF A ROTATOR TIGER AND A BikeE**

I had a chance recently to ride my first SWB bike, and only my second recumbent. A friend brought along his new Rotator Tiger and we took turns riding two five-mile stints each on it and on my BikeE AT/AA (with rear suspension). The rides took place on a flat concrete trail with 25–30 mph quartering head-wind. Admittedly, this was both a first and a very limited experience for me, so please consider my observations those of a newbie.



**Rotator Tiger**

Impressions: the higher bottom bracket of the Tiger was very much easier to ride into the wind. On the BikeE, I could feel the wind full on in the chest and I was bothered more by cross-wind gusts.



**BikeE AT/AA**

The higher bottom bracket made the lateral muscles in my butt hurt in new places. Although the seat needed to go back further, the position felt much more natural than that of the semi-recumbent BikeE. When I switched back to the BikeE, it felt much too upright in comparison and I felt that I had less leverage.

The Tiger was much faster in all scenarios, but especially going down long hills on the ride over to the trail head. My friend on the Tiger disappeared just coasting while I pedalled as hard as I could in a futile attempt to catch up. On the flats, into the wind, my friend (with whom I have never ridden before, so I don't know his strength) on his Tiger could ride along easily while I worked hard to keep up. When we switched bikes, I disappeared without much effort on the Tiger.

This was my first ride on a SWB bike. Its steering feel was not appreciably different from the CLWB BikeE at slow speeds but it seemed to track a little truer at speed. It seemed less affected by pedalling than the BikeE, especially at slow speeds.

The BikeE AT/AA was great flying over the rutted out parking lot between the trail head and our starting point while the Tiger seemed to bounce all over the place. I could sustain much better speeds because of the suspension on the BikeE.

—Bud Shaw <bshaw@hepar.unmc.edu>  
*(I asked for permission to reprint this letter to the hpv@ihpva.org list because of the contrast with the findings of the strong and highly experienced Zach Kaplan. There could be several alternative explanations of the apparently slower performance of the BikeE, including possibly inferior or partly inflated tires. - ed.)*

#### **CLIMBING ABILITY ON A RECUMBENT WITH A LOW BOTTOM BRACKET**

This note is about a 78-km ride up and around Mt. Tamalpais [north of San Francisco, CA] that I took on a Gold Rush Replica with body stocking. I was with a friend riding an upright. He prides himself on his climbing ability. This was my first climbing test of the bike against a strong upright rider. While he wasn't in peak shape yesterday I found I had to slow down for him on the climbs. He appeared to be really struggling climbing out of the saddle while I had some 20 beats more per minute to go before reaching my aerobic threshold and felt absolutely great. No lactic-acid build-up in the legs as with bikes with high bottom brackets. I think it is fairly clear now the GRR is the fastest-climbing recumbent I have ridden and that is with the full body-stocking package and mudguards. I was frequently seeing speeds of 20 km/h on climbs on which I seldom

top 15 km/h climbing on a high-BB bike. My spin feels smoother with the low BB, more like the natural pedalling dynamics of a road bike vs. doing bench presses. When I went to my cycling podiatrist (who answers medical questions in *Bicycling* magazine) for a bike fitting the other week he remarked this bike was a much better configuration than the previous recumbents I had brought in for fittings. He explained how blood circulation and lactic-acid removal is better with a low BB. Must be why Ed Pavelka went that way too. The bike climbs great and amazingly I have had zero rear-end pain on it. I thought I'd get it with the upright (by my standards) seat back but for some unexplainable reason don't. Could it be because I am using that prototype padding from Eric House's seat? Could it be because I pressed the seat back into its most laid-back position and have a 559-mm rear wheel giving an even-more laid-back position? (I did once get pain on a Tour Easy seat but it was fairly upright and used a different type of foam.

Coming down the mountain was a blast. It was quite gusty yet the bike didn't get blown around much. I would have been blown off the road descending at those speeds on a Lightning F-40. The inherent stability of the LWB was also much appreciated on the descent. I had to wait up several times for my roadie friend. At the bottom of one descent I remarked "this is the ultimate recumbent for Marin County, fast for a recumbent on the climbs, a reasonable speed advantage on the flats and downhill

but not so aerodynamic that cross winds and brake heating become problems."

The token LWB in the fleet is becoming my favourite bike. Once I get the Festina with fat tyres I'll do some more rigorous climbing and coast-down tests between the two and decide which I take on the Terrible Two this year. Based on the poor rough-road handling of the skinny-tired Festina I had been riding combined with inherent lack of gearing range due to its configuration I don't have much hope for it being the Terrible Two bike. After all I haven't even put fat tires on the GRR yet which I would do for the rough roads of the Terrible Two. Ah...the beauty of a 406/559 GRR: too bad you can't get them that way from the factory! I look forward to the Rans Limbo.

I am still getting experience with this bike and trying to figure out why it climbs so well. My background is mostly with high-BB bikes. I had resisted low-BB designs in part due to their lack of acceptance in Europe and general thoughts of the LWB being an archaic configuration in comparison to high-BB SWBs based on what I had read about SWBs being better climbers and inherently more aerodynamic..

—Zach Kaplan  
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**Tandem human-powered hydrofoil from a Yamaha team, competing in the 1997 human-powered boat race on Lake Hamana, Japan. Photo, courtesy Toshio Kataoka.**

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## EDITORIALS

### REVOLUTIONS

“How can people/industry/politicians be so crazy?” This is the theme of many contributions to Internet mailing lists, letters to the editors of bicycling magazines, and even editorials of those magazines when the excesses of today’s car culture are brought up. Even in a country like the USA where fitness has become an obsession, most people exercising do not seem to think it illogical to drive automobiles to gyms while doing their best to avoid walking or—horrors!—bicycling as part of their daily lives. Huge quantities of tax money are regularly voted to fund research on strange improvements in automobile transportation, such as “intelligent vehicle systems” and hybrid and turbine engines. It is easy to think that we who enjoy commuting and travelling by our own exertions are in a hopeless minority, derided or at best tolerated by the great majority.

When I feel discouraged by these thoughts I am buoyed up by contemplating the movement for nonsmokers’ rights. I was involved in a small way in this battle when the situation had a lot in common with the present one of nondrivers’ rights. Everyone, it seemed, smoked everywhere: in classrooms, restaurants, theatres, transportation systems, even religious meetings. I set myself up as the local disciple of John Banzhaf, an MIT engineer who went on to law school and later started an organization called ASH: Action on Smoking and Health. He was given a small grant by, I believe, a patient of a Harvard thoracic surgeon who was also concerned about the effects of smoking on health. Banzhaf used the money to have some TV “public-service” advertisements made. At that time there was a “fairness doctrine” that was applied to TV broadcasting, and he went to the courts to claim that unopposed advertisements extolling smoking was manifestly unfair. The courts agreed. I formed the first local branch of ASH, called, since we were in Massachusetts, MASH, and was laughed at far and wide. “Dave, be real” my friends would say. “Everyone smokes. The tobacco lobby is huge. Politicians are in its pockets. You can’t change America!”

The change that John Banzhaf brought about is so great that it is bizarre. Tobacco companies are talking about being driven

out of business. Even politicians who greedily accept huge donations of tobacco bribes - apologies, donations - have turned against them.

Automobile companies are not evil, as I believe the tobacco companies were evil. But the effects of the almost-unopposed automobile culture all over the world are far greater and far more destructive. We need a prophet like John Banzhaf to lead us out of the wilderness!

### GOOD NEWS, BAD NEWS!

The motor-vehicle industry is changing in many ways. It has rather suddenly decided to go further in reducing emissions and in providing safety measures than government regulations require, after decades of fighting tooth and nail against earlier, milder regulations. It has also found that it has a large over-capacity, and it is targeting China as a country ripe for traffic jams, shopping malls, endless dreary suburbs with filling stations on every corner and dumps of rusting vehicles everywhere. Just as the tobacco companies have always found scientists who maintained that smoking was not harmful to smokers or nonsmokers, the automobile companies are supported by scientists who claim that there is no danger of global warming or the destruction of the few wild places left on the earth.

Switching to our own industry, each one of us must puff out a little with pride when we read HPV magazines from Britain, Germany, the Netherlands, Switzerland and several other countries where HPV groups have become active and have created exciting vehicles and events. I eagerly await each issue of *RCN-Recumbent Cyclist News*—and now *Recumbent UK*—to see what new models have been brought out for our enjoyment and to enhance our healthful lifestyle.

Then I wistfully hope that these halcyon times persist. The HPV industry is at about the stage of the automobile industry in, say, 1905: trying out all kinds of exciting and different approaches, but not a universal concern (with honorable exceptions) for such factors as safety and weather protection. The reports in the last issue of exploding aluminum rims saddened me. The bicycle industry sold bicycles for decades that had almost no braking when the (chrome-plated-steel) rims got wet. When government regulation threatened, it switched to aluminum rims to solve the

wet-weather-braking problem while introducing another danger that is impracticable for the ordinary user to foresee or solve. (Obviously I’m pointing at the wider bicycle industry here, on which we in the HPV branch depend for most of our components).

So the bad news is simply my arbitrary selection of three news items. Some auto manufacturers are fitting air bags in the doors and over the heads of drivers and front-seat passengers; drivers in the U.S. are switching to ever-bigger sports-utility vehicles and trucks so that they are more likely to survive a collision with a smaller vehicle; and we ride bicycles and HPVs on wheels, the rims of which can explode at any moment, and we seem to puff out our macho chests. Something is out of kilter. We should insist, and be prepared to pay for, something better.

### RECUMBENT MAINSTREAM?

The first two issues of *Recumbent UK* have arrived with color covers, crisp clear printing, news items, editorials, humor (some provided by Wade Nelson), cartoons, attractive advertisements and, in general, an air of authority and “place”. In other words, editors Richard Loke and Richard Taylor have avoided giving any impression that this is a magazine for a lunatic fringe. That alone is refreshing. It is also far-ranging rather than insular: the cover [of the second issue] is a beautiful photo of a Double Vision being propelled past what could be a great estate, and the back cover is of a Greenspeed trike equipped with the lighting of a Mack truck and cruising up a steep hill with “regulars” in cheerful pursuit. The note at the end of the editorial page: “Blame the editors for anything unattributed” is informative, and also means that authors’ names are scrupulously given for the contributions not written or harvested by the two Richards.

The magazine complements rather than competes with Bob Byant’s *Recumbent Cyclist News*. To spring fully formed like Zeus from the womb of the British HPV movement is either an act of great courage or is a sign of UK/European vitality that is very encouraging. We wish *Recumbent UK* well: it can do our movement a great deal of good, as *RCN* has done. May you both survive and prosper!

—Dave Wilson

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