Report for the Submission of Data Supporting World Record Runs in the Category Dead Upwind Vehicle

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On 16 June 2012 Rick Cavallaro made a number of runs with a wind powered vehicle, the “Blackbird”, on the Runway 30L in New Jerusalem, California. This was done in a bid to establish the first world record in the category of wind powered vehicles capable of exceeding the wind speed steady state – directly upwind. This report will present the data logged in accordance with the rules for this new category as set forth by the North American Land Sailing Association (NALSA). On hand representing the record attempt were:

Rick Cavallaro: Vehicle designer, builder, and driver
Steve Morris: Aerodynamics consultant

It should be noted that John Borton (JB) was also instrumental in the design and building of the vehicle as configured for direct downwind operation. JB was not however involved in the reconfiguration of the vehicle for upwind operation nor the record attempt, and was not on site.

On hand representing NALSA as official observers were:

Bob Dill: NALSA Secretary
Kimball Livingston: Editor at large for SAIL magazine

Others on site included Richard Jenkins (Current holder of the world record for fastest sailing yacht), Michael Cavallaro, Monica Cavallaro, Harry Dill, Justin Shaffer, Adam Fischer (Writer for Wired), Kent Mason, Don Eigler, Tom Speer, and others.

Vehicle Description

The Blackbird is a vehicle initially designed and built with the sole purpose of traveling directly downwind, faster than the wind, powered only by the wind, steady state. It was subsequently modified for direct upwind operation. The primary changes in configuration involved replacing the propeller blades with turbine blades (custom designed and build for this application), reversing the direction of the chain drive transmission, and changing the gearing such that the turbine would drive the wheels rather than the wheels driving the propeller. It has a tricycle configuration and an 18’ diameter two-bladed turbine on the top of a set of pylons over the vehicle’s rear axle. The propeller is connected to the rear axle through a simple chain-drive transmission and ratchets. This configuration permits the turbine to turn the wheels via the fixed ratio transmission, while allowing the turbine freewheel during braking. The pitch of the turbine blades can be controlled by the pilot “on the fly”. By design, such a configuration cannot be accelerated through the use of stored energy/momentum. The vehicle makes no use of any controls or actuators other than those operated directly by the pilot with human power.

Analysis demonstrating that the vehicle is capable of DUWFTTW

In order to run in this NALSA category it must be demonstrated that the vehicle is capable of going directly up wind, faster than the wind, powered only by the wind, steady state. While this has been a hotly debated topic on the internet, the principle can be described in relatively simple terms.

The following case study will demonstrate the principle:

Consider a cart with an turbine geared directly to its drive wheels. We'll assume the following reasonable set of parameters:

Transmission efficiency: 95%
Turbine efficiency: 85% *
Coefficient of rolling resistance: 0.02
Vehicle gross weight: 650 lbs
Coefficient of aerodynamic drag: 0.3
Projected frontal area: 20 sq-ft

*NOTE: turbine efficiency is often expressed as a percentage of the total wind energy theoretically available in the stream-tube defined by the diameter of the turbine that is converted to useful work. This definition is relevant for a stationary turbine intended to produce electrical power, but is not the appropriate definition of turbine efficiency for a vehicle mounted turbine intended to propel the vehicle into the wind.

It is well known that a traditional wind turbine cannot produce more output power than 59% of that theoretically available to it in the above mentioned stream-tube. This is known as the Betz limit. The reasons for this limitation are two-fold:

1) A significant portion of the air in the abstract stream-tube defined above does not in fact pass through the disk defined by the turbine blades, but instead goes around that disk due to the high pressure region created immediately upstream of the turbine disk.
2) It is not possible to extract ALL of the energy from the air that does pass through the disk as it would be necessary to bring that air to zero velocity to do so. Clearly this cannot be done as the air must go somewhere after passing through the turbine disk.

Fortunately, we need not concern ourselves with the wind that passes around the turbine, nor the energy that we didn't extract from the air that did pass through the turbine disk – as neither of these contribute to the drag force of the wind on the turbine. What *does* contribute to that drag force is the amount by which we *do* decelerate the wind that *does* go through the turbine disk.

Thus, the efficiency we concern ourselves with will be defined essentially in the same way that efficiency is defined for a propeller. In this case it will be the useful energy produced by the turbine (i.e. torque on the shaft x rotational rate of the shaft) divided by the force of the wind along the axis of the turbine (due to its deceleration) x the free-stream velocity of that wind. Using this more relevant parameter, a value of 85% is reasonable to achieve. Traditional analysis suggests that our turbine should achieve 85.7% efficiency at the design point under this definition.

For the purpose of this analysis we won't consider the issue of accelerating to speed, but rather the cart's ability to maintain faster-than-the-wind speed and further accelerate from that point. Thus we'll imagine that we have towed the vehicle up to a speed of 18 mph in a 15 mph head-wind and then let it loose. In this situation the vehicle will experience a relative head-wind of 33 mph – thus this will be the relevant free-stream velocity when considering turbine efficiency. We'll adjust the pitch of our turbine blades such that they produce a net aerodynamic drag force of 200 lbs while in this state (still being towed). Note that this 200 lbs is the net drag force the turbine places on the vehicle while being towed – we're not talking about the torque on the turbine shaft. This tells us that the turbine will be producing power at its shaft at a rate of 0.85 x 33 mph x 200 lbs (5610 mph-lbs).

We deliver that power to the drive wheels through an imperfect transmission. Thus, the power transmitted to the drive wheels will be 5329.5 mph-lbs (5610 mph-lbs * 0.95). Given the vehicle's ground speed of 18 mph, we can see that the wheels will be generating 296.08 lbs of thrust (18 mph x 225.18 = 5329.5)

Now let's cut our tow line and see what happens. Given our vehicle gross weight of 650 lbs and coefficient of rolling resistance of 0.02, we can calculate that we'll lose 13 lbs of thrust to rolling resistance. We lose another 200 lbs at the turbine disk due to above mentioned aerodynamic drag. This leaves us with an excess of 83.08 lbs (296.08-200-13).

Finally, we have to consider the aerodynamic drag we experience in this state:

Aero_drag = Drag_coeff * frontal_area * ½ * rho * Vel * Vel

In which rho is air density and vel is the relative air velocity experienced by the vehicle.

Aero_drag = 0.3 * 20 * ½ * 0.002329 * 48.4 * 48.4 = 16.37 lbs

Where 0.002329 is the air density in slugs/ft^3 and 51.3 is our velocity in ft/sec.

Subtracting our aero drag of 16.37 lbs from our excess thrust of 83.08 lbs, gives us a remaining excess thrust of 66.71 lbs. This shows that such a vehicle will continue to accelerate from its current state at a rate of about 3.3 ft/sec/sec, while it is already going directly upwind faster than the wind.

The explanation is that the vehicle acts as a lever between two media (the ground and the air). Like any lever we can trade a small force over a large distance for a larger force over a smaller distance. This is how we get more thrust from the wheels than we create drag at the turbine disk (since the turbine disk is moving through the air faster than the wheels are moving over the ground – due to the headwind).

Considering the vehicle from another perspective, we can start with an ice-boat that's tacking into the wind. We know from experience and collected data that an efficient ice-boat can achieve "velocity made good" (or VMG) upwind faster than wind speed by tacking. If we consider two such ice-boats running side-by-side on alternate tacks, connected by a telescoping pole, we can think of this as one ungainly vehicle whose center of gravity is indeed going directly upwind faster than the wind. This is more similar to the Blackbird in its upwind configuration than might be immediately apparent. In fact the blades of the turbine are simply airfoiled "wings" (much like the sail of our ice-boat above) that each maintain a continuous upwind helical tack as they move upwind with the vehicle and cross-wind due to their rotation. The transmission and wheels then provide the same kinematic constraint to the turbine blade motion that the ice-blades provide to the sail of the ice-boat.

Proof that the vehicle performs best directly upwind

As can readily be seen from the above analysis, the vehicle performance is driven significantly by the turbine efficiency. This of course is primarily a function of the Lift/Drag ratio of the airfoil of the turbine blades at its operating angle of attack. The turbine blades on the Blackbird in its upwind configuration are based on the NACA 6412 airfoil which has it's maximum L/D at 4.0 degrees, and has a twist such that the airfoil at each spanwise station is presented at that angle of attack (AOA). When the relative flow is aligned with the propeller axis, that AOA can be maintained at all spanwise stations throughout the complete rotation. Any cross-wind component from the right will cause the AOA for the top blade to increase while the angle of attack of the bottom blade is decreased. A cross wind component from the left will have the same effect in the opposite direction. In both cases the AOA will depart from its optimum value to varying degrees over the full rotation of the prop in this case – reducing the turbine performance – and thus the overall performance of the cart. The cart employs no other aerodynamic surfaces that can take advantage of a cross-wind component.

The above effects are readily apparent in two ways when operating the Blackbird in even modest cross-winds. First, the pilot feels a pronounced pulsing effect as each blade goes through a lower and then higher AOA over its rotation, and ultimately from the noticeable decrease in vehicle speed relative to cart speed when not aligned with the wind.

Analysis of 10 second run for measurement category C4

It is easiest to review the following data with the use of the "AnaGraph" analytical plotting program provided – but all data is in ASCII format and is described in detail below. The following can be seen by opening "results.agr" in AnaGraph, and is also depicted in Fig 1 below.

Please note that UTC time rolled over in the middle of our session, so I modified the UTC-time format to allow it to count higher than a single day of seconds. Note also that I refer to this as "GPS time" in the data file headers – this was simply a case of loose terminology on my part.

The subject run begins from a dead stop at 88080 seconds. The upwind cart self-starts with no outside assistance at this point and accelerates briskly from 88102 through 88165 (with a brief deceleration when I increased turbine pitch intentionally at 88142 to insure an acceleration period while passing one of the stationary wind stations).

At 88177, with the vehicle speed effectively maxed out for this wind condition, I again adjust the pitch briefly to decelerate the cart temporarily. I then bring the pitch back in and allow the cart to accelerate at a much more modest rate to qualify for a valid run under NALSA rules for this category. The result is a period from 88212 through 88221 that shows an increase in vehicle speed of 0.207 mph (the yellow curve represents instantaneous upwind cart speed).

The red curve represents the ratio of values of the instantaneous upwind cart speed (yellow curve) divided by the instantaneous true wind speed (blue curve). The green curve represents the same ratio filtered by a 10-second moving average – this shows that the Blackbird achieved a ratio of 2.1 x wind speed, directly upwind, over the 10 second average of the above defined measurement period.

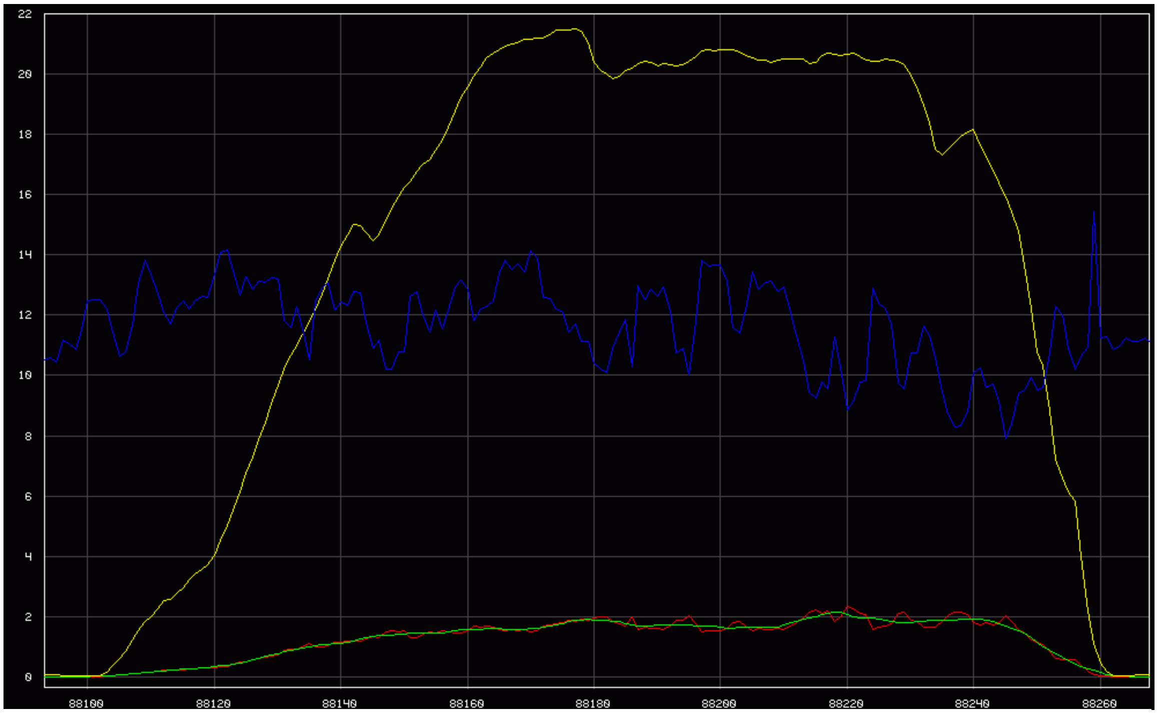

Fig 1. Speeds of the cart, true wind, and ratio thereof for the entire submitted run.

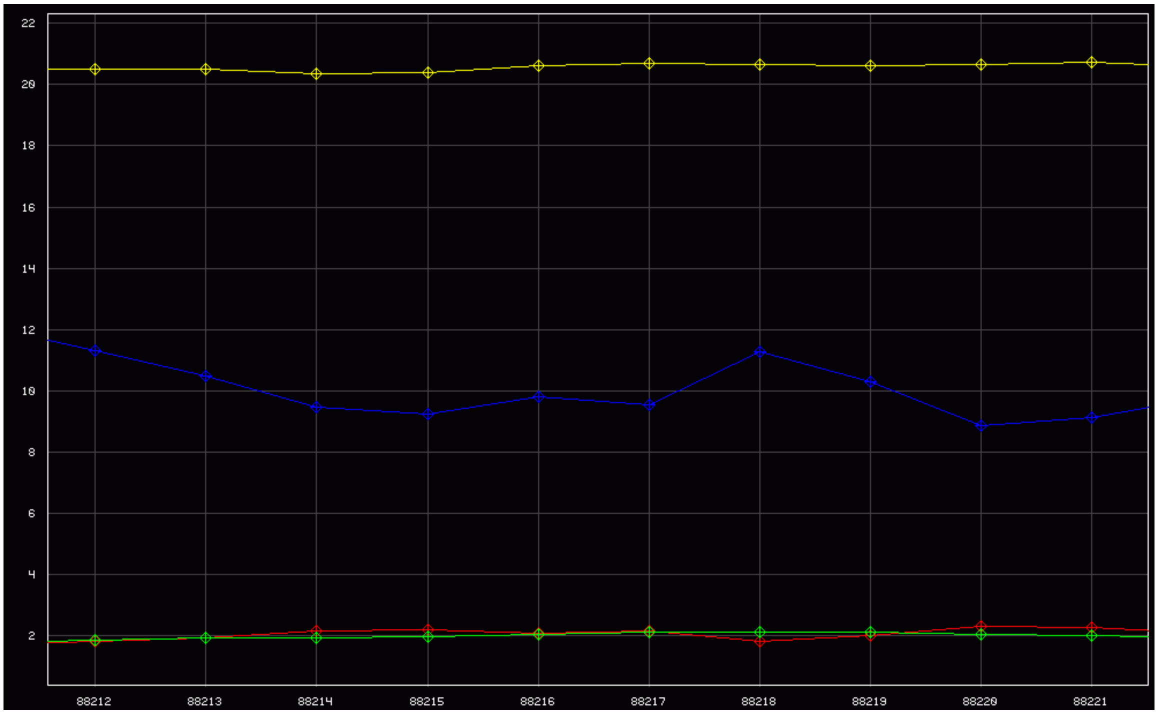

Fig 2. Speeds of the cart, true wind, and ratio thereof for the 10 second measurement period.

Alignment with the wind

Wind direction readings for the submitted measurement period were taken from the MetOne 034B anemometer mounted on the chase vehicle just above the hub height of the upwind cart. The raw data from that sensor was logged in file: “16_11_06.log”. The raw data in that file is decoded into the flat ASCII file “wind.txt” for plotting and analysis.

For the MetOne 034B anemometer, wind direction readings are given as a range of 0-1023 counts over an angular range of 0-356 degrees (with a 4 degree null). This tells us there are 2.8764 counts/deg.

The heading data for both the upwind cart and chase vehicle was obtained from GPS logs recorded by Bob Dill on GPS receivers he provided.

The raw NMEA sentences for the chase vehicle can be found in:
“BOB DILL 2_chase_1003289_20120616_181420.txt”
This data is translated to flat ASCII data in “DILL_2_chase.txt”.

The raw NMEA sentences for the upwind cart can be found in:
“BOB DILL 5_cart 832000343_20120616_175001 cart.txt”
This data is translated to flat ASCII data in “dill5_cart.txt”.

By plotting the wind direction reading from the chase vehicle anemometer during all upwind runs and averaging the reading, I conclude that a reading of 518.2 counts is "straight ahead" for the chase vehicle. This is based on the fact that the wind was well aligned with the runway for all runs and we aimed directly into the true wind to the best of our ability during the runs.

Bob Dill and I aligned the wind sensor on the chase vehicle with the null directly toward the aft end of the vehicle - as best we could by eye. Given that the wind vane outputs a range of 0-1023 counts, this would suggest that "straight ahead" would equate to 511.5 counts. This differs from the above computation by 6.7 counts or 2.33 degrees – which is consistent with my estimate that we were able to align the sensor with the vehicle axis within approximately 3 degrees based on previous experience.

The data shows that:

- The chase vehicle heading averaged over the 10 second measurement period was 319.048 degrees.
- The upwind cart heading averaged over the 10 second measurement period was 319.275 degrees.

For reference, the runway heading was determined to be 319.72 degrees as measured from Google Earth.

Next we look at upwind cart and chase vehicle headings during the 88212 to 88221 UTC time period:

- From 88212 to 88221 the chase vehicle maintained a GPS heading of 319.048 degrees average (with a min of 318.76 and a max of 319.4)
- From 88212 to 88221 the upwind cart maintained a GPS heading of 319.275 degrees average (with a min of 318.86 and a max of 319.93)
- From 88212 to 88221 the wind direction measured from the chase vehicle was 516.098 counts (max 531 counts; min 503 counts)

If we assume that 518.2 counts is "straight ahead on the chase vehicle" (per the initial calculation above), we compute that the relative wind over the chase vehicle was off-axis by 2.1 counts.

If we assume that 511.5 counts is "straight ahead on the chase vehicle" (as computed by the eyeball alignment of the instrument by Cavallaro and Dill), we compute that the relative wind over the chase vehicle was off-axis by 4.598 counts.

In the first case this would be 0.73 deg of relative wind or 2.19 degrees off true wind.

In the second case this would be 1.60 deg of relative wind or 4.80 degrees off true wind.

Given the difference in heading of the upwind cart and chase vehicle of 0.189 degrees, we compute a wind offset relative to the upwind vehicle's heading to be 2.379 degrees according to the above calculation, or 4.99 degrees based on the Cavallaro/Dill eye-ball alignment of the instrument. This shows that in the worst case the alignment between the heading of the upwind vehicle and the true wind falls well within the 10 degree requirement.

Support for the submission for a record in category C3 Upwind

As noted by Bob Dill in his observer's report, we also request ratification of a record for maximum speed in a turbine craft going directly upwind. The Blackbird achieved a maximum speed of 22.9 mph (3 second average) in turbine mode on June 16, 2012 at UTC 89996. The raw data supporting this is found in the following log file from a recording GPS receiver placed on the Blackbird by Bob Dill: *"BOB DILL 5_cart 832000343_20120616_175001 cart.txt"*

I'd like to thank NALSA for the help, encouragement, and accommodation they've afforded us throughout this entire process. And I'd like to offer particular thanks to Bob Dill and Kimball Livingston for taking their own time to not only observe, but also assist, in this effort.