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# Bicycle Design: A different approach to improving on the world human powered speed records

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**Abstract**

The current International Human Powered Vehicle Association world records for faired bicycles stand at 133.284km/h for the 200m flying start speed record and 91.562 km for the hour record. Traditionally the recumbent bicycles that have been developed for breaking one of either of these records have been optimized around a specific, relatively small rider, enabling the overall size to be kept small. Creating the smallest frontal area possible and optimal aerodynamic shape were then the design goals. This paper discusses the development of the Velox recumbent bicycle, which has been designed using another approach.
The power required to break either of the records depends mostly on air resistance. Therefore small riders have the advantage of allowing for smaller frontal areas, whilst larger riders are able to provide more power. Performance optimization, lead to a design based around an average 1.95m tall male rider for Velox. The aerodynamic shape of Velox was then developed around the above criterion and designed with CFD and validated with wind tunnel and road tests. Essential for the rider's performance is that the rider feels comfortable whilst riding the bicycle. Therefore the uncontrolled lateral dynamics and the required rider steer control input were investigated. The bicycle's geometry was optimized for low speed stability and the required control input.



*Keywords:* Bicycle; conceptual design; aerodynamics; high speed wobble; human power output

## 1. Introduction

The UCI, the cycling governing body, banned the use of aerodynamic devices in 1913 in an attempt to keep the sport about the cyclist and not the technology. In 1932 French amateur cyclist Charles Mochet single handedly changed cycling history by developing a recumbent bicycle with which he won races

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against the best professional athletes of that time. The recumbent bicycle was a huge step in conceptual design, radically reducing the aerodynamic resistance by greatly reducing the rider's frontal area. As a result the UCI amended its rules in 1934 such that the recumbent no longer falls under what is understood to be a bicycle [1]. The rule change prevented further major developments of the bicycle with respect to rider aerodynamics and only left room for minor adjustments to the rider posture, many of which have been quickly banned once implemented (such as the superman position)[2]. As a result of this rule change the recumbent bicycle was basically forgotten until the International Human Power Vehicle Association was formed in 1976 which introduced a new championship for all "UCI banned bicycles" [1]. At present (February 2012) there are two human powered vehicle (HPV) world records that are actively contested: the hour record, 91.56 km set by Franchesco Russo (2011); and the 200m speed record with flying start for which the current record stands at a staggering 133.284km/h! (Set by Sam Wittingham, 2009). Since the 1970s quite some effort has been put into the development of sleeker and more aerodynamic human powered vehicles with which the developers have attempted to break the world records [2]. This has resulted in a dramatic increase in the speeds reached from the 1974, 200m speed record of 69.23km/h to the present record which stands at 133.284km/h. Chester Kyle performed some of the most notable research on the aerodynamic design for cycling during some 4 decades [3-6]. Most record breaking human powered vehicle concepts have focused on the aerodynamic design as air resistance is the most predominant factor that has to be overcome [2]. This paper discusses the development of the Velox, a fully faired recumbent bicycle, where the major conceptual difference has been to develop a bicycle around the most powerful motor (rider) instead of perfectly around a single specific rider.

## 2. Velox Concept

The Velox recumbent bicycle was not, unlike most other recumbent world record bicycles, developed around a specific rider. Instead it was developed around the concept of integrating the largest possible motor to be able to achieve the largest and longest possible acceleration. The acceleration ($F_{acc}$) of a bicycle can be determined by:

$$F_{acc} = F_{rider} - (F_{air} + F_{slope} + F_{roll} + F_{bump}). \qquad (1)$$

Where: $F_{rider}$ is the force the rider applies to the wheel; $F_{air}$ is the air resistance on the full vehicle. $F_{air} = 1/2 C_D A \rho v^2$. Where $C_D$ is the aerodynamic drag coefficient, A the frontal area, ρ the air density, and v the relative air speed; $F_{slope}$ is the force due to gravity as a result of the slope of the road. $F_{slope} = mg.\sin(\theta)$. Where θ is the slope angle; $F_{roll}$ the rolling resitance due to tyre deformation. $F_{roll} \approx C_r mg$ [7]; and $F_{bump}$ the resistive force as a result of road unevenness. On a flat level road the acceleration is therefore only a function of the force the rider can produce, the air resistance and the rolling resistance. Air resistance is quadratic with the forward speed while rolling resistance is proportional to the weight carried by the wheel. To be able to increase the acceleration with respect to a reference situation one can decrease the aerodynamic resistance coefficient ($C_D A$) , decrease the mass of the machine (and rider) (m), or increase the rider output force ($F_{rider}$). Most HPVs are designed around a specific rider (fixing the $F_{rider}$) such that the aerodynamic drag coefficient is minimized. Furthermore most of these riders are relatively small (but powerful). Small rider size is an advantage as it enables the HPV to be smaller in size. With a smaller rider both a smaller frontal area (A) and a shorter fairing; reducing the distance that there is turbulent airflow along the fairing which decreases the drag coefficient ($C_D$), can be achieved. Sam Wittingham's, HPV (with a $C_D A$=0.021, and $C_r$=0.003 [2]) was built around his posture. At 1.71m tall and weighing 73kg he can produce 650W (8.9W/kg) in the final 30 seconds of a speed record attempt [2]. It can be expected that there are many far more powerful athletes than Wittingham as the power top level athlete produce is related to the athlete's mass [7]. However these athletes are also larger in size. Sebastiaan

Bowier one of the two athletes that was chosen to ride the Velox for example is 195cm tall, weighs 95kg and can produce 1000W (10.5W/kg) during the final 30 seconds of the speed run (SRM crank measurement data). That is a staggering 54% more power than Wittingham produces. Therefore if a 1000W rider is placed in Wittingham's HPV and if besides the rider power nothing else is changed and if the 200m distance is covered at the terminal velocity i.e. all 1000W applied by the rider is used to overcome air resistance and rolling resistance such that there is no further acceleration, then a speed of 156 km/h can be achieved! Furthermore a 1000W, 95kg rider, under identical circumstances can have an HPV with a $C_DA$ value that is 59% higher ($C_DA = 0.033$, assuming $\rho = 1.05 kg/m^3$ from [2]), and the same speed as the record could still be achieved. The concept that the team pursued therefore consisted of building the most streamlined HPV capable of fitting the most powerful riders; riders capable of providing 1000W power.

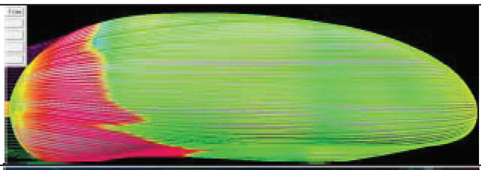
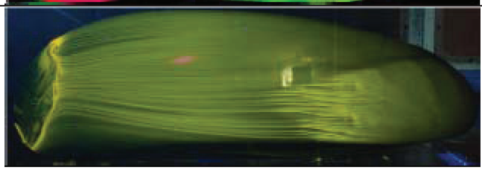
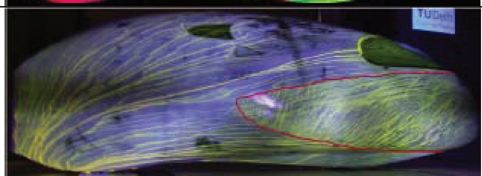
## 3. Conceptual Design Choices

Based on preliminary power measurements of a variety of amateur and professional athletes it was decided to make the HPV suitable for an average rider length of 1.95m and capable of accommodating a minimum rider length of 1.90m and maximum 2.00m. As this was the team's first attempt at building an HPV not every aspect could be optimized within a year. It was decided to focus on two areas: the aerodynamics; and the rider control and bicycle self-stability. Therefore a number of assumptions had to be made: Firstly a laid back rider posture would be a implemented similar to most (racing) recumbent bicycles on the market as opposed to the forward leaned posture used in a prone bike. Secondly it was decided that the rider would face forward and not use a device (mirror, periscope, or camera system) to see where he is going. Therefore a window would have to be placed somewhere in front of the head of the rider. Thirdly, due to the nature of the races, where virtually no steering is required (a maximum steering angle of 5 degrees was designed for), it was decided that the HPV would be front wheel driven. This eliminates a long chain to drive the back wheel but introduces a steering torque when pedaling. Finally despite literature [7] suggesting that very short crank arm lengths of 110mm do not significantly influence the amount of power that a rider can produce, it was decided that 155mm cranks would be used (standard BMX length) as shorter lengths were deemed to feel "strange" for the riders and thereby prevent their optimal performance. The use of larger crank arms means that more space is required for the motion of the feet, and thus the volume of the enclosure, which can be a significant (aerodynamic) design restriction. Other conceptual design choices included that the HPV would be constructed from a frame with fairings (the aerodynamic shell) around it, as opposed to a monocoque design where the fairing is a structurally loaded member and eliminates the frame. To reduce the size of the required gearing a standard size 28 inch wheel rim was used for the front wheel. Due to the rider seating orientation and the feet requiring to extend in front of the front wheel, the wheel size also limits the minimum size of the rider! A small 24 inch rim was chosen for the rear wheel despite its larger resistance due to road unevenness ($F_{bump}$) in order to reduce the overall length of the bicycle, and therefore its aerodynamic drag. The smaller wheel also allows the rider's shoulders and head to lean over the forward end of the rear wheel. Finally a mountainbike downhill disk brake was connected to the rear wheel to slow the bike down after the finish. The disk brake adds aerodynamic drag but it was deemed unsafe to use standard bicycle rim brakes as the induced heat could cause the tire pressure to rise beyond the permissible.

## 4. Aerodynamic Design

The aerodynamic design was dictated by the desire to have the least amount of surface area, and the largest possible laminar airflow length over the body. The shell was designed starting with the Selig s1016 NLF profile (designed for HPV use) as the horizontal cross sectional shape and the NACA 7 series as the vertical cross section. From there more organic shapes were developed in a manually performed iterative loop using the VSAero CFD simulation software. To create a larger extent of laminar flow, the pressure gradient should be flat or slightly negative for a longer distance. To achieve this while keeping a close fit of the fairing around the rider, the seat angle was changed from the original 16 degrees to the horizontal to 20 degrees making the fairing slightly higher but shorter, and placing the widest point more towards the rear. This increased the extent of laminar flow while keeping total surface area the same. Eventually a shape with a $C_DA$ value of 0.0062 was found. To validate this shape a 1:3 physical scale model was made and placed in the wind tunnel. The scaled wind tunnel test model performed far less well, having a $C_DA$ of 0.013. Adjustments of empirical model parameters in VSAero then lead to a new optimized shape with a computed $C_DA$ of 0.015. This shape fairings, used on the actual Velox were then produced and tested in an open jet wind tunnel and found to have a $C_DA$ of 0.030. Oil streak tests on both the scale model and actual Velox showed far more turbulent flow length than that predicted by the CFD model. Further tests with the Velox on the open road where the rider applied a specific amount of power and the time for a specific distance was recorded showed that then too the $C_DA$ value was roughly 0.03. With this value and the expected power output from the rider, the world record would be roughly achievable. Figure 1 shows the different designs, and their $C_DA$ values.

Table 1. Development of the Velox aerodynamic shape

| | |
|---|---|
|  | Original CFD model with $C_DA$ =0.0062. Green indicates laminar flow. Pink turbulent flow. |
|  | 1:3 scale model in oil streak wind tunnel test. Yellow colour indicates where oil is present. Large yellow surface indicates laminar flow, streak lines indicates turbulence. $C_DA$= 0.013. |
|  | Optimized CFD model after using scaled model experiment information. $C_DA$ = 0.015. |
|  | Full scale oil streak wind tunnel test. prior to surface smoothing. Red line indicates the laminar flow region. Note that the window causes turbulent flow. $C_DA$ = 0.030. |
|  | Final product. Smoothed outer shape (sticker), Wind tunnel test $C_DA$ = 0.030, open road test $C_DA$= 0.032. The red line indicates the wind tunnel laminar flow region. |

## 5. Vehicle Dynamics

One of the most profound examples of bad HPV vehicle dynamics was seen with the Mango HPV, which was uncontrollable at high speed and crashed during an attempt at the 200m speed record [8]. To ensure that a similar situation would not occur with the Velox, the uncontrolled (open loop) stability of the vehicle with a rigid rider attached was investigated and used to determine parameters of the steering geometry (trail and head angle) and frame torsional stiffness. The required rider steering power to recover from a lateral moment (as a result of a gust of wind), and continue in a straight line was also investigated and used to determine the steering geometry.

The lateral stability was investigated both at low speed and at high speed. At low speed because the HPV is laterally unstable in this speed range and has to be steered to be stabilized and remain upright. A highly unstable bicycle requires large steering angle feedback gains to be stabilized which is not possible due to the design restriction of 5 degrees. Secondly at high speed a wobble mode could destabilize the HPV, a potentially dangerous situation as seen with the Mango.

The low speed investigations were performed based on the benchmarked linearized equations of motion of the Whipple bicycle model [9], which are implemented in the Matlab program JBike6 [10]. These equations of motion have been validated for low speeds and assume that the bicycle is composed of four rigid bodies connected via three revolute joints where the wheels make slip free, point contact with the ground. Fig.1 shows a screen dump of the Jbike6 model with above the input design values and below left the configuration and inertias and masses of the 4 rigid bodies. Below right the eigenvalues for the HPV at different speeds are shown. Real eigenvalues define exponential behavior, corresponding to exponential growth of lean and steer angles if the roots are positive and to decays of lean and steer angles if the eigenvalues are negative. Complex eigenvalues come in complex conjugate pairs and are associated with exponentially growing or decaying oscillatory motion depending on the signs of their real parts. Between 7 and 15m/s all eigenvalues have a negative real part and the vehicle is completely self-stable.

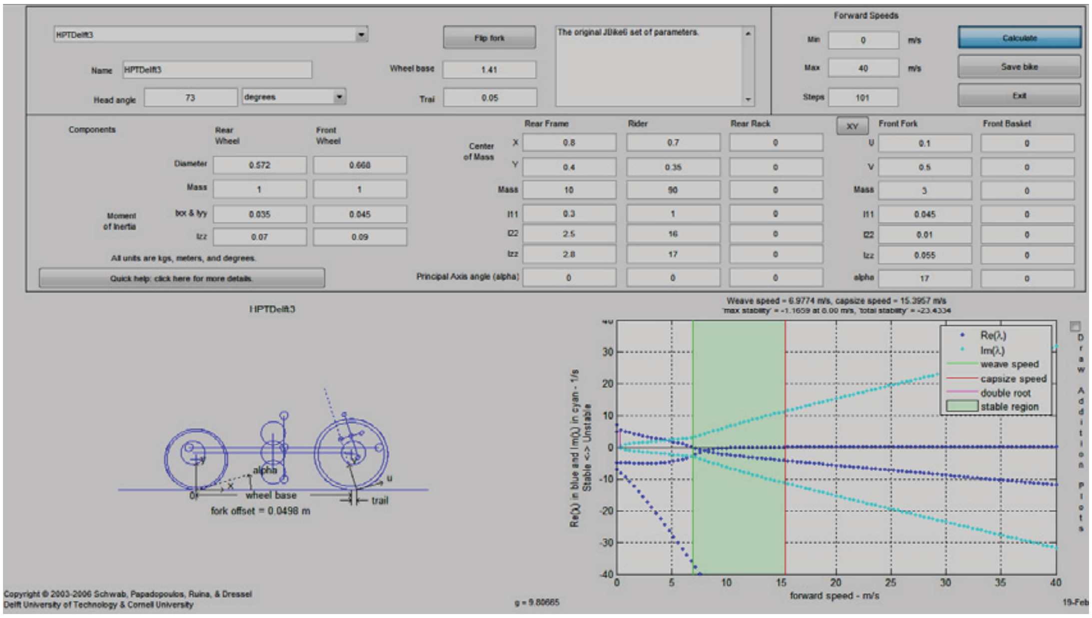



Fig. 1. Jbike6 screen dump of the Velox showing the low speed self-stable speed range between 7 and 15m/s

The rider control torque required to stabilize the HPV was investigated by implementing a simple "steer into the fall controller" [11] in the Whipple bicycle model. By investigating the control torque and power for different configurations and speeds trends in the HPV's stability and controllability were found. The control depends mostly on the velocity and trail whilst the head angle has little influence. Increasing the trail or speed was found to give similar results – the response is faster but smaller – smaller is deemed a good aspect, as it makes the HPV less responsive to small steering adjustments, but a faster response could make the HPV very "nervous", and difficult for the rider to control.

At high speeds frame and tyre flexibilities become significant and the Whipple model no longer holds. Therefore the Velox was also modeled in the multibody software package ADAMS. In the ADAMS model tyres and frame flexibility were included. To verify that the ADAMS model was configured correctly the low speed uncontrolled motion was compared with that of JBike6. Next the eigenvalues of the model were investigated at high speeds and the frame and tyre stiffness was varied. For low tire and frame stiffness's wobble was found. As no detailed structural analysis of the frame stiffness had been carried out due to the difficulty in modeling carbon fiber and imprecise production method it was decided, based on the ADAMS simulations trends, to incorporate extra layers of carbon fiber to further stiffen the frame to ensure that the wobble would not occur at a speed that the bicycle could reach. During none of the runs performed with the Velox has wobble been noted.

## 6. Conclusion

The Velox was developed around a novel concept to incorporate the most powerful possible rider instead of minimizing the aerodynamic drag area ($C_DA$) value. The developed HPV reached a speed of 129km/h on the 200m flying start speed race and it covered 88km in the first attempt at breaking the hour record (using 2 different riders). These results are very promising for the concept. However the vehicle's $C_DA$ was found to be 0.03, right on the edge of what was predicted would enable it to break the world speed record. The control and stability of the Velox was found to be very good, with no dangerous situations occurring due to wind gusts or high speed wobble. Further rider orientation and aerodynamic optimization can certainly lead to a lower $C_DA$ value, and will form the basis for the Velox II design.

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