Measuring the Speed of a Model Land Yacht with Varying Sail Shape and Wind Power

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Introduction: Sailing is one of the oldest modes of transport for our civilization, allowing societies to explore and discover the globe. The evolution of yacht racing began with the oldest sporting trophy in history, the first America’s Cup in 1851. The 33rd America’s Cup in Valencia, Spain was won by the USA yacht the BMW Oracle and these yachts as well as those participating in the global Volvo Ocean Race are the finest examples of highly optimized yachts with breakthrough technology. The modelling of yachts currently relies extensively on twisted wind tunnels and computer programs such as the velocity prediction programs for optimization. This extensive and expensive equipment is a more accurate version of the procedure and data found in this experiment and used for more highly tuned yachts such as those racing in the Volvo Ocean Race or the Louis Vuitton America’s Cup. Sailing relies on tactical intelligence, yacht handling and fitness but also heavily depends on yacht design. This paper looks to analyze the best optimization of a sail on a run, 180° from the true wind by varying sail area, shape and wind speed.

The centre of effort on a sail is the geometric centre (please refer to Figure 5) where all wind forces are assumed to act and be optimized. The wind forces on a run are purely a thrust force and unlike all other points of sail, the sail produces no lift forces.

The top part of the sail is referred to as the head of the sail. The edge of the sail closest to the mast is called the luff and the edge furthest away is the leech. The stern of the yacht is the back of the yacht. The pole supporting the sail is the mast and the pole perpendicular to this is the boom.

Methods: The model yacht was constructed of two wooden dowels 0.70m ±0.01m and 0.50m ±0.01m with the shorter fastened with zap-straps perpendicular to one end of the longer wooden dowel that created the stern. At either end of the stern, a Lego wheel was taped with two Lego wheels taped to the bow of the yacht. The mast was made of carbon fibre and measured 0.975m±0.01m and placed roughly 10cm from the bow of the yacht. The carbon fibre boom, measured 0.40m±0.01m was attached to the mast ~0.145m above the hull.

The sails were constructed from clear 0.20mm plastic sheets of two shapes. One shape was a triangle, while the other was roughly the shape of half an elongated semicircle. A schematic representation of the sails used, A to D is shown in Figure 1. A digitizer converts an analog signal of a discrete set of points into digital

<table>
<thead>
<tr>
<th>Sail</th>
<th>Area (cm²)</th>
<th>Mass (kg)</th>
<th>Friction (g-F)</th>
<th>Friction (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23.95±0.005</td>
<td>0.29±0.005</td>
<td>6.0±0.5</td>
<td>5.8±2±4.5±3</td>
</tr>
<tr>
<td>B</td>
<td>21.62±0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>21.63±0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>20.22±0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Table of initial parameters of sail areas. The mass of the boat found on an analytical balance and the friction force found with a gram-force spring scale. The friction force calculated by pulling the yacht at rest until breaking the friction barrier.
form. The digitizer equipment used shown in Figure 2. Using a digitizer, Sail A had a surface area equal to 23.06 cm$^2$± 0.005 cm$^2$ and sails B, C, and D areas of 21.62 cm$^2$±0.005 cm$^2$, 21.63 cm$^2$±0.005 cm$^2$ and 20.22 cm$^2$±0.005 cm$^2$. All sails required a 0.241 m±0.01 m baton to prevent the head collapsing, placed 0.15 m from the head at a 115$^\circ$ angle. The mass of the yacht with the sail was measured using a digital scale and the static friction using a 110g-force spring scale.

The parameters of the yacht used in this experiment are shown in Table one with the difference of sail weight between A and D falling within the tolerance parameters outlined.

The yacht was placed on a polished cherry wood table at least a metre and a half long. A Honeywell household fan was placed at one end of the table, angled so that the yacht will travel 1.02 m±0.05 m on a run. The yacht was then timed to travel the set distance with varying wind power, by using the low, medium and high fan settings. A photograph of this setup is shown in Figure 3.

**Results & Discussion:**

**Influence of Sail Area of Average Speed**

The average times for each of the sets of data are shown in Table 2 and the calculated average speed of the model yacht. It is clearly shown in Table 2 and Figure 3 that as the wind speed increases the average speed of the yacht increases, regardless of sail shape or area. A sail with smaller area was attempted at 16.53 cm$^2$±0.005 cm$^2$ but the yacht only travelled 0.73 m±0.005 m in comparison to sails A through D which would roll off the end of the 1.20 m±0.05 m table.

Analyzing Figure 3, it is shown that the slope of the best fit lines for the same sail with the same speed yet different fan placements have different vertical placements on the graph; however, the slope of the lines are the same. The slope of the best fit line for Sail A aligned with the centre of the sail is 0.035 m s$^{-1}$ v$^{-1}$ wind$^{-1}$ and slope for the best fit line aligned with the mast is 0.033 m s$^{-1}$ v$^{-1}$ wind$^{-1}$. This shows that the fan placement is causing the difference in average speed rather than varying airflow across the sail since the slopes are the same. The same slope shows that the increase in wind speed correlates to the same increase in average speed implying the placement results in the difference in speed. To average the force applied to the yacht the average force generated by the two different fan placements are used. The averaging of power generated by the difference in fan placement results in Figure 5.
The slope and placement of Sails B and C with a difference of 0.01cm$^2$ have best fit lines almost on top of each other in Figure 5. This demonstrates sail area is one of the main determinants in yacht speed. The slopes of the best fit lines for Sails A, B, C and D are 0.018 ms$^{-1}v_{wind}^{-1}$, 0.017 ms$^{-1}v_{wind}^{-1}$, 0.018 ms$^{-1}v_{wind}^{-1}$ and 0.022 ms$^{-1}v_{wind}^{-1}$. The same slope reveals that an increase in wind speed relates to a linear increase in average speeds for sails A, B, and C. For sail D it is slightly higher which may be due to the aerodynamics of the small triangular sail.

**Influence of Sail Area of Yacht’s Net Force**

The yacht for each trial and variable change is on a run at 180° to the true wind and there is no lift created by the sail as explored in a twisted wind tunnel by Richard et al. [1] and only a thrust force driving the yacht forwards. Using Newtonian Mechanics,

$$F = ma$$  \hspace{1cm} (1)

The thrust force provided by the wind, as discussed by Flay et al. [2] is equivalent to

$$F_{thrust} = 0.01917A_{sail}v_{w}^2$$ \hspace{1cm} (2)

where $A_{sail}$ is the surface area of the sail in metres squared and $v_{w}^2$ is the wind velocity squared. The wind velocity was not found in this experiment, as the equipment to do so was not available. The force resisting motion was the static and kinetic friction. The kinetic friction is slightly less than the static friction; however, the tread used in the rubber Lego wheels causes both static friction and kinetic friction. To simplify the friction force, as the static friction measured is the entire friction force opposing the yacht’s motion. Since all yacht models have the same weight, they also...
have the same friction as calculated in Table 1 and restated as:

\[ F_f = 5.88 \times 10^{-2} N \quad (3). \]

By substituting equations 2 and 3 into 1:

\[ F_{net} = ma = F_t - F_f, \]

\[ F_{net} = 0.01917A_{sail} v_w^2 - 5.88 \times 10^{-2}N \quad (4). \]

The formula for the average speed, as referred to from Semat [3] is

\[ V_{avg} = \frac{V_o + V_f}{2} \quad (5), \]

where \( V_{avg} \) is the average velocity, \( V_o \) is the initial velocity and \( V_f \) is the final velocity. Since the model yacht started from rest, Eq.5 is transformed into

\[ 2V_{avg} = V_f \quad (6). \]

Semat [3] also discusses a formula for acceleration, stated as

\[ a = \frac{V_f - V_o}{dt} \quad (7) \]

moreover, by substituting Eq. 6 into Eq. 7 the new transformation of Eq.4 is

\[ \frac{2mV_{avg}}{dt} = 0.01917A_{sail} v_w^2 - 5.88 \times 10^{-2}N \quad (8). \]

From Eq.8, the net force acting upon the model yacht should change proportionally to the change in sail area. The net force can be calculated by multiplying mass and the left hand side of Eq.8 as shown in the Net Force column of Table 3. The trend shown in Table 3 is that both wind speed and sail area are proportional to the net force. Using the calculated net force for Sail A at various wind speeds, the estimated value is proportional to the decrease percentage in area. Most estimated values were slightly more than the calculated value. The estimated value should be slightly more due to the rolling tread friction from the Lego tire wheels not accounted for. The anomalies are present in Sails B and C at low and high wind speeds.

**Influence of Sail Shape on Average Speed**

In studies done by Hochkirch et al. [4] the aerodynamics of sail shape are discussed with emphasis on how the height and placement of the centre of effort on a sail affect the speed of the yacht. Due to the variation in sail shape of B and C and thus the alteration of the geometric optimization of a sail’s centre of effort, the force generated varies even with the same area. To evaluate how the centre of effort placement on sails B and C affect the overall speed of the yacht is shown in Figure 6. Figure 6 reveals Sail C has the extreme values and thus the averaging of fan placement speeds decreases the estimated net force. The slopes of the trend line for sail B and C with the fan aligned with the centre of the sail are \( 0.044ms^{-1}v_{wind}^{-1} \) and \( 0.041ms^{-1}v_{wind}^{-1} \) versus sails B and C aligned with the

<table>
<thead>
<tr>
<th>Sail</th>
<th>Wind Speed</th>
<th>Net Force (N)</th>
<th>Estimated (N)</th>
<th>( \Delta N ) (Est.-( F_{est} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Low</td>
<td>0.0201</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.0286</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.0363</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>0.0179</td>
<td>0.0189</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.0263</td>
<td>0.0268</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.0354</td>
<td>0.0340</td>
<td>-0.0014</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>0.0196</td>
<td>0.0189</td>
<td>-0.0007</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.0258</td>
<td>0.0268</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>0.0356</td>
<td>0.0340</td>
<td>-0.0016</td>
</tr>
<tr>
<td>D</td>
<td>Low</td>
<td>0.0112</td>
<td>0.0176</td>
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</tr>
<tr>
<td></td>
<td>Medium</td>
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<tr>
<td></td>
<td>High</td>
<td>0.0308</td>
<td>0.0318</td>
<td>0.0010</td>
</tr>
</tbody>
</table>

Table 3 - Table of the difference between the net force estimated by the change in sail area and the calculated net force from Eq. 4 and 7.
centre of the sail of $0.030\text{ms}^{-1}v_{\text{wind}}^{-1}$ and $0.028\text{ms}^{-1}v_{\text{wind}}^{-1}$. This can be explained because the luff of the sail is not in use when the fan is more aligned with the sail centre causing the decreased average speed values in comparison.

Sail C had faster average speeds than B when the fan was aligned with the centre of the sail. Sail B had faster average speeds when the fan was aligned with the mast. Crudely using the methods outlined by Hochkirch et al. [4] the geometric centre of effort for sails B and C are shown in Figure 7. By aligning the fan with the mast, the thrust force is closer to Sail B’s centre of effort and as such has higher average speeds. In comparison, aligning the fan with the centre of the sail, the thrust force is closer to the centre of effort of Sail C and as such has higher average speeds than Sail B.

**Conclusion:** In this experiment, by eliminating the water component of sailing the effects of sail area, sail shape and wind speed are more apparent. To optimize a yacht’s performance, a larger sail area increases the thrust force generated by the wind on a run thus increasing the speed. An increase in wind speed linearly increases the average speed of yachts. The centre of effort of sails is determined by shape and the closer the wind force is centralized to the centre of effort, the average speed of yachts increased. Skippers and crew must take this information into account and as such causes the constant trimming of sails when racing.

**References:**