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Wind Assist Marine Demonstration for Ferry Districts on the San Francisco Bay: Project Report

Prepared for the Bay Area Air Quality Management District

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Executive Summary

The purpose of this report is to document the findings of a physical sailing test and analysis project that attempts to determine if the same wind conditions that are used daily by commercial sail boat operators on the San Francisco Bay (SF Bay) can be utilized by the ferry systems to decrease their fuel consumption and emissions. A 2008 feasibility study by Morrelli & Melvin Design and Engineering, Inc. concluded there could be fuel costs savings and greenhouse gas and emissions reduction on Bay Area ferries by up to forty percent.

This “real world” sailing vessel testing, data collection and analysis study is titled the “Wind Assist Marine Demonstration Project for Ferry Districts on SF Bay.” In the study, a series of controlled tests were performed under careful conditions, accomplished by using the Wingsail wind-assist technology developed by Wind+Wing Technologies in conjunction with Photon Composites.

As initially outlined in the grant agreement with California Air Resources Board and the Bay Area Air Quality Management District, the demo vessel was originally going to be the U.S. Navy’s X-2 vessel. However, due to problems with the X-2 vessel and wing it was unavailable for use and the grant was amended. Per the amendment, the project involved building a carbon fiber wing that was then mounted on a 42’ trimaran test vessel. The test vessel was outfitted with a complete instrumentation package with data recording capability. The test vessel was then operated on the SF Bay on a daily basis, over a three-month period. Data from polar routes and actual ferry routes was captured and was sent to the University California Berkeley for statistical analysis. The results in this report are based on the polar routes data only. The ferry routes that were collected were to and from the San Francisco ferry building and included Treasure Island, Alameda, Sausalito, Richmond, and Redwood City, with the most advantageous route identified being the one between San Francisco and Sausalito. This was a real world test, with real winds and tidal currents on and around the SF Bay.

The test results were conclusive for a test vessel traveling at seven knots though open water; by using this wind assist technology, a significant percentage of the fuel burned is saved, 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 these scaling effects by boat size and speed is suggested for further investigation.

Acknowledgments

The work reported in this document 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, the Bay Area Air Quality Management District and the University of California Berkley Transportation Sustainability Research Center, by provided funding, management, coordination and technical support making this a successful project. The support of Wind+Wing Technologies is especially appreciated.

Research Project Overview

This project consists of a demonstration/test and data collection plan associated with retrofitting a 42' overall length x 24' 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 SF Bay. Project test data were collected for a three-month period from February through April of 2014.

The project plan includes collecting second-by-second energy use along with other data related to wind speed and speed over ground and speed through water. The goal is to collect data that can be generalized to a longer period of operation. The project also suggests that there are potential fuel savings as extrapolated to larger and faster vessels, for example a 149-passenger ferryboat, subject to future modeling and larger vessel test efforts, to better characterize how the findings in this study can be extended to inform expected savings from wind-assist for commercial ferry boat operation.

Pictured below in Figure 1 are the Wingsail and full trimaran vessel. The Wingsail functions as an independent system onboard the vessel, using the small solar panel to provide electrical power for a 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. For more technical information on the research vessel and the current ferry service, see Appendix C.

Figure 1: Photographs of New Wingsail (left) and Test Vessel (right)

Of significance to this study is the fact that there is extensive ferry boat service around SF Bay at present, and with potential for future expansion. The current ferry routes and “under study” potential future service areas are shown in Figure 2.

Figure 2: Current and Proposed Ferry Routes for SF Bay

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 work are identified.

Data Collection and Analysis Plan

The data analysis task for the project can be broken down into two key sections and analysis:

Task 1) How does the Wingsail 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?

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

The first issue is a practical measurement challenge using the Wingsail 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 task, 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.

Task 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.[1] Additional “run” data for potential real-world ferry routes are also collected for analysis but not included in this report. Shown below in Figure 3 is an example of a polar diagram, showing the potential boat speed at various angles of sailing relative to the true wind direction, for an example Maxi 95 sailing vessel.

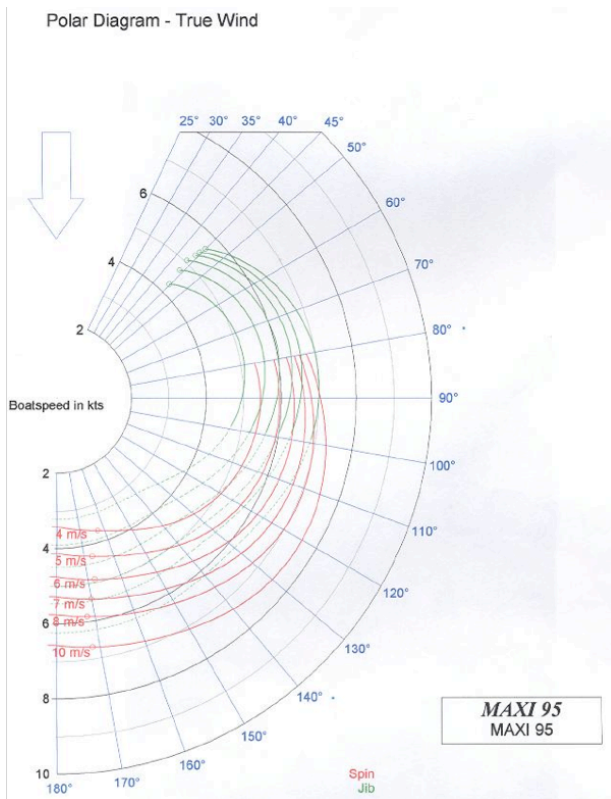

Figure 3: Example Polar Diagram Showing Boat Speed as Function of Wind Angle

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 Wingsail to be turned on. At that point the Wingsail 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 Wingsail. This movement is the only action needed to correctly set the Wingsail at an angle of attack to provide thrust from the Wingsail to the

[1] For more on use of polar sailing data: http://www.oppedijk.com/zeilen/create-polar-diagram

vessel. Once activated, the Wingsail 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 Wingsail controls and commands were driven by a 15" square solar photovoltaic panel, one on each side of the Wingsail, charging an internal battery system. If the Wingsail 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 Wingsail 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 boat’s speed through water constant at seven knots through water by adjusting the engine’s rotations per minute (RPM), and collected 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 through water and speed over land that was also recorded.

The process of collecting the polar data involves 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 will be done in non-moving water (as near as possible) as these will give the most accurate measurement of the potential benefits of usage of the wing.

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 percentage 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. See Appendix B for an example of the polar sailing data collected during the study.

The effort needed for Task 2 (generalization of study findings to a longer time period) consists of first gathering historical data for winds in the SF 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 Task 1.

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

- Download the test data (see Appendix A for full data list);
- Indicate in data the status of “wing on” and “wing off” for each event of data collection;
- Annotate the spreadsheets 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 are stored on a secure University of California Berkeley server with regular backup, along with other backups including those by Wind+Wing Technologies.

For Task 2, data collection includes examining historic wind data speeds and patterns from NOAA in the Bay Area. Hourly wind speed and direction data have been aggregated into monthly averages for the business hours of 6am to 7pm. These are 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. in Ithaca, New York).

Polar Data Fuel Rate Improvement Results

The following section of the report documents the findings from the collection of the “polar” sailing performance data. 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.

Study Data Sample and Observations

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 in this report are for Quality Level 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” than with “wing off” (see Figure 4).

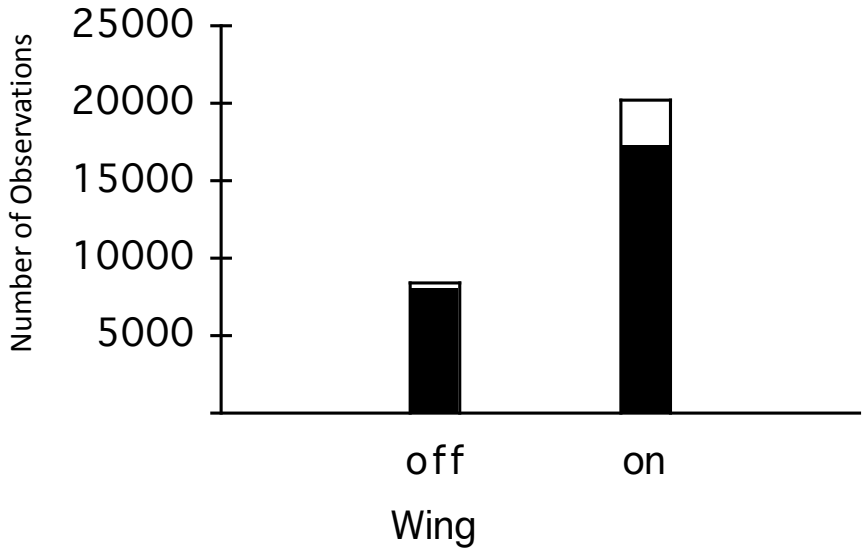

Figure 4: Bar-chart of Number of Observations with Wing Off and Wing On and Data Quality = 1 (white), and Data Quality = 2 (black)

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 5. 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., 90 degree starboard observations were combined with 90 degree port observations).

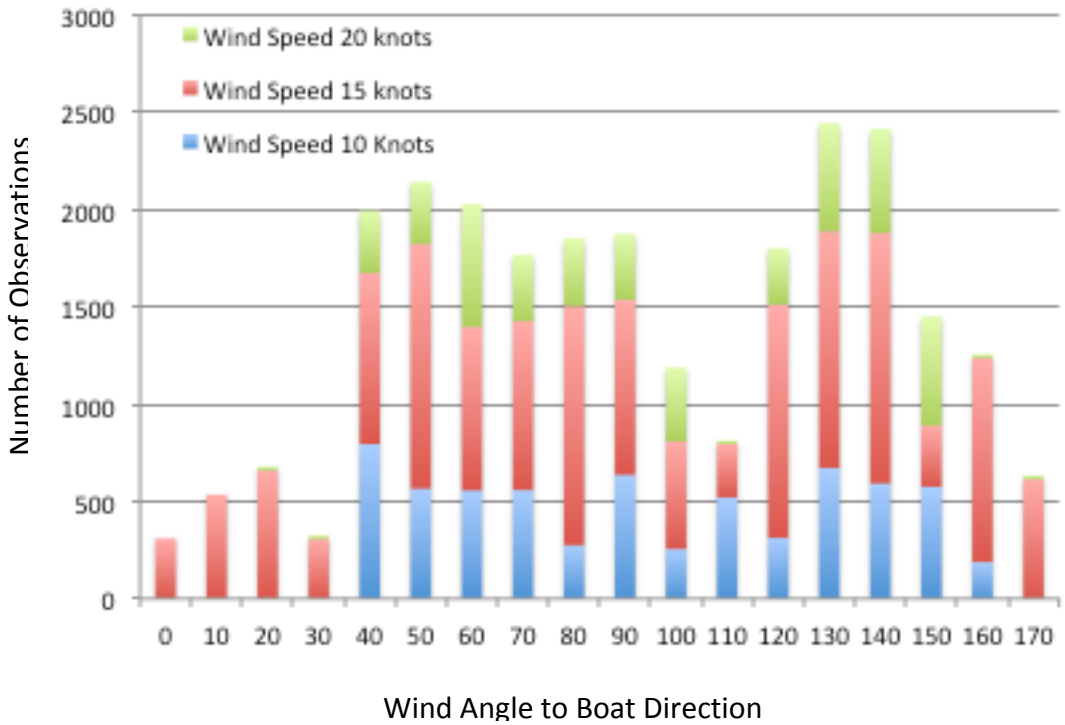

Figure 5: Distribution of Observations in Study by Wing Angle to Boat and Wind Speed

During the experiment, the boat attempted to hold a steady speed of seven knots through water. It can be seen in a histogram that the boat speed through water was highly centered on seven knots (Figure 6). Thus, we can justify the assumption that the results in this report are comparable with respect to speed of boat through water.

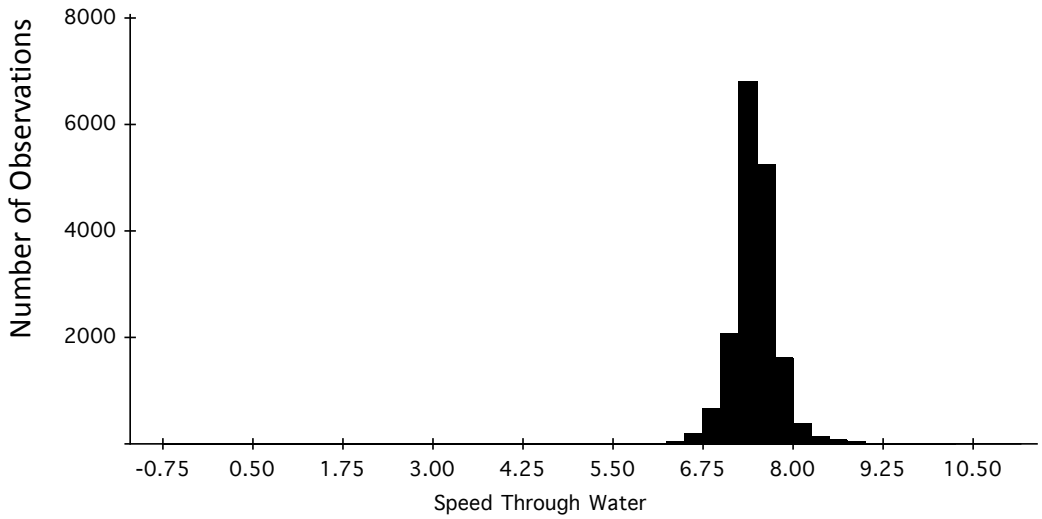

Figure 6: Distribution of Number of Observations at each Speed of boat through water (knots)

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 rate is 0.71 g/hr, while with the "wing on"; the average fuel rate is 0.48 g/hr. 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 concluded that the "wing on" at 10-knots of wind speed reduces fuel rate by 26.0%.

The relation between wind speed and reduction in fuel rate is quadratic (non-linear) as can be seen in Figure 7. Thus, the more wind, the more 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.

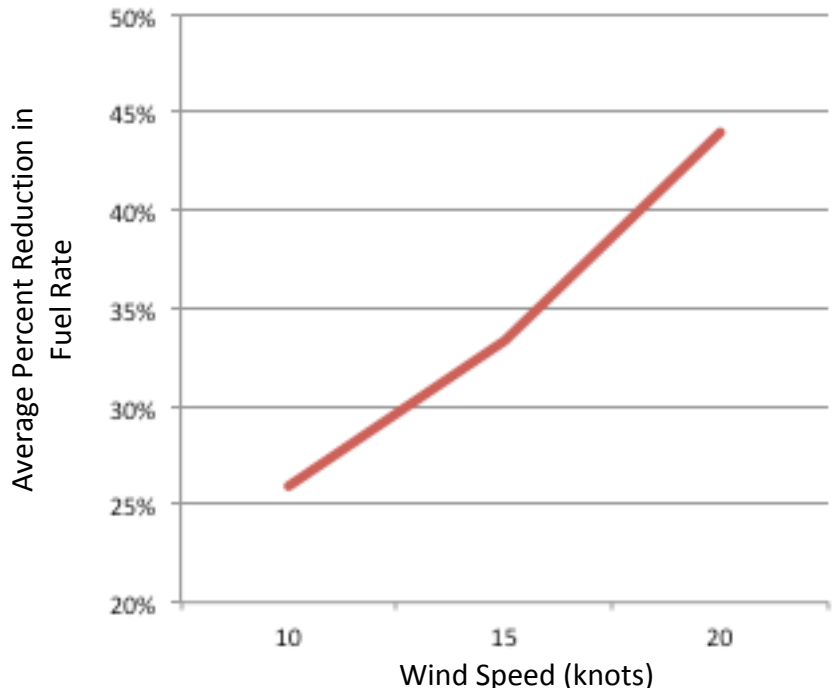

Figure 7: Average Percent Reduction in Fuel Rate by Wind Speed from Use of Wingsail

Table 1: Percent Improvement in Fuel Rate by Wind Speed and for "Average" and "Optimal" Wing Angles

Wind Speed (knot)	Avg. Fuel Rate Percent Improvement	Under Optimal Wind Angles
10	26.0%	34.4%
15	33.3%	36.9%
20	44.4%	56.1%

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 8. The difference is most likely due to a combination of wind direction, and water current direction and speed during the sample period.

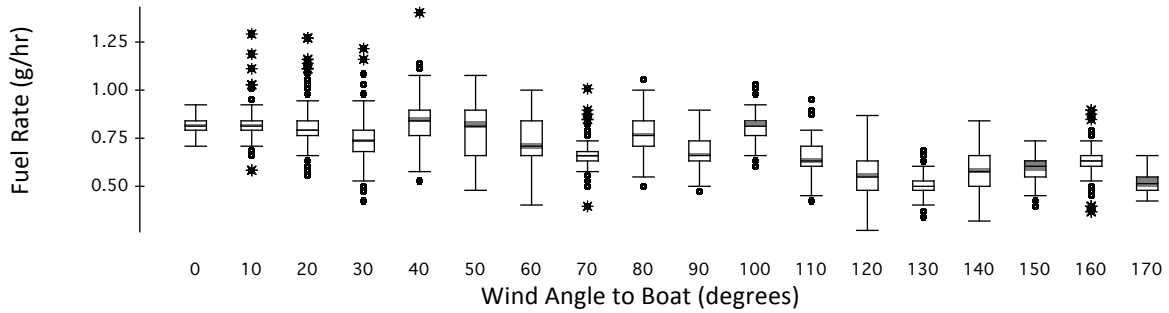

Figure 8: Box-plot of Median Fuel Rate by Wind Angle to Boat with Wing Off
(note: each box represents the 25th to 75th quartile range with the median as the line down the middle, and with error bars and dots indicating the remaining distribution and outliers)

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 9. Although it is tempting to draw conclusions about the best wind angle from this figure, we cannot, as a subtraction from the "wing off" values (Figure 7) must occur first.

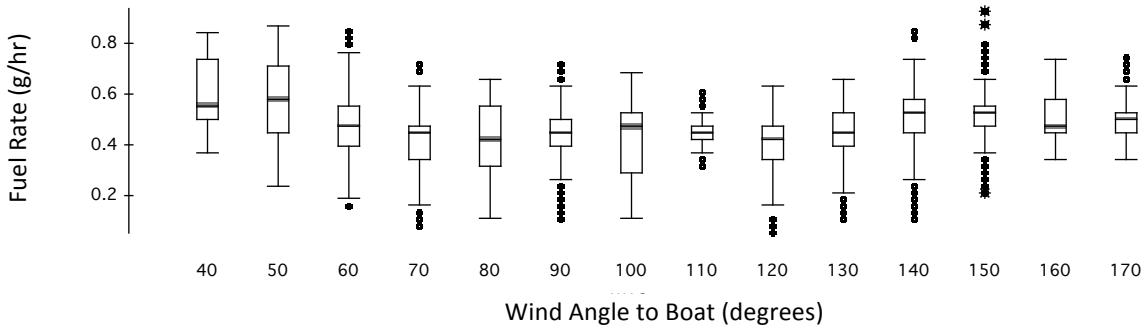

Figure 9: Box-plot of Median Fuel Rate by Wind Angle to Boat With Wing On
(note: each box represents the 25th to 75th quartile range with the median as the line down the middle, and with error bars and dots indicating the remaining distribution and outliers)

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 10).

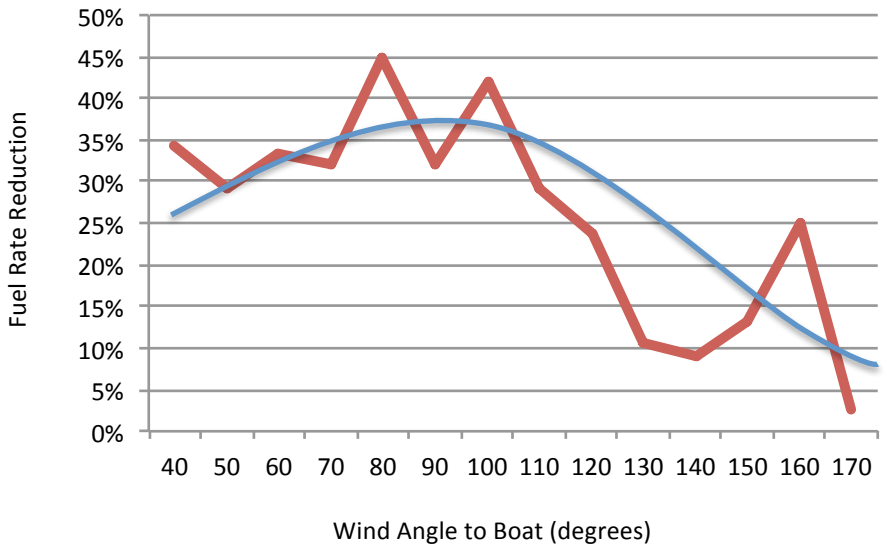

Figure 10: Plot of Median Fuel Burn Rate Reduction by Wind Angle to Boat (with trend line)

Estimated Annual Fuel Efficiency Gains

Historical Data Analysis

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 National Oceanic and Atmospheric Administration (NOAA) and other sources.[2]

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 11. Notice that the winds pick up speed in the summer months dramatically, suggesting the largest potential for wind-assist during this season, particularly in July and August

[2] Sources: http://weather.noaa.gov/pub/data/raw/sx/sxus86.kmtr.omr.dar.txt. http://windandtides.com

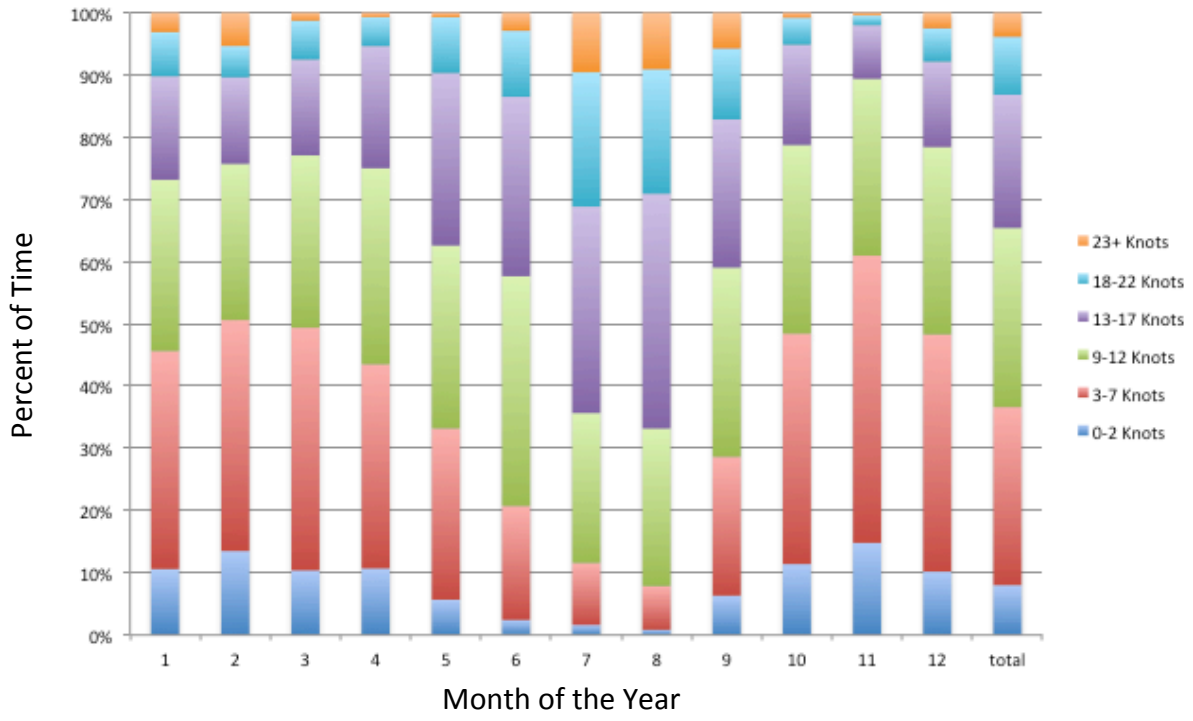

Figure 11: Distribution of Historical Wind Speed by Month

Another way to visualize annual wind data is in Table 2, which more clearly shows the faster winds in the summer months.

Table 2: Wind Speed (knots) Statistics in Knots by Month of Year

Month	Count	Mean	Median	StdDev	Lower 25th %tile	Upper 25th %tile
1	1659	9.3	8	6.6	5	13
2	1471	8.9	7	7.2	4	12
3	1150	8.5	8	5.5	4	12
4	816	8.7	8	5.2	4	13
5	916	10.4	11	5.3	6	14
6	1602	11.8	11	5.2	8	15
7	1646	14.6	14	5.8	11	19
8	1638	14.9	14	5.5	11	18
9	1594	11.5	11	6.5	7	15
10	1546	8.3	8	5.3	4	12
11	1466	6.8	6	4.6	4	10
12	1657	8.7	8	5.9	5	12

Estimated Annual Fuel Rate 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 burn 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)

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

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. Thus, this may be a candidate for operating under optimal or nearly optimal wind angle conditions most of the time. Thus, the 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 report. 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 begs the question: What does this analysis potentially 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 mentally 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 will be realized by the typical or average voyage or $201,500 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 Operating at a Speed of 7 Knots ($1 million baseline fuel cost)

	Average	Optimal
Annual Fuel Cost:	$1,000,000	$1,000,000
In Service Factor:	80%	80%
Annual Savings:	$160,442	$201,646

However, in this example we again caution that more investigation is needed to assess how wind-assist applies to larger vessels than the test vessel, even operating at the same speed of seven knots, as well as for operation at faster ferryboat service speeds (15-30 knots).

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 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 at optimal angle to the wind the average efficiency gain is 25%. The findings from this study are for a study vessel traveling at a constant rate of seven knots through water and therefore represent the upper bound of possibilities of fuel reductions for a ferryboat in service traveling at higher speeds. 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 findings described herein.

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. We 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.

All results are assuming the wind angles and wind speeds as shown in Figure 4. Historical as well as study period wind speeds and directions would need to be used to weight this distribution for a more representative set of results. This is beyond the scope of the study.

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 approximately the most efficient speed for a boat of this size (42-feet). 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 (or potentially even 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.

Future Work and Next Steps

Based on Existing Experimental Data
As actual experimental runs were captured in this study in addition to the polar data runs, where data were captured while traveling from actual end point to end point, these data elements could be utilized in subsequent analyses. This could be done to make greater gains in understanding the benefit of wing-assist while subject to various water currents, wind speeds and angles across representative ferryboat operating patterns.

Also, a next step of this analysis could be to collect historical and study period data on wind at more representative locations around the entire bay (for all routes) and to also get surface water current data so that these variables can be accounted for in future models.

Furthermore, future models may also want to incorporate efficiency factors for various hull configurations, which may include retrofitting current ferries, and designing several different types of new ferries.

Last, detailed data on fuel burn rates by time and location of the current ferry system would be invaluable in attempts to extrapolate this test run data to in-service runs. A complete analysis of the current ferry system duty-cycle would assist in better understanding this study's relevance to estimating actual in-service fuel rate reductions.

Based on New Experimental Data
If the opportunity for more data collection were to arise, more detail on a simulated ferry service duty cycle could be collected for estimates of relative fuel consumption during docking, at idle and embarking activities as compared to at full speed travel in open waters. Even more data on actual ferry service routes/runs under various wind and water conditions will also help complete the picture. And certainly, varying the speed of the study boat through water to capture more data at different ferry service speeds would also be beneficial.

In the design of a future study, use of a larger vessel would have obvious interest and would allow for more accurate extrapolation to actual ferry service. But, also important for investigation with a larger vessel is the ability to have systematic variation of vessel speed through water during the data collection, using a stratified sample design by wind speed, angle to the wind, and vessel speed through water. This would allow for a more complete assessment of the ability of these novel Wingsails to reduce fuel consumption in the ferryboat context.

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 and a steady speed of seven knots, the study vessel in open waters experienced fuel efficiency reductions of approximately 50%. However, when these wind speed 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.

APPENDIX A:
List of Data Collected on Wind-Assist Demo Vessel
February – April 2014

Data Items and Test Equipment (Make and Model):

Date/Time—B&G T8

Fuel Rate (g/hour)—Maretron FFM100

Tachometer (RPM)—Maretron EMS 100

Barometric Pressure (inHg)—Maretron WSO100

Outside Temperature (F)—Maretron WSO100

Course Over Ground (degrees)—B&G ZG100

Latitude—B&G T8

Longitude—B&G T8

Speed over Ground (knots)—B&G T8

Rate of Turn (degree/minute)—B&G ZG100

Rudder Angle (degrees)—Simrad AC12 Autopilot

Speed through Water (knots)—Airmar DST200

Pitch (degrees)—B&G ZG100

Wind Angle True (degrees)—B&G T8

Wind Angle Apparent (degrees)--Maretron WSO100

Wind Speed True (knots)—B&G T8

Wind Speed Apparent (knots) —Maretron WSO100

Polar Coordinates—Data log

APPENDIX B:
Example Polar Data from Study Testing

DATE/TIME(UTC)	Wing	WindAng	WA2	WindSpd	DataQual	Fuel Rate ()	Tachometer	Barometric P	Outside Tem	Course Over	Lat.	Long.	Speed Over Ground	Rate of Turn	Angle	Speed Through Water
3/5/14 8:05	on	90S	90	10	2	0.47550969	1543			134.496113	37.8674895	-122.37129	7.095032397	50.83922555	3.7414144	7.444924406
3/5/14 8:05	on	90S	90	10	2	0.5019269	1549	30.0910498	55.544	137.698947	37.8674658	-122.37126	7.289416847	55.80558791	3.7929806	7.561555076
3/5/14 8:05	on	90S	90	10	2	0.47550969	1547			137.996885	37.8674463	-122.37124	7.095032397	109.8483637	3.7929806	7.678185745
3/5/14 8:05	on	90S	90	10	2	0.5019269	1550	30.0910498	55.562	140.09964	37.8674226	-122.37121	7.095032397	142.3713819	3.68411862	7.639308855
3/5/14 8:05	on	90S	90	10	2	0.42267528	1554			139.899105	37.867398	-122.37119	7.095032397	151.3365958	2.09129595	7.794816415
3/5/14 8:05	on	90S	90	10	2	0.47550969	1548	30.0910498	55.562	144.597359	37.8673721	-122.37116	7.192224622	153.913939	0.34950426	7.833693305
3/5/14 8:05	on	90S	90	10	2	0.44909249	1549			146.797517	37.8673455	-122.37113	7.192224622	113.5637086	-0.6474423	7.833693305
3/5/14 8:05	on	90S	90	10	2	0.47550969	1548	30.0910498	55.562	148.596604	37.8673181	-122.37111	7.192224622	72.72854096	-1.6615776	7.833693305
3/5/14 8:05	on	90S	90	10	2	0.44909249	1547			148.699737	37.8672901	-122.37109	7.192224622	49.11788128	-2.1142143	7.678185745
3/5/14 8:05	on	90S	90	10	2	0.44909249	1548	30.1205798	55.58	148.894542	37.8672621	-122.37107	7.095032397	31.95525282	-1.8621128	7.600431965
3/5/14 8:05	on	90S	90	10	2	0.5019269	1548			151.0947	37.8672273	-122.37104	6.997840173	-6.152599853	-1.76471	7.561555076
3/5/14 8:05	on	90S	90	10	2	0.44909249	1548	30.1205798	55.58	149.696683	37.8671991	-122.37102	6.997840173	-9.266768709	-1.4610424	7.503239741
3/5/14 8:05	on	90S	90	10	2	0.44909249	1548			148.195534	37.8671766	-122.37101	7.386609071	1.74626793	-0.3495043	7.561555076
3/5/14 8:05	on	90S	90	10	2	0.39625808	1548	30.1205798	55.58	148.499201	37.8671495	-122.37098	7.095032397	-43.33419463	0.0515662	7.522678186
3/5/14 8:05	on	90S	90	10	2	0.42267528	1551			149.295613	37.867122	-122.37096	7.192224622	-26.20712536	0.49847328	7.561555076

APPENDIX C:
Additional Project Technical Details

Wingsail Technology

Photon Composites of Alameda, CA designed and built the 12m carbon fiber Wingsail used on the 42' trimaran vessel for the Test Project. Richard Jenkins, the founder of Photon Composites, designed and built the wing specifically for the Wind Assisted Ferry Demonstration Project. The vessel and fairing was provided by Wind+Wing Technologies.

The wing consists of a 14m long main spar that supports the symmetrical wing and extends approximately 3m below the wing into the bearing support fixture mounted inside of the vessel. This is the only connection to the vessel. There is a 150mm diameter bearing at the keel connection and a 350mm diameter bearing at the deck connection. There is no electrical connection from vessel to wing. The wing has built in battery, photovoltaic panels, linear actuator, wind sensor, GPS, computer and wireless on/off control all integrated inside.

The control trim tab extending up and aft approximately 3m off the top of the Wingsail controls the angle of attack for the wing when the control tab is deflected. If the control tab is straight then the wing feathers perfectly into the wind, when the actuator moves the control tab it is deflected approx. 15 degrees and the wing now sets itself to the correct angle of attack to generate lift (thrust).

Richard Jenkins developed this wing control technology while pursuing his goal of setting the world land speed record of 126.1 mph on a wing powered land sailor. The 126.1 mph world record was set with just a 30 mph wind[3]. This speed record is more than four times the speed of the wind.

Richard found that he could not control the wing properly, and get maximum thrust at the apparent wind speeds that he was encountering. His solution was the control trim tab on the wing, which was able to respond to the 130+ mph apparent wind.

Wind Assist

SF Bay winds are consistent and reliable but there are times when the winds do not blow or when they are not in the correct direction. The wing technology is an assist to the propulsion system. So at those times when there is not enough wind then the wing feathers into the wind and has very little drag and the ferry goes about it schedule with no problem.

Wind assist can work with almost any amount of wind and will benefit the fuel burn rate of the ferry corresponding to the relative strength of the wind.

Wind assist can be used with any fuel source, diesel, LNG, hydrogen, battery electric. Another benefit of wind assist in addition to lower fuel burn rate, lower emissions and lower greenhouse gas emissions is less wear and tear on motors, transmissions, shaft bearings and extending the life of batteries in all battery electric ferry.

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[3] http://www.gizmag.com/wind-powered-car-world-record/11346/

True Wind vs. Apparent Wind
Apparent wind is the combination of the true wind speed *and* the wind developed by the boat speed. It is the wind that you "feel" when on the deck of a moving vessel and also the wind that the vessel with wing or sails can actually use.

> **Example Demo Vessel** – A vessel going **7** knots through the water, with a true wind angle of **60** degrees and a true wind speed of **16** knots will have an apparent wind angle of **42** degrees and an apparent wind speed of **21** knots.
>
> **Example Ferry Vessel -** A vessel going **17** knots through the water, with a true wind angle of **60** degrees and a true wind speed of **16** knots will have an apparent wind angle of **29** degrees and an apparent wind speed of **29** knots.

This increase in the apparent wind speed is what gives the vessel more power (thrust) and allows the vessel to go even faster and is why a vessel or vehicle can exceed, (doubling or more) the speed of the wind.

New Build Ferry Vessels vs. Existing Ferry Vessels
The United States Coast Guard is the sole regulatory agency controlling construction and operation of ferry vessels. One of the main criteria that the Coast Guard regulates is the stability of the vessels and it issues a stability letter for each vessel based upon the route, the passenger capacity, the unique construction and layout of the vessel.

While it is possible to add a wing to an existing vessel we believe that the best approach is to design and build a new vessel optimized to take advantage of the benefits from the wing and with the correct stability characteristics built in.

Catamaran vessels are inherently more stable than mono-hull vessels and are therefore the best design platform for wing technology.

Sailboats have keels that resist side slippage; ferries traditionally do not have keels. This is another argument in favor of building a wind assist ferry from the ground up. There are many catamaran designs that do not have traditional sailing keels, but use an asymmetric hull shape to stop the side slippage that can be caused by the wing assist.

Speed of Demo Vessel compared to Ferry Speed
The target speed of the vessel used in the demonstration project was 7 knots (8mph). This is a very efficient target speed, which uses the least amount of fuel to achieve that speed. The fuel burn rate at that target speed was .60 gallons per hour at approximately 1750 rpm. The motor in the vessel is a Yanmar 4jh-te 54 horsepower diesel motor. A Brunton autoprop was fitted for the demo also.

Ferries typically operate at higher speeds than the Project Vessel and can be classified by:
- Lower speed – 17 knot routes
- Medium speed – 25 knot routes
- High speed – 32 knot routes.

Lower Speed Routes – Sausalito-San Francisco route, proposed Treasure Island-San Francisco route

Medium Speed Routes – San Francisco-Alameda route, proposed Berkeley-San Francisco route

High Speed Routes – Vallejo-San Francisco route

34th Americas Cup 2013

The 34th Americas Cup contested on SF Bay in 2013 in 72' wingsail catamarans was a vivid demonstration of the power capable of being extracted from the wind. The wind speed limits placed upon the races was 22 knots maximum and yet the boats were regularly sailing at up to 48 knots (55 mph) in speed.