DESIGNING A HUMAN POWERED VEHICLE TO WIN THE DEMPSEY-MACCREADY PRIZE

Jennifer Reid and Eric Wang
University of Nevada, Reno, USA

The objective of this paper is to investigate whether or not a human powered vehicle (HPV) is capable of sustaining 90 km/h for an hour, the distance required to win the Dempsey-MacCready Prize. Three types of vehicles, a standard upright bicycle, a recumbent bicycle, and a faired recumbent bicycle were investigated. The reduction in power requirements due to hills, wind, and elevation were analyzed for each of the three vehicles. It was found that at 1500 m with a 9 km, 1% grade hill and a 10 m/s tailwind over half the course, a healthy male could win the prize with a current world-class HPV. More realistically, however, other improvements in vehicle design will be required to save approximately 100-200 Watts of power.

KEY WORDS: Dempsey MacCready, human powered vehicle, bicycle

INTRODUCTION: The hour record has always been a coveted prize in cycling. In 1876, the first recorded one-hour record for a standard bicycle was set in England at 25.508 km on a high wheeler. In 1914, the first recorded streamlined bicycle race took place in Berlin. In 1938, a recumbent streamlined bicycle was the first to exceed 50 km in one hour (Abbott and Wilson, 1995). Since that time the hour record for a traditional bicycle, without an aerodynamic fairing, has increased to 56.375 km. In comparison, the current hour record for a human powered vehicle (HPV) was set in 1999 by a German team at 81.158 km, which represents a 30% differential in speed.

The relatively high speeds of HPV's, as compared to standard bicycles, are due to the aerodynamics of the vehicle. It has been shown that at speeds above 80 km/h, the aerodynamic drag on the vehicle is more than 70% of the total drag force (Tamai, 1999). The attention to vehicle aerodynamics has been motivated largely by the competitions organized by the International Human Powered Vehicle Association (IHPVA). The IHPVA came into existence in the mid 1970's because the Union Cycliste International (UCI) has prohibited the use of anything other than a standard bicycle (i.e. no aerodynamic enhancements) since the early 1900's. Thus, the original intent of the IHPVA was to encourage innovative thinking by eliminating the restrictive rules of the UCI (Abbott and Wilson, 1995).

To further stimulate innovative approaches in vehicle design, a new one-hour competition has been organized which eliminates some of the restrictive IHPVA rules. The Dempsey-MacCready Prize, which will be given to the first HPV to cover 90 km in one hour, eliminates the wind, grade, and elevation restrictions. This creates an atmosphere more conducive to innovation, and allows and even encourages vehicles that that are capable of performing under less than ideal conditions. The objective of this paper is to determine whether or not it is possible to win the Dempsey-MacCready prize with current world-class HPV's simply by taking advantage of the relaxed rules.

METHODS: The power required to propel a HPV is shown by equation 1 below, where P is the power (W), Cd is the coefficient of drag, A is the frontal area (m^2), ρ is the density of air (kg/m^3), V is the vehicle velocity (m/s), Vw is the tailwind velocity (m/s), m is the combined vehicle/rider mass (kg), g is gravity (m/s^2), Crr is the coefficient of rolling resistance, and s is the slope of the hill (%).

$$P = \frac{Cd \cdot A \cdot \rho \cdot (V - Vw)^2 \cdot V}{2} + m \cdot g \cdot Crr \cdot V + m \cdot g \cdot s \cdot V \qquad (1)$$

For this study, three different types of vehicles were considered. The first is a standard upright bicycle without aerodynamic fairing. The rider is in the crouched racing position. The second type is a standard recumbent bicycle without any aerodynamic fairings. The third type is a "world-class" HPV: a semi-recumbent bicycle completely enclosed in an aerodynamic fairing.

The data used for all analyses, is shown in Table 1 for each of the three configurations (Gross et al, 1983; Tamai, 1999; Weaver, 2001).

Table 1 Characteristics of Different Bicycle Configurations

	Standard Upright Bicycle (full crouch)	Standard Recumbent Bicycle	World-class Faired Recumbent
Cd	0.88	0.77	0.11
Crr	0.003	0.005	0.004
A [m^2]	0.36	0.35	0.28
Mass [kg]	80	85	90

To investigate the impact of the relaxed rules, three variables were explored in this study: hills, wind, and the elevation of the course. According to the Dempsey-MacCready Prize rules, the vehicle must make at least one complete circuit of the course, and end within 9 km of the starting line. This means that it is possible to have a hill during the first 9 km of the course so that the rider gets the benefit of going down the hill twice while only climbing it once. Thus, for a 1% grade it is possible to gain the energy associated with 90 vertical meters. Equation 1 was rearranged to isolate the velocity. This equation was then applied to each of the 4 sections of the course (downhill, flat, uphill, and downhill) and the power required to go 90 km in one hour was calculated. Hills with slopes of 1% and 0.5% were compared to the baseline case of no hill. Each hill was assumed to be of constant slope without any wind and the elevation was at sea level.

For the wind analysis, it was imagined that it would be possible to select an out-and-back course that had no wind for the first 45 km and a constant tailwind for the second 45 km. The analysis was conducted at sea level, on a level course, and assuming that the wind was steady and transitioned instantaneously. Using Equation 1, the power required to average 90 km/h with and without wind were compared. Tailwind velocities of both 5 m/s and 10 m/s were used.

To investigate the effect of elevation, the difference in power requirements between sea level and 1500 m was compared using Equation 1. Again, the course was assumed to have no wind and no hills.

RESULTS: As a baseline comparison, Equation 1 was solved for velocity as a function of power. Figure 1 shows the power requirements for each of the three different vehicle configurations at sea level, on a flat course with no wind. It can be seen that the world-class HPV requires approximately 400 W, and that it is not possible for either of the non-faired vehicles to win the prize.

Figure 2 illustrates the power requirements as a function of *Cd* and *A* for a 90 kg vehicle/rider mass and *Crr* of 0.004 at sea level on a flat course with no wind. The three vehicles investigated are also indicated. Figure 2 clearly demonstrates that even a world-class HPV cannot sustain 90 km/h with less than 400 W.

Table 2 lists the difference in power requirements for each of the analyses conducted. The first row shows how many Watts each vehicle requires to go 90 km/h at sea level with no wind. The second and third rows show how many Watts can be saved by utilizing a 9 km long hill of 1% and 0.5% grade respectively. The fourth and fifth rows show the power saved as a result of a 5 m/s and 10 m/s tailwind respectively. The last row shows the reduction in power achieved by increasing the elevation of the course from sea level to 1500 m.

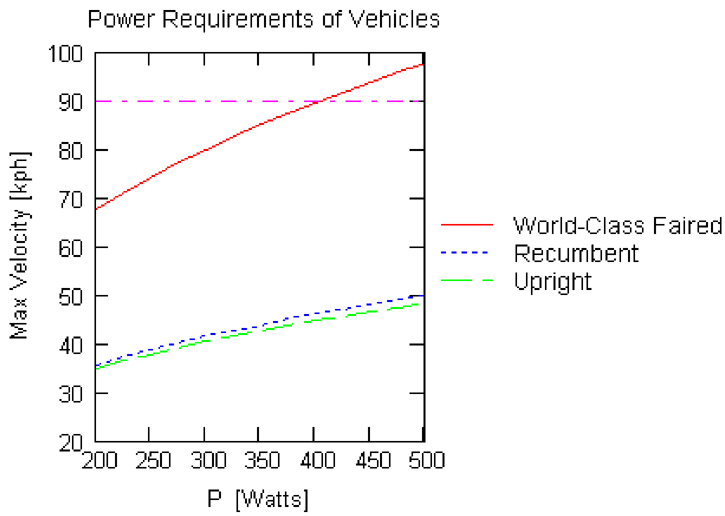

Figure 1 - Power requirements for the three different vehicle configurations. The 90 km/h goal is shown as a dashed-dot line.

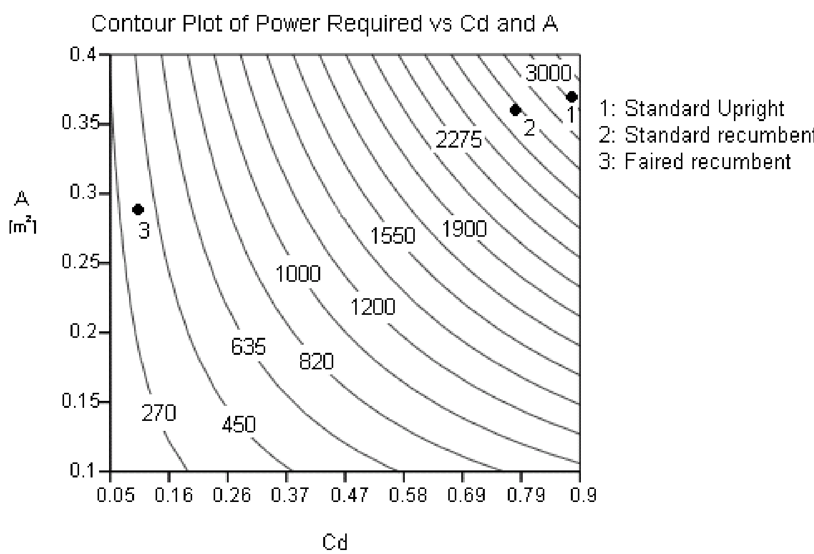

Figure 2 - Contour plot of power (Watts) needed for the three vehicle configurations at standard conditions (sea level, flat, no wind).

Table 2 Change in Power Requirements at 90 km/h for the Various Analyses. All values are in Watts.

	Upright	Recumbent	Faired
Power required at 90 kph	3091	2683	404
9 km 1% hill	-18	-18	-29
9 km 0.5% hill	-9	-9	-28
5 m/s (18 kph) tailwind	-551	-473	-82
10 m/s (36 kph) tailwind	-993	-853	-130
1500 m change in elevation	-413	-351	-43

DISCUSSION: Of the three scenarios investigated, the tailwind scenario is the most unrealistic. Since prevailing winds typically take several hours to develop, this analysis is extremely optimistic in terms of the amount of power that can be saved. Note that this scenario represents the largest potential savings in power (Table 2). Thus, if a course could be located with these wind conditions, the power requirements would be greatly reduced.

Nonetheless, a general conclusion that it is not possible to win the Dempsey-MacCready prize with current world-class HPV's can be made. Given that a minimum of 330 Watts is required without wind, and that a healthy male can only generate about 250 watts for one hour (Abbot and Wilson, 1995), it does not seem possible to achieve the 90 km record. On the other hand, a healthy male with the aid of a tailwind over half the course could win the prize. Similarly, a first class athlete can put out approximately 375 watts for an hour (Abbot and Wilson, 1995), which would be enough even without the tailwind.

However, HPV's do not handle like traditional bicycles and it is often very difficult for anyone other than the designer/builder to ride it without a considerable amount of training. Additionally, most first class cyclists have trained exclusively on upright bicycles rather than on recumbents. Because of this, it is unlikely that a HPV will be able to sustain 90 km/h for an hour until a HPV can be designed that only requires 250 watts to operate.

A laminar flow vehicle represents one proposed method of building a vehicle that drastically reduces the power required (Weaver, 2000; Weaver, 2001). A laminar flow vehicle is a HPV which maintains a laminar flow condition, as opposed to turbulent, for the entire vehicle surface. This has the potential of reducing *Cd* by 50-60%. According to Figure 2, this would lower the power requirements to less than 250 W, even at sea level. However, in order to maintain laminar flow, the fairing must be perfectly shaped with no bumps, seams or dimples and the vehicle cannot vibrate on the road surface. Thus, maintaining laminar flow for an entire hour may be optimistic.

Another approach, which utilizes the relaxed rules in Demsey-MacCready prize, would be to extract energy from a crosswind. If the fairing is shaped correctly it can generate a significant lift force to propel the vehicle forward. At 90 km/h, even relatively small lift forces can result in substantial power. For example, an 8 N thrust would equate to additional 200 W. While sailing is within the rules, the vehicle would have to be very stable. Additionally, there would be an added penalty associated with the rolling resistance due to the increased side loads on the tires (Tamai, 1999).

CONCLUSION: Human Powered Vehicles have become extremely optimized during the past few decades, to the point that drastic changes must be made to get more performance out of them. As was shown in this paper, changing the location of where a record attempt is held can have significant effect on the outcome. This effect is reduced considerably, however, as the vehicle's performance improves. A standard bicycle requires 413 fewer watts to sustain 25 m/s at 1500 m than it does at sea level, whereas a world-class HPV saves only 43 watts. If the same HPV is taken from a flat course at sea level to a 1500 m course with a 9 km 1% grade at the beginning, it is possible for a world-class HPV to attain the Dempsey-MacCready prize if a first class athlete that is well trained on the vehicle is the rider. More realistically, additional improvements in vehicle designs will have to be made in order for the Dempsey-MacCready to be won.

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