Wind-Assist Marine Demonstration for San Francisco Bay Ferry Districts: Prospects for Saving Diesel Fuel with Wind Power

Timothy Lipman, PhD
Transportation Sustainability Research Center
University of California at Berkeley
2150 Allston Way, Suite 280
Berkeley, CA 94704
telipman@berkeley.edu

Jeffrey Lidicker, PhD
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931
lidicker@mtu.edu

August 1st, 2014

Words: 4632, Tables: 4, and Figures: 7
(Totals: 7382)
ABSTRACT

This sailing vessel testing, data collection and analysis project examined the “real world” potential for a novel carbon-fiber “wingsail” technology to reduce fuel use in potential passenger ferryboat applications. In the study, a series of controlled tests were performed, accomplished by using a wingsail wind-assist technology developed by Wind+Wing Technologies. The project involved building a carbon fiber wingsail that was then mounted on a 42-foot (14-meter) trimaran test vessel. The test vessel was outfitted with a complete instrumentation package with data-recording capability. The vessel was then operated on the San Francisco Bay on a daily basis over a three-month period. Data from polar routes and actual ferry routes was captured, compiled, and used for statistical analysis. This was a real world test, with a fully capable vessel and actual winds and tidal currents.

The test results were conclusive that for a test vessel traveling at seven knots through water, up to 25 to 40 percent of the fuel burned can be saved through the use of the wingsail, depending on wind speed, with a corresponding reduction in greenhouse gases, toxic and criteria pollutant emissions, and fuel costs. These estimated fuel efficiency gains at a speed through water of seven knots will not necessarily translate directly to those at actual ferryboat service speeds (at 17 or more knots) but may due to the inherent ability of larger boats to sail at higher speeds at optimal efficiency points. Additional exploration of this scaling effect by boat size is suggested for further investigation.

Key Words: ferryboat, diesel fuel, wind, sail, wing, marine, energy, sustainability
INTRODUCTION

This project consisted of a demonstration/test and data collection and analysis effort associated with retrofitting a 42-foot (14-meter) overall length by 24-foot (8-meter) beam trimaran sailboat with a newly-fabricated carbon fiber “wingsail” to assess the ability of the wing to reduce the use of diesel fuel compared with “motoring” around the San Francisco (SF) Bay. Project test data were collected for a three-month period from February through April of 2014 and subsequently analyzed and reported here.

The project plan included collecting second-by-second energy use along with other data related to wind speed, speed over ground, and speed through water. The goal was to collect data that can be generalized to a longer period of operation. The project also aimed to determine if there are potential fuel savings that can be extrapolated to larger and faster vessels, subject to future modeling and larger vessel test efforts that will better characterize how the findings in this study can be extended to inform expected savings from wind-assist for commercial ferry boat operation.

A 2008 feasibility study by Morrelli & Melvin Design and Engineering, Inc. concluded there could be fuel costs savings and greenhouse gas emissions reduction on Bay Area ferries by up to forty percent [1]. They considered designs for a 149-passenger vessel as well as a full-sized vessel with a hull length of 118 feet (38 meters) and ability to accommodate 400 to 750 passengers and 50 to 100 bicycles. However none of these designs has been physically tested and validated under monitored conditions until the demonstration project described here was conducted, albeit for a more modestly sized vessel as a first investigation.

For this project, Wind+Wing Technologies of Napa, California, worked with Proton Composites, the California Air Resources Board, the Bay Area Air Quality Management District, Adventure Cat Sailing, and the Transportation Sustainability Research Center (TSRC) at the University of California (UC) - Berkeley to conduct a novel test of a state-of-the-art “wingsail” coupled to a sophisticated data gathering and collection system. The team developed a data collection and analysis plan at the start of the project, while the wingsail was under construction, and then implemented the data collection and analysis plan as described here.

Pictured below in Figure 1 are the wingsail and full trimaran vessel. The wingsail functions as an independent system onboard the vessel, using a small solar panel to provide electrical power for a geographical positioning system (GPS) unit, an ultrasonic wind-speed monitor, and the wing-trim tab that is used to set the wing to the optimal angle relative to the incident wind direction. Additional technical information on the research vessel and the current ferry service is provided below and reported in more detail by the authors in a project research report [2].

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1 Further details: http://www.windwingtech.com/149paxferry.html
                           http://www.windwingtech.com/400paxferry.html
Of significance to this study is the fact that there is extensive ferryboat service around SF Bay at present, and with potential for future expansion. Steady winds in parts of the SF Bay, especially in the summer, are aligned with key existing and planned ferry routes. This suggests the possibility for wind-assist to help with reducing fuel use and improving the environmental sustainability of future passenger ferryboat operations, and potentially other marine operations such as cargo transport.

As described below, this project included the development of a careful data collection and analysis plan, analysis of the data once collected, and reporting of key findings. Additionally, key areas for future research are identified.

**DATA COLLECTION AND ANALYSIS PLAN**

The data analysis task for the project can be broken down into two primary sections of analysis:

Part 1) How does the wing affect propulsion (fuel burn) on the trimaran test platform and what are the trends? What angles to the winds are there gains or losses to be had?

Part 2) What are the potential gains in efficiency or fuel burn rates from the wing assist on the existing and proposed ferry routes for the trimaran over a full year of seasonal wind variation?

The first issue is a practical measurement challenge using the wing and the test platform to quantify fuel efficiency gains under various conditions (such as wind speed). The second issue is a statistical extrapolation challenge. Using measured wind data averages from prior years and a weighted application of the various efficiency gains estimated from the first part of the analysis,
a potential range of annual savings will be produced. As SF Bay winds are relatively reliable and predictable, these estimates will be delineated for each month as well.

Part 1 is relatively straightforward and primarily involves collecting two sets of “polar” sailing data, with and without wing assist (with “wing on” and “wing off” conditions – see below), but with the boat at stratified angles to the wind, similar to the polar diagrams used extensively for sailboat racing. Additional “run” data for potential real-world ferry routes were also collected for further analysis but not analyzed and reported here.

Please note that “wing off” conditions mean that the wingsail is disengaged, leaving only motor power for propulsion of the vessel. “Wing on” means that the carbon fiber wingsail is engaged, providing with both wind-propulsion as well as propulsion from the fuel-powered motor as needed. Comparing operation under these two conditions gives an estimate of the potential gains that can be achieved through the use of the wingsail.

Wingsail engagement is controlled by a wireless connection, activated by a key fob remote control. Operation is a simple matter of pressing a button for the wing to be turned on. At that point the wing would read the wind speed and wind angle in relation to the vessel. Then the computer sends a command to the actuator, which moved the control trim tab approximately 15 degrees to leeward of the wing. This movement is the only action needed to correctly set the wing at an angle of attack to provide thrust from the wing to the vessel. Once activated, the wing immediately starts to provide thrust while the computer automatically controls the trim tab as necessary. If the course is changed to the other direction, the control trim tab would return to center as the wing rotated through the eye of the wind and then would again return to a 15-degree angle to leeward when on the new course.

All wing controls and commands were powered by a 15x15” (38x38 cm) square solar photovoltaic panel, one on each side of the wing, charging an internal battery system. If the wing failed during use and could not be turned off by the key fob control, then there was an alternate method to move the actuator by manual commands from a switch. If that failed, a line could be cut with a knife and the control trim tab centered into the neutral/off position.

Also note that in the “neutral/off position,” due to its aerodynamic shape, the wing presented only 10% of the “windage” (wind resistance) that a normal sailboat mast and rigging would have. So when the wing is off it acts like a weather vane and has negligible effect on the operation of the vessel in docking maneuvers and very little added wind resistance (penalty) if the boat has to motor due to no wind.

**STUDY DATA – USE OF POLAR SAILING OBSERVATIONS**

The primary polar data collected during the study are the most useful as they represent relatively controlled conditions with regard to wind speed and relative direction and ocean current. In this case, “polar” refers to the angle in degrees of the wind direction to the direction of the boat. This angle is referred to as “wind angle.” Unlike the typical use of polar data to graph boat speed through water, in this case the team worked to keep the boat’s speed through water constant at seven knots by adjusting the engine’s revolutions per minute (RPM), and collected wind-angle data to later analyze the rate of fuel burn. This is done with “wing on” and “wing off” as part of a sail plan that gets repeated in different wind speeds to identify the trends. This ideally needs to be done in as close to zero current as possible as current speed and direction are ignored for this study. But correction factors may be possible for future study based on analysis of “speed

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2 For example, see: http://www.blur.se/2012/07/19/j111-polars-tuning-guides/
through water” and “speed over land” that was also recorded. An effort to control for current speed and direction was done by comparing matching wind angles in the analysis.

The process of collecting the polar data involved motoring at constant heading (assuming wind does not shift) for 5 minutes, then turning around and doing the reverse, with 0-180 angles broken up into 10-degree segments. The polar sailing plots were done in non-moving water, to the extent possible, as these give the most accurate measurement of the potential benefits of usage of the wingsail.

Once the polar data are obtained, there are several useful trend lines that can be plotted to start to understand the data. The data can then be used to create lookup tables of percent fuel savings for a given wind speed and direction. This then could be extrapolated to higher boat speeds (and potentially larger boats), with work to understand the impact of apparent wind.

The effort needed for Part 2 (generalization of study findings to a longer time period) consists of first gathering historical data for winds in the Bay, which are plentiful, and examination of the full seasonal cycle of wind patterns. Once compiled and aggregated for best applicability to this study, the wind data can be averaged by month. Then potential annual savings in terms of fuel burn can be assessed based on the lookup tables created in Part 1 of the analysis.

DATA COLLECTION EQUIPMENT AND PROCEDURES
Data are collected and stored onboard the vessel using the following data collecting and recording equipment attached to a “NMEA 2000 backbone” system. Key study data collection equipment includes (make and model):

- B&G T8 – measures date/time, latitude/longitude, speed over ground, wind angle, and wind speed
- B&G ZG100 – measures course over ground (degrees) and rate of turn
- Maretron WSO100 – measures barometric pressure, outside temperature, and apparent wind angle and wind speed
- Maretron EMS 100 – measures engine RPM
- Maretron FFM100 – measures fuel use rate
- Airmar DST200 – measures speed through water
- Simrad AC12 Autopilot – measures rudder angle
- Maretron VDR100 – records the various measured data
- Maretron USB100 – for configuration of the backbone
- Maretron DSM150 – a screen to show data, and alert if a recording problem
- Simrad RS35 – communications radio

For Part 1, the data collection procedure was as follows. At the end of each test day:

- Download the test data from the data collection system;
- Indicate in data the status of “wing on” and “wing off” for each event of data collection;
- Annotate a notational spreadsheet with any notes, corresponding to the correct time stamp, with things that might affect the results (e.g. slowing down for a larger boat crossing), or numbers that should be discarded; and
- Send a copy of the results to multiple sources via email to prevent loss of data.

Project data were stored on a secure UC Berkeley server with regular backup, along with other backups including those by Wind+Wing Technologies.
For Part 2 of the analysis, data collection includes examining historic wind data speeds and patterns from the National Oceanic and Atmospheric Administration (NOAA) in the SF Bay Area. Hourly wind speed and direction data were aggregated into monthly averages for the business hours of 6am to 7pm. These were then used to generate weighted estimates of annual fuel consumption efficiency gains representative of a full year of Bay Area seasonal changes. Once collected, study data were analyzed using the Data Desk software package (by Data Description Inc. of Ithaca, New York).

**POLAR DATA COLLECTION AND FUEL RATE IMPROVEMENT RESULTS**

Polar data were collected (by varying the angle in degrees of the wind direction to the boat direction) under both “wing on” and “wing off” conditions (as described above) and at differences of 10-degrees, so that careful comparisons of sailing performance and the benefits of wind-assist could be ascertained. There were a total of 28,668 observations collected in the study, over the three-month collection period. This large sample is due to a high resolution of data capture at the rate of one record per second. Of these records, the majority is of the highest quality rating of “Quality Level 2,” while 3,148 are of “Quality Level 1,” and none are of Quality Level 0 (unusable). Quality Level 1 indicates that wind speed was not consistent enough during a particular run to trust its use. All results reported here are for Data Quality 2 only unless specifically stated otherwise.

Most of the sample was collected with the “wing on” and where wind-assist is possible. Conditions with “wing on” are more variable than with “wing off” meaning more could be learned by emphasizing data collection with “wing on” after a set of baseline “wing off” data were collected. More than twice the numbers of study observations were performed with “wing on” (71%) than with “wing off” (29%).

The distribution of observations by wind speed and wind angle (angle of boat travel direction with respect to the wind direction) in the sample is shown in Figure 2. For example, the figure shows that no data were collected at a wind speed of 10 knots for wind angles to the boat of 0–30 degrees. All results shown in the subsequent sections are assuming this distribution of wind angle and wind speed as shown in this figure unless otherwise noted. The data were collected with wind angles specific to port and starboard, but since the boat and the sail are symmetric, the port and starboard data were combined (i.e., 30-degree starboard observations were combined with 30-degree port observations).
During the experiment, the boat pilots attempted to hold a steady speed of seven knots through water. The mean speed for the sample was 7.5 knots with a standard deviation of 0.33, which is relatively very small. A comparison between “wing on” versus “wing off” indicates the speeds virtually the same with the wing being on as slightly higher (7.47 knots with SD 0.32 and 7.45 knots with SD 0.34, respectively). Thus, we have support for the assumption that the results reported here are comparable with respect to speed of boat through water.

**EFFECT OF “WING ON” OR “WING OFF” ON FUEL RATE OF USE**

Considering the overall sample, there is a statistically significant difference in the fuel rate of consumption between observations with “wing on” versus “wing off”, even when adjusting for differences in wind speed ($p<0.0001$, ANOVA). With the “wing off”, the average fuel use rate is 0.71 gallons/hour (2.7 liters per hour), while with the “wing on”, the average fuel use rate is 0.48 gallons/hour (1.8 liters per hour). This constitutes an overall fuel usage reduction of 33.3% for the sample.

The wind speed also had a statistically significant effect on fuel rate, even after adjusting for “wing on” or “wing off” ($p<0.0001$, ANOVA). The effect on fuel rate was highest for the 20-knot wind speed: a 44.0% reduction in fuel rate. The 15-knot wind speed reduced fuel rate by an average of 33.3%. A comparison of the 10-knot winds could not be directly compared, as there was no “wing off” data in the sample at 10 knots.

However, an indirect analysis on the 10-knot wind speed is possible as there is no statistical difference in fuel burn between the 15 and 20-knot wind speeds when in “wing off” (0.70 g.hr and 0.71g/hr, $p=0.73$, ANOVA). Thus, we can be confident that the fuel rate is the
same for the “wing off” with the wind speed of 10-knots. With this assumption it can be
collapsed that the “wing on” at 10-knots of wind speed reduces fuel rate by 26%.

The relation between wind speed and reduction in fuel rate is quadratic (non-linear) as
can be seen in Figure 3. The higher the wind speed, the greater is the reduction in fuel rate. By
selecting out the best wind angles determined from the next section, a range of wind angles is
averaged to produce much better improvements. A summary of these results appears in Table 1,
where Optimal Wind Angle results refer to those averaged over only the best (most productive)
five wind angles.

**FIGURE 3** Average percent reduction in fuel rate by wind speed from use of wingsail

**TABLE 1** Percent Improvement in Fuel Rate by Wind Speed and for “Average” and
“Optimal” Wing Angles

<table>
<thead>
<tr>
<th>Wind Speed (knot)</th>
<th>Avg. Fuel Rate Percent Improvement</th>
<th>Under Optimal Wind Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>26.0%</td>
<td>34.4%</td>
</tr>
<tr>
<td>15</td>
<td>33.3%</td>
<td>36.9%</td>
</tr>
<tr>
<td>20</td>
<td>44.4%</td>
<td>56.1%</td>
</tr>
</tbody>
</table>
EFFECT OF WIND ANGLE TO BOAT DIRECTION

Before an estimate of fuel rate reduction due to “wing on” can be made by each wind angle, it must be determined whether or not there is a difference in fuel rate by wing angle when in “wing off” mode. As it turns out, to complicate matters somewhat, with “wing off”, there is a statistically significant difference in fuel rate by wind angle even after adjusting for wind speed ($p<0.0001$, ANOVA). This effect can be seen in Figure 4. The difference is most likely due to a combination of wind direction, and water current direction and speed during the sample period.

FIGURE 4 Box-plot of median fuel rate by wind angle to boat with wing off
(Note: each box represents the 25th to 75th quartile range with the median as the line down the middle, and with error bars and dots indicating the remaining distribution and outliers)

During periods with “wing on”, the effect of wind angle is even more dramatic and also statistically significant, even after adjusting for wind speed ($p<0.0001$, ANOVA). A depiction of the effect appears in Figure 5. Although it is tempting to draw conclusions about the best wind angle from this figure, we cannot yet as a subtraction from the “wing off” values (Figure 4) must occur first.

FIGURE 5 Box-plot of median fuel rate by wind angle to boat with wing on
(Note: each box represents the 25th to 75th quartile range with the median as the line down the middle, and with error bars and dots indicating the remaining distribution and outliers)
By subtracting the median fuel rate values from the “wing off” and “wing on” observations, we find that the optimal wind angles are centered around 90 degrees to the wind direction with the best reduction at an angle of 80 degrees (see Figure 6).

**FIGURE 6** Plot of median fuel burn rate reduction by wind angle to boat (with trend line)

**ESTIMATED ANNUAL FUEL EFFICIENCY GAINS**

As mentioned above, there are plentiful data on historical winds in the SF Bay. Data on wind speed and direction were analyzed for the period from May 2006 to March 2008 of the Golden Gate Bridge area of the SF Bay, using data from the NOAA [3] and other sources [4].

In order to project one quarter’s worth of data collection to a full year, a look up table of wind speed by month for the business hours from 6am to 7pm was created. A visual representation of the entire lookup table appears in Figure 7. Notice that the winds pick up speed in the summer months dramatically, suggesting the largest potential for wind-assist during this season, particularly in the July and August months.
Another way to visualize annual wind data is in Table 2, which more clearly shows the faster winds in the summer months in the “Mean” and “Median” columns. As shown, the peak wind speed of over 14 knots is found in July and August, with “double digit” average wind speeds also occurring in May, June, and September.

**TABLE 2 Wind Speed (knots) Statistics by Month of Year**

<table>
<thead>
<tr>
<th>Month</th>
<th>Count</th>
<th>Mean</th>
<th>Median</th>
<th>StdDev</th>
<th>Lower 25th %tile</th>
<th>Upper 25th %tile</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>1659</td>
<td>9.3</td>
<td>8</td>
<td>6.6</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>1471</td>
<td>8.9</td>
<td>7</td>
<td>7.2</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>1150</td>
<td>8.5</td>
<td>8</td>
<td>5.5</td>
<td>4</td>
<td>12</td>
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<td>4</td>
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<td>8.7</td>
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<td>5.2</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
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<td>916</td>
<td>10.4</td>
<td>11</td>
<td>5.3</td>
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<td>14</td>
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<td>1602</td>
<td>11.8</td>
<td>11</td>
<td>5.2</td>
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<tr>
<td>7</td>
<td>1646</td>
<td>14.6</td>
<td>14</td>
<td>5.8</td>
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<td>1638</td>
<td>14.9</td>
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<td>5.5</td>
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<td>1657</td>
<td>8.7</td>
<td>8</td>
<td>5.9</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>
ESTIMATED ANNUAL FUEL RATE REDUCTION AND COST REDUCTIONS

To extrapolate the collected seasonal data for a full year of service, the data in Table 2 is crossed with the collected data through the lookup table (Table 1), providing an estimated fuel rate reduction (FRR) by month and for the entire year (see Table 3). This is applicable for the test vessel at a speed of seven knots through water. The average or representative values are in the middle column labeled, “% FRR.” The third column contains the estimates in the event the ferryboat is able to travel the entire trip, both ways within the optimal wind angle range and is labeled, “% FRR at Optimal.” This last column represents an optimal scenario or upper bound.

TABLE 3 Estimated annual fuel rate reduction (FRR)

<table>
<thead>
<tr>
<th>Month</th>
<th>% FRR</th>
<th>% FRR at Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.2</td>
<td>21.3</td>
</tr>
<tr>
<td>2</td>
<td>15.7</td>
<td>19.6</td>
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<tr>
<td>3</td>
<td>15.6</td>
<td>19.4</td>
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<tr>
<td>4</td>
<td>17.1</td>
<td>21.1</td>
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<td>5</td>
<td>21.1</td>
<td>25.8</td>
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<tr>
<td>6</td>
<td>25.1</td>
<td>30.9</td>
</tr>
<tr>
<td>7</td>
<td>31.0</td>
<td>38.0</td>
</tr>
<tr>
<td>8</td>
<td>31.9</td>
<td>38.9</td>
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<tr>
<td>9</td>
<td>23.4</td>
<td>28.9</td>
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<tr>
<td>10</td>
<td>15.5</td>
<td>19.3</td>
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<tr>
<td>11</td>
<td>11.1</td>
<td>14.1</td>
</tr>
<tr>
<td>12</td>
<td>15.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Year</td>
<td>20.1</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Based on this analysis, the overall estimated annual savings percentage is 20.1% (only out in open waters and thus does not include docking, embarking, or loading and unloading fuel consumption). However, for the particular run of Sausalito to San Francisco, the path of the ferryboat is directly across the prevailing winds that come through the Golden Gate all year. Thus, this may be a candidate for operating under optimal or nearly optimal wind angle conditions most of the time. Thus, the “% FRR at Optimal” column in Table 3 may be able to represent this one particular route’s upper bound capabilities (again for a vessel traveling at seven knots through water). It should be clarified that data from this actual route was not used for the primary analysis discussed in this paper. This analysis is based on polar data collection from elsewhere in the SF Bay. This route is singled out as a possible route that may be in the optimal wind angle range during both directions of the ferry route to illustrate potential fuel use and economic savings.

However, this analysis ultimately begs the question: What do these findings suggest with regard to future ferryboat fuel cost savings? As an example, if a single ferryboat ordinarily uses $1 million of diesel fuel (hypothetical number for ease of extrapolating results) and travels at a
rate of 7 knots through water, and we assume that for logistical operational reasons, only 80% of
the fuel rate reductions from this study are maintained once a ferryboat is in actual operation
(“in-service” factor = 80% due to docking, disembarking, scale-up to larger boat, and extreme
weather situations), then an annual fuel savings of $160,500 (16%) will be realized by the typical
or average voyage or $201,500 (20%) for the optimal voyage that manages to sail year round
within the optimal wind angle range (see Table 4).

### TABLE 4 Estimated annual fuel savings for typical and optimal ferries based on analysis
of a small 8-meter trimaran operating at speed of 7 knots ($1 million baseline fuel cost)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Fuel Cost</td>
<td>$1,000,000</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>In-Service Factor</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Overall Fuel Savings (%)</td>
<td>16%</td>
<td>20%</td>
</tr>
<tr>
<td>Annual Savings</td>
<td>$160,442</td>
<td>$201,646</td>
</tr>
</tbody>
</table>

We again caution that more investigation is needed to assess how wind-assist applies to
larger vessels than the 42-foot (14-meter) test vessel, even operating at the same speed of seven
knots, as well as for operation at faster ferryboat service speeds (15-30 knots). Also further
research is needed to understand the full costs and benefits of wingsail adoption in ferryboat
applications, including financial “payback times” depending on the initial capital cost of the
wingsail systems and their incremental costs of adoption into complete ferryboat designs.

### SUMMARY OF KEY STUDY FINDINGS

At wind speeds of 10 to 20 knots and with a boat speed of seven knots through open water,
average fuel rate reductions from wind-assist for the study period ranges from 26 to 44%. If the
test vessel is traveling in an optimal angle to the wind, these efficiency gains ranged from 34 to
56% (depending on wind speed). The optimal angle to the wind for efficiency gain is around 80
degrees port or starboard.

When this information is extrapolated to annual wind conditions accounting for year
round seasonal variation in winds speeds, the representative average fuel efficiency gain is 20%
and when only at optimal angle to the wind the average efficiency gain is 25%. Approximations
for savings on actual ferry routes range from 16-20% of total fuel used. However we note that
further investigations are needed to determine if these levels of fuel efficiency gain can be
captured under commercial ferryboat operational conditions, and if not how close the gains can
be to those found here.

### STUDY LIMITATIONS AND CAVEATS

One of the key assumptions for this study is that the water currents are low and therefore have a
negligible impact on study findings. The authors accounted for this in the wind angle analysis by
comparing each wind angle with “wing on” to the same wind angle with “wing off”. Thus, any
water currents in a given direction did not affect the results. However, this adjustment assumes
that the water currents relative to the wind direction are essentially the same for the entire period
of the study regardless of the day data was collected.
Once again, all data in this study were gained at a steady speed of seven knots through water, which is not representative of ferryboat operational speeds that typically range from 17 – 32 knots. However, the boat speed through water used here, of seven knots, represents the most efficient hull speed for a boat of this size (42 feet or 14 meters). Larger vessels have higher “optimal” hull speeds through water, and at those higher speeds and increasing wind force effects for larger wing surface areas, the impacts of wind-assist may well be approximately the same (but potentially better or worse) than those reported here. Future research on larger vessels or more importantly at higher and varying boat speeds through water will help to better understand fuel use reductions from wind-assist for larger vessels operating at higher speeds.

CONCLUSIONS

In conclusion, this study has found that significant fuel use savings are possible from the use of carbon fiber wings on sailing vessels that otherwise would be operating on motor power. Wind speed and wind angle of the boat heading to the wind direction both significantly impact fuel efficiency gains. At high winds with the optimal angle to wind (80 degrees) and a steady speed of seven knots, the study vessel experienced fuel efficiency reductions of approximately 50%. However, when these wind speeds and angles are applied to typical wind conditions for a full year of seasonal variations, the average fuel consumption reduction may be as high as 20%. If the test vessel is traveling the ferryboat route from San Francisco to Sausalito, the prevailing winds are typically at almost optimal angle to the route of the boat and thus a fuel reduction of up to 25% may be possible. Future experimental projects using larger vessels traveling at faster speeds and on additional actual ferry routes are now needed to further understand the impacts of wind-wing technology in potentially reducing fuel use for ferryboat operations.

ACKNOWLEDGEMENTS

The work reported here was partially funded by California Air Resources Board’s Air Quality Improvement Program (AQIP) under State of California Grant Number G10-AQIP-11. The project benefitted from the participation of Wind+Wing Technologies, Photon Composites, Inc., Adventure Cat Sailing Charters, and the Bay Area Air Quality Management District. The fantastic efforts of Jay Gardner, Richard Jenkins, and Zac Neubauer of Wind+Wing Technologies and Photon Composites, Inc. are especially appreciated.

REFERENCES


