Efficiency Measurements of Bicycle Transmissions - a neverending Story?

by Bernhard Rohloff and Peter Greb (translated by Thomas Siemann)

In *Human Power 52 (Summer 2001)* there was a report of an efficiency test of bicycle transmissions "The Mechanical Efficiency of Bicycle Derailleur and Hub-Gear Transmissions" by Chester. Kyle PhD, and Frank Berto. The test included three derailleur systems with from 4 to 27 gears as well as eight gear hub transmissions with from 3 to 14 gears. The results of the test are summarized in the table below:

Table 1: Derailleur and gearhub transmission efficiencies measured by Kyle and Berto.

Transmission Type:	Efficiency (%)
Derailleurs	87-97
Gear Hubs	86-95
Note: Test performed with 80W, 150W, 200W input.	

The motivated reader of the report will find contradictions behind their measurements. Our specific interest in giving a critique of the publication is based on differences of the results compared to our efficiency measurements. These can be summarized as follows:

Table 2: Derailleur and SPEEDHUB 500/14 efficiencies as measured by Rohloff.

Transmission Type:	Efficiency (%)
Derailleurs	95-98.5
SPEEDHUB 500/14	95-98.5
Note: Test performed with 400W input.	

The lower range of Kyle and Berto's measurements are up to eight percent lower than those made by Rohloff. The reasons for this are presented in this document.

1. Verifiability - The text does not say if only single measurements were performed or if the measurements were confirmed by repeated measurements. Furthermore, there is no information about the duration of break-in time the testing samples underwent. This is especially important for hubs with dragging seals which need a minimum run-in time in order to level off friction losses from the seals. Rohloff has determined this to be extremely important for tests under 200W; this will be discussed later in this document.

2. Precision of measurement – The results are shown as absolute values with no information about the tolerances of the measurements. Only the precision of the dynamometer and the tachometer were given without any information about the width of the measuring range and the related tolerance variations. The ergometer wheel produced variable losses of over 2% with different loads. The ergometer wheel losses at different speeds were not measured. However this is important when evaluating transmissions with a large range of gears such as the 27 speed derailleur system or the Rohloff SPEEDHUB 500/14, because the speed differences between the smallest and largest gear are more than 500%.

3. Plausibility - The report regarding the gearhubs states correctly that the efficiency of planetary gear systems drops as the number of active gears increases. This fact should reflect itself in the measurements of the efficiency of the gearhubs.

The speed-ratio of the Sachs three speed hub is reducing in gear one, increasing in gear three, and direct drive in gear two. Unlike gears one and three, there shouldn't be any gearing losses in gear two. At 80W the measured efficiency of gear two is much lower than those of gear one and gear three, which is not evidently plausible. At 200W the results are very similar in all three gears with efficiency values of 94.1%, 94.9%, and 94.1% for gears one, two, and three respectively.

The trend shown that the efficiency of the SPEEDHUB 500/14 drops in higher gears is also in contrast to the design of the transmission as well as the fact that gear four and gear nine are more efficient than the direct drive gear eleven. In gear eleven there cannot be any gearing losses since no planetary gears are rotating, unlike in all other gears. As can be seen in Table 3, in the first seven gears there is always one more gearset active than in the higher seven gears. Therefore, the losses in the higher seven gears must be smaller than the losses in the lower seven gears.

Table 3: Active gear sets in the Rohloff SPEEDHUB 500/14 for each gear.

Gear	1	2	3	4	5	6	7	8	9	10	11	12	13	14
No. of active gearsets	2	2	3	1	3	2	2	1	1	2	0	2	1	1

There are three planetary gear sets linked in series in the SPEEDHUB 500/14. The single gears are the result of different combinations of gears within those three gearsets.

The efficiency variations of the Shimano four speed, Shimano seven speed, and Sturmey-Archer 7 speed transmissions do reflect the construction of the transmission.

4. Validity – The validity of the testing method. The measurements made by Kyle and Berto were performed while applying constant torque with power input at 80W, 150W, and 200W. Those loads were meant to reflect a typical bicycling situation. Rohloff does not believe that the loads or the power applied sufficiently model a typical cyclist. The power produced by the cyclist consists of a relatively constant speed and widely variable torque due to the crank kinematics. Measurements show that while speed variations of about 5% are typical, the torque variations can be over 90% throughout a single crank revolution. Table 4 shows the results at different power inputs.

Table 4: Maximum and minimum torque measurements during a pedal stroke.

Power input (W), Speed (rev/min)	100 W, 75 rpm	300 W, 75 rpm	575 W, 50 rpm
Max. Torque (N·m)	21.6	68	200
Min. Torque (N·m)	3.8	8	20

The power characteristics are largely governed by the torque component.

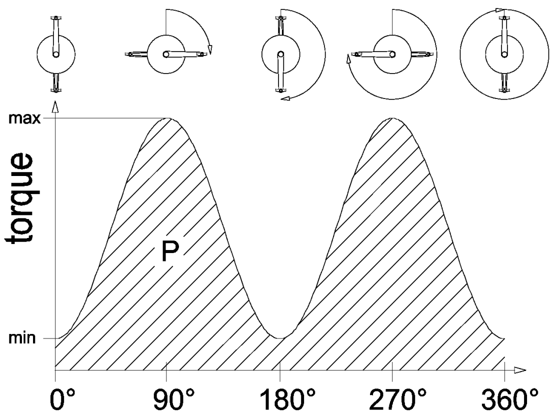


Figure 1: Torque vs. crank angle for one crank revolution. Power is area under curve.

The cyclical torque of a cyclist produces an alternating load situation on all power transmitting parts, chainlinks, chainrings, bearings, gears, etc, which is very important to keep in mind when evaluating the mechanical losses which effect the efficiency.

A precise simulation of the cyclical torque is not easy to produce in the laboratory and from a measuring point of view, excessively costly. For this reason electric motors with a constant power input are used. This brings up the question of how to choose the appropriate power input when using a constant torque so that the efficiency measurement correlates to the efficiency that would be measured with the cyclical load actually applied in the real world.

We encountered a similar problem when designing our chain and chainring wear test, which is operated at constant torque. Extensive comparisons between components used in real world and components worn out on the test bench showed the following: If the field-tested components were used at an average of 150 W with an average cyclic torque between 5 Nm and 30 Nm, this correlated to a chain tested at a constant torque of 30 Nm in our laboratory.

It can be assumed that the reasons that cause the wear of components are the same ones that are responsible for the efficiency. Therefore you can deduce from the comparisons that a in a lab test, a constant power input using the maximum value of the cyclic load produces results that are closer to reality than choosing a constant power input using the average load.

For example, an average cycling power 80W in real life should be simulated by a test bench power of 160W at the same speed.

5. Interpretation of the measurements – In order to give a correct interpretation of the results it is important to establish what the losses are composed of.

Losses are created by friction. The value is determined by the type of friction (rolling or sliding), the size of surfaces in contact, type of surface finish, material hardness, lubrication, combination of the rubbing parts. Two separate types of losses exist in bicycle transmissions:

A) Power dependent losses. These are created by friction of parts that are moving under a driving load, i.e. chainlinks, gears, bearings, etc. The quantity of the loss grows proportionally to the transmitted power.

B) Power independent losses. These losses are created by friction of moving parts and are not changed by the driving load, in other words these losses are constant regardless of the load applied, e.g. Gaskets and shims. With lubricants, the quantity of loss depends on speed, temperature, and lubricant viscosity.

In the following example, two bicycle transmission systems are compared. Both have a 91% efficiency at 50W input. They have two different power dependent and power independent losses.

In system A, seven percent of the input power is lost due to power dependent friction plus one Watt of power independent friction for each value of input power. The values shown in Table 5 are input powers from 50 W to 500 W with their respective efficiency ranging from 91%-92.8%.

Table 5: System 'A' power loss components.

Input Power (W)	50	100	200	300	400	500
Power dependent losses (7%) (W)	3.5	7	14	21	28	35
Power indepedent losses (W)	1	1	1	1	1	1
Total loss (W)	4.5	8	15	22	29	36
Total efficiency, (%)	91	92	92.5	92.7	92.75	92.8

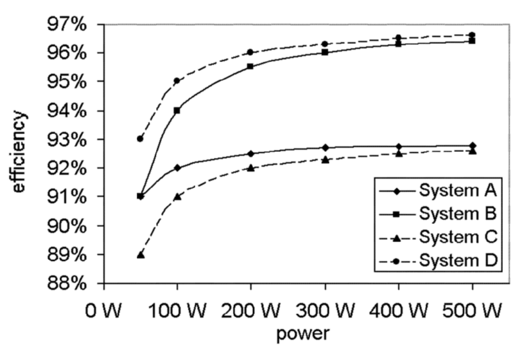
Table 6: System 'B' power loss components.

Input Power (W)	50	100	200	300	400	500
Power dependent losses (3%) (W)	1.5	3	6	9	12	15
Power independent losses (W)	3	3	3	3	3	3
Total loss (W)	4.5	6	9	12	15	18
Total efficieny (%)	91	94	96	96	96.3	96.4

In system B, only three percent of the input power is lost due to power dependent friction that exists in the chain, gears, etc. An additional 3 W of power is lost due to power independent friction that exists due to tight seals.

At 50 W power input the efficiency of system 'B' is at 91%, the same as system 'A.' At higher power inputs, the overall efficiency increases until it reaches 96.4% the efficiency is significantly higher than the efficiency of system 'A.' This is due to the fact that the power dependent losses become dominant over the power independent losses at higher power inputs.

Figure 2: Total efficiency of system A through D.



In addition to curves for systems A and B, Figure 2 also shows curves for systems C and D. The curve for system C describes how the power independent losses increase from one to two Watts due to temperature or lubricating film changes at the seal of system A. The curve for system D describes the efficiency changes of system B with a reduction from three to two Watts of the power independent loss for the same reason. The examples show that for power input of less than 200 W that even small changes of +/- 1W of power independent losses play a large role in the overall efficiency. Since power independent losses are the result of a complex relationship between speed changes, temperature changes (created by own friction heating), and lubrication. These variations can occur in the test situation. If power input is less than 200 W, it must be confirmed that the influence of those variations are verified by repeated tests. Over 200 W the influence of power independent losses can be neglected.

Knowing that, all measurement values shouldn't be absolute values, but rather represented as a range of values showing the corresponding upper and lower boundaries.

6. Reason for efficiency measurements – The reason for efficiency measurements is to find out which one of the different bicycle transmissions converts the most of the bicyclist's power into forward motion. To propel the rider forward in the most efficient manner, it is important that the rider be able to choose an appropriate gear for the given load or riding situation, a gear that is suitable to the rider's fitness level.

The development of power in the muscles is subject to a grade of efficiency. This efficiency is the ratio of metabolic capacity and the delivered mechanical power, i.e. the power at the crank. The efficiency depends on the muscle power combined with the speed of movement, if both variables reach their optimum, the muscle efficiency can increase by 25%. [See also article by Too and Landwer in this issue. Ed.]

The differences in muscle efficiency between positive and negative fatigue ratios (bodily stress/developed power) can easily vary by 10%. This is of much larger value than the variation of mechanical efficiencies of various bicycle transmissions systems.

Table 7: Comparison of muscle and mechanical efficiency of the bicycle-rider system.

	Rider A	Rider B
Muscle Efficiency (%)	24	22
Transmission Efficiency (%)	93	97
Overall Efficiency (%)	**22**	**21**

Rider A is using a perfect gear ratio for the situation and his muscle efficiency is 24%. His bicycle transmission is moving in a gear with relatively poor mechanical efficiency of 93%. Rider B is using an unfavorable gear with a high efficiency of 97%., however, because of the unfavorable speed, his muscles work at 22% efficiency. The overall efficiency shows taking into consideration muscle and transmission losses that rider A is riding more efficiently even though his transmission efficiency is lower than rider B's.

In order to use the rider as a "bicycle engine" most effectively, the ratio increments between the gears are as important as a good mechanical efficiency. The most efficient energy conversion is very limited using transmissions with only a few gears. A larger selection of gears with smaller increments make a favorable energy conversion possible in a wider range of riding situations, but only if the correct gear is used. Sport medical research shows that the increments between gears must be smaller than 15% to benefit the rider's efficiency.

Under this point of view it does not make sense to compare transmissions with only a few gears, large gaps, and small overall range, with transmissions with many gears, small increments, and a large range of gears. A comparison of different transmission systems should always take the application into consideration.

7. Conclusions

A) All measurements below 200 W need to be evaluated cautiously because the influences of the variations of the power independent losses are high.

B) From a practical point of view changes of efficiency play a major role only when riding above the recreational level i.e. greater than 100W.

C) When comparing transmission systems, gear range and number of gears should be taken into consideration in addition to the efficiency.

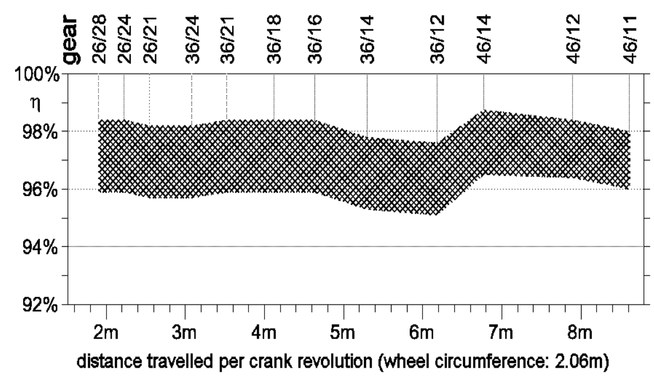
Rohloff measurement results – We would like to point out that the points represented here should be a stimulus for a discussion since there are so many open questions in the field of practical efficiency measurements of bicycle transmission systems. As a comparison to Kyle and Berto's results, our results in Figure 3 and Figure 4 show our efficiency measurements of a 24-speed derailleur system with 46-36-26 toothed chainrings and Shimano XT 11-28 toothed cassette, and the Rohloff SPEEDHUB 500/14 with a primary gearing of 46 tooth chainring and 16 tooth hub cog. Both systems had been run in for 100 km.

The measurements include the losses of the complete transmission, bottom bracket, chain, hubs, etc. In order to simulate a strong rider who applies about 160 W and produces a maximum torque of 50 Nm (285 N @ pedal), the measurements were taken at a power of 314 W with constant torque.

Table 8

crank speed (rev/min)	60
brake power, constant (W)	314
torque (Nm)	50

Figure 3: Efficiency of a 24-speed mountain bike drivetrain.



The reproducibility of the results and their precision was verified by repeated test runs. Figure 3 shows the efficiency of the derailleur system plotted vs. distance per crank revolution. Note the gear ratios are not consistently spaced as can be seen on the plot.

The derailleur system was tested first in clean and well-lubricated conditions. In order to achieve results closer to real-life use, the chain and the sprockets were replaced with components which had been subjected to 1000 km of field use and had not been cleaned. The average efficiency was measured to be 1% lower than the clean drivetrain. The plot in Figure 3. includes the data for a new and used drivetrain and a +/- 0.5% uncertainty.

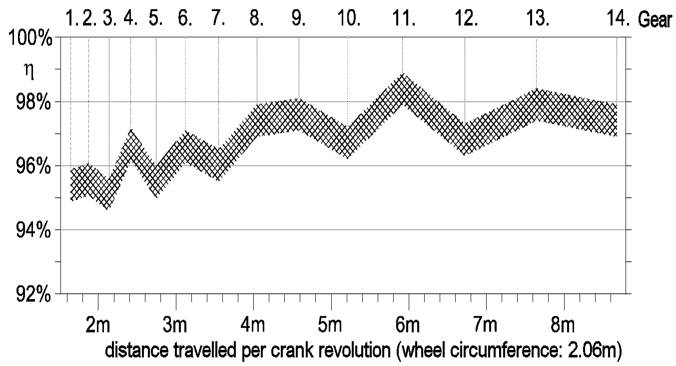


Figure 4: SPEEDHUB 500/14 efficiency

Figure 4 shows the efficiency range of the Rohloff SPEEDHUB 500/14 plotted vs. distance traveled per crank revolution. The increase between all gear ratios on the SPEEDHUB 500/14 is always the same percentage. Sprocket and chain were replaced by components ridden 1000 km. Efficiency differences were not measureable. The range of efficiency represents the used and unused drivetrain plus the +/- 0.5% uncertainty.

Figure 5 shows the efficiency ranges of Figures 3 and 4 on the same plot for comparison.

The efficiency of internally geared hubs drops when the number of working planetary sets increases. This fact must be shown in the efficiency results of the gear hubs tested. In the SPEEDHUB 500/14 there are three planetary gear sets that can be used in series. The unique gear ratios are created by engaging different combinations gears within these planetary sets. Table 3 shows the number of the active (working) planetary gear sets per gear. Figure 6 shows the range of efficiency of the SPEEDHUB 500/14 plotted vs. gear number. The efficiency plots confirms the number of the active planetary sets as represented in Table 3. Gear 11 has the highest efficiency because it is the direct drive gear, no planetary gearsets are activated. The curve between gear 1 and 7 corresponds with the curve between gear 8 and 14. This is due to the fact that the first two planetary gear sets are shifted between gears 1 and 7 in the same way as they are between gears 8-14, however gears 1-7 have an extra planetary gearset activated providing a compound low gear. The efficiency between gear 1-7 is about 2% lower due to the use of the third planetary gear set. In order to show this fact more clearly the curve between gear 8-14 has been copied and shifted to the left so that it can be compared with the curve representing the efficiencies of gears 1-7. The results correspond to the gear combination or respectively to the number of active planetary gears inside the hub.

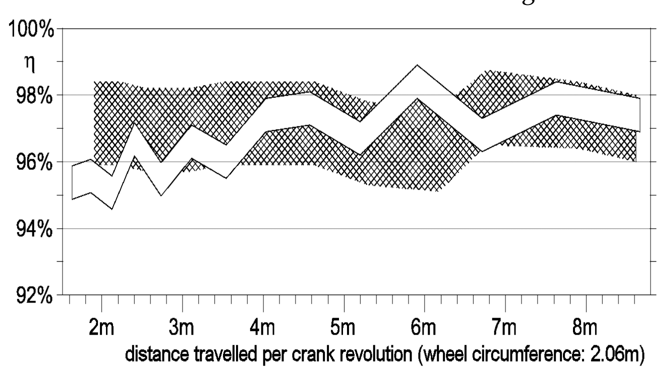


Figure 5: Efficiency of both derailleur drivetrain and Rohloff SPEEDHUB 500/14

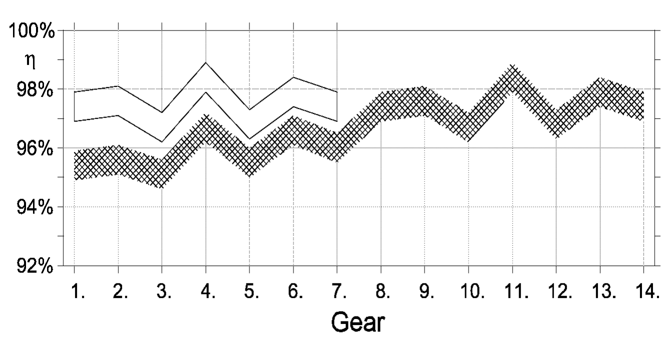


Figure 6: SPEEDHUB 500/14 efficiency comparison.

Gears 8-14 shifted to the left to compare with gears 1-7.

Conclusion – The explanations show that efficiency of bicycle transmissions depends on many factors of which exact measurements may involve prohibitive costs. In order to measure real-life values, factors such as contamination, lubrication, wear, and production tolerances should be included as well as sports medical research. We think that there is still a lot of room for tests and discussions.

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Reply from Chester Kyle

Dear Editor,

I have read Rohloff's remarks on our transmission efficiency tests and have several comments on their discussion.

Our tests were run over a two day period. It would have been better to test repeatedly over longer periods, but this was not possible due to limited time and funds. However, we feel that the results are valid under the conditions we tested.

We understand the position of Rohloff, whose transmission did well in our tests when compared to other hub gears, but whose efficiency was about 2% lower than the derailleur transmissions. It's natural for researchers to question the test methods of others when results don't agree with their own. However, the principle reason for the Rohloff's disagreement is the difference in applied power input between the two test methods. We will comment more on this later. Rohloff's laboratory efficiencies were about 2% higher than ours, but this is understandable given their methods.

All of our transmissions were tested and compared under the same conditions. Our test efficiencies were repeatable to within less than one percent over two separate test sessions several months apart. For the conditions we tested under, our methods were sufficiently accurate to discriminate between transmissions and gears and to rank order the efficiency of the transmissions. All of the hub gear transmissions were tested using light oil as a lubricant. However, the Rohloff was new and not worn in before testing. This could have affected the efficiency under low loads, but probably not under loads of 200 watts or more.

We chose to compare all of our transmissions at 200 watts average load or less and at a constant cadence of 75 RPM. Ordinary hub gears are never used in bicycle racing and are seldom even in recreational cycling. They are, however, commonly used on European city commuter bikes where speeds are almost always below 25 km/h. Power requirements for low speed commuting are normally less than 150 watts. 200 watts average power is sufficient to propel a bicycle at over 32 km/h on level ground with no wind. Therefore except in laboratory experiments, hub gears are almost never subjected to the high loads that derailleur transmissions are. Rohloff is correct in saying that efficiency improves as the load increases. They tested at 400 watts, double what we did and found efficiencies approaching 98%. We tested only one transmission at more than 200 watts and found the Shimano derailleur transmission in 25th gear, under loads from 307 to 370 watts input, was about 98% efficient (our Figure 14).

Because of the high inertia of the bicycle rider system, the speed variation due to variable torque (pedal force) at the crank is very small. At racing speeds a computer simulation shows speed variation is less than plus or minus 0.13% due to the variable torque of the crank. We therefore felt that testing at a constant speed of 75 RPM was realistic. Racers pedal at a higher cadence, but the purpose of our tests was to approximate more normal riding conditions.

Simulating variable crank torque is not practical with an electric motor dynamometer and as far as I know, no current or past transmission test apparatus has successfully used this technique. Rolhoff applied a much higher constant torque than our average to simulate maximum chain tension and gear and chain wear, but this also is not realistic. Transmission efficiency varies continuously around the crank cycle - it is high under high torque and lower under low torque. The average efficiency is somewhere in between. Testing only at high torque as Rohloff did, does not give an accurate comparison. Unless transmissions are tested on the road or in the laboratory using a precision research crank dynamometer with an actual cyclist, there is really no certainty which of the laboratory test methods is more valid. Unfortunately highly accurate laboratory crank dynamometer tests have not yet been developed.

To summarize, we are reasonably confident that the rank order between transmission efficiencies that we found would not change appreciably as load is varied within a normal range. In other words, transmissions should rank about the same at either low or high loads. We feel that the loads we tested under are typical of the actual conditions under which hub gears are used and represent a reasonable average efficiency. In our article we therefore concluded that hub gears are about 2% less efficient that derailleur transmissions under typical field conditions. We see no reason to change that conclusion.

The Rohloff is an excellent transmission - in fact it is quite elegant in its function - it shifts sequentially from gear 1 through gear 14 easily and logically - unlike triple chainring derailleur transmissions. The Rohloff would probably serve well for HPV racing since it would much simplify the chain line.

– *Chester Kyle*

[Ed. Comment, also applying to the article by Vernon Forbes on the next page: I never cease to be amazed at the extremely high torques standard hub gears will stand without failing even when used in very heavy and sometimes powered vehicles, such as the 550-1400kg Thuner Trampelwurm (described in HP54), or my Velocity Dolphin electric bicycle with a normal hub gear taking up both the torque from a 250 W electric motor and from a 24 speed derailleur drive, or various other electric vehicles.]

ERRATA FOR HUMAN POWER NUMBER 54, SPRING 2003

Page 6, Eq. 11:

„ρ“ should be „**p**“

Page 6, Fig. 3:

Re = pV/(R m T) should be:
Re = **L**pV/(R m T)

Page 23: first column, lines 16-17:

...seen in figure **5** (not 7), the combination I=1.06 and G=**2.0** (not 3.8) is optimal.

Page 23: second column, lines 27-29:

..G at **2.0** (not 3.8) and I at 1.06 kgm^2, however lowering G to **1.5** (not 2.85) or even **1.14** (not 2.17) may result in a reasonable compromise...

ANNOUNCEMENT

A new association, tentatively known as the Human Power Institute (HuPI), has been formed in order to promote the development and use of human power for an environmentally sustainable and socially just society. Launched in January, 2004, HuPI seeks to establish a website information database and foster the international exchange of information amoung all parties interested in the technologies and benefits of human power. HuPI has primarily a virtual presence on the internet as the most economic means of making information and resources available worldwide.

HuPI is to be a locus for research and development in all areas of human power in a scientific and engineering context. Much of this work is technological in nature and has to do with specific tasks, such as the design of machines for transport. As well, HuPI is devoted to exploring and understanding how human power technology benefits society across a wide range of areas, including economics, agriculture, social rubric, psychology, and general well being.

HuPI´s first project is initiated and sponsored by Dave Wilson, editor of Human Power for 18 years. He wishes to make the wealth of information in previous issues of Human Power more easily accessible, and to this end commissioned a compilation of all issues in the PDF format, complete with searchable index. This archive is to be made available on the IHPVA website and on a CD-ROM, which will be available for sale at nominal prices from some IHPVA member associations, in particular the HPVA.

In mid-2004, HuPI plans to start the Human Power International Journal, a web-based open electronic journal. Initially editted by Theo Schmidt, HPIJ will be available for free via the HuPI website: **http://www.hupi.org** which is also the primary contact to HuPI.

Why was HuPI formed? The IHPVA and its members are concentrating on HPV racing, records and events. HuPI wishes to complement that worthy endeavor with readily available internet-based information to help foster a greater application of human power in daily life.

Founders of HuPI are: Richard Ballantine, Theo Schmidt, John Snyder, Elrey John Stephens, Brian Wilson, David Gordon Wilson.