COMPARISON OF DOWNWIND SAILING PERFORMANCE PREDICTED FROM WIND TUNNEL TESTS WITH FULL-SCALE TRIALS FROM AMERICA'S CUP CLASS YACHTS

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SUMMARY

This paper compares of wind tunnel sail data with full-scale performance, using trials data gained during the 32nd America's Cup event. VPP calculations were made using sail coefficients obtained from the wind tunnel and sailing speeds and angles were compared with measurements of the ACC yachts' performance. Causes for the differences that were found are discussed and relate to both the modeling and difficulties with trials measurements.

Data is also presented showing the differences between different sail shapes and sizes, which is a matter of interest to designers when developing sails. The differences found between wind tunnel results and sailing trials are discussed.

1. INTRODUCTION

The 32nd held in Valencia in 2007 was an extraordinary event in that teams could build two America's Cup Class (ACC) Yachts without constraints on development time from the Cup Protocol. Although this class has been superseded by multihulls much of the data obtained remains unpublished although it is valid for other monohull yachts and for validation of experimental and numerical modeling methods.

By kind permission from Luna Rossa Challenge some of the wind tunnel downwind sail data was published at the INNOVSail 2013 conference, Campbell (2013), for the purpose of comparing tests from different wind tunnels to help validate the use of wind tunnels for testing of sails.

The aim of this paper is to extend the work to the comparison of wind tunnel sail data with full-scale performance, using trials data gained during the 32nd America's Cup event. This data was measured and analysed by the performance team at the time of the event but has been re-examined for this paper for comparison with VPP calculations made using the wind tunnel data.

Two questions can be posed:

Do wind tunnel tests produce sail forces representative of full-scale sailing?

And can wind tunnel tests distinguish the performance differences between different sail designs?

Other direct methods have been used to address the scaling question, e.g. by measuring sail forces on a boat, Masuyama, (2013); or comparing sail shapes, Mausolf et al. (2011); or comparing pressures, Motta et al. (2013). By comparison performance measurement is an indirect method since sail forces are compared with speed predictions based on hydrodynamic forces. Nevertheless hydrodynamic forces can be predicted with reasonable accuracy and all the methods are subject to the problems of wind measurements in the real environment.

Comparison between sails is of particular interest to designers and sailors, since competition provides the incentive to find a faster sail. Numerical modeling for performance e.g. using RANSE CFD, as distinct from just inflating mould shapes to predict flying shapes using panel codes, is now available to sail designers, Wright (2010). Whilst CFD modeling of the flow may differ from that in the wind tunnel there remains the common issue that the flying shape is under the sailors' control and the sail forces vary with the flying shape. The flying shape is adjusted in the wind tunnel to optimise sail forces but although Luna Rossa Challenge used the Sail Vision on-board system shape matching of downwind sails proved difficult.

2. LUNA ROSSA CHALLENGE FOR 32ND AMERICAS CUP

The challenge was launched through the Yacht Club Italiano, the oldest sailing club in the Mediterranean, established in 1879 in Genoa, Italy. The two partners in Luna Rossa Challenge 2007 were the Prada Group and the Telecom Italia Group.

In February 2004, the Luna Rossa team was the first to set up its base in Valencia, where it started training in May with ITA 74, the yacht which had raced in the semi-finals of the Louis Vuitton Cup for the 31st America's Cup in New Zealand, and ITA 80, a similar design.

The team Luna Rossa Challenge 2007 (sailing team, design team, shore team, weather team, performance team, boat builders, sail loft, logistics, administration and management) included about 110 people from 18 different countries. At the time this organization was larger than the School of Engineering Sciences at the University of Southampton where the author worked. However the competition was immense with 11 challengers, having varying resources, seeking to race the Cup Defender Alinghi and with racing in different "Acts", in house 2-boat tuning and informal match racing.

The Cup Protocol permitted each team to build two new America's Cup Class yachts and the Luna Rossa Challenge launched ITA 86 in 2006 and ITA 94 in 2007, with Miuccia Prada being godmother. Considerable research and development went into the design of these yachts and the author was involved in the experimental work in the towing tank, the wind tunnel and on the water.

Sadly for Luna Rossa Challenge they were beaten in the Finals of the Louis Vuitton Cup by Emirates Team New Zealand, who then lost in the races for the America's Cup to the Defender Alinghi. The subsequent 33rd and 34th America's Cups were raced by fewer challengers in multihulls so the pinnacle of development of the match racing displacement monohull remains the defender Alinghi's SUI 100 from 2007.

Figure 1 Luna Rossa racing Emirates Team New Zealand

3. WIND TUNNEL TESTS

The new wind tunnel (galleria del vento) became available at the Politecnico di Milano in 2004 and Luna Rossa Challenge conducted 12 weeks of upwind and downwind sail testing during the 3-year campaign for the 32nd America's Cup. The data in this paper comes from the 8th session conducted in February 2006 and represents the development phase for the downwind sails but not their final configuration used in the Louis Vuitton Cup. A total of 175 measurement runs were taken on 10 different asymmetric downwind sails during this session.

3.1 Wind tunnel

The Politecnico di Milano wind tunnel had a closed circuit, with a bank of fourteen fans driving the air through the final bend into the large 14m x 4m low speed section. The tunnel floor was smooth, with a 35m long section, which allowed the boundary layer to grow to a thickness of approximately 300mm. There were consistent lateral and vertical variations in flow speed across the location of the model. These were associated with the flow pattern from the individual fans and amounted to an rms variation in pitot pressure of approximately 5%. The tunnel had a high speed section on the return circuit below the low speed section with a contraction ratio of approximately 3:1, which helped produce a relatively uniform speed in this smaller section. So to avoid the problems with the flow variations and effects from the presence of the model the mean flow speed was taken from measurements in the high speed section. Campbell (2013).

The tests were conducted with a twisted flow device, Zasso et al. (2005), using a true wind gradient measured in Valencia for the prevailing sea breezes. The gradient was curve fitted by a power law of between 1/20 and 1/30, which was considerably lower than the conventional 1/7 or 1/10 curves. The twist between the centre of effort and mast head was approximately 3 degrees and between the centre of effort and the boom approximately 5 degrees. The apparent wind angles in the wind tunnel tests were referenced to the centre of effort not the mast head.

3.2 Model parameters

The model particulars were:

Scale 1:12.5
Reference length 1500mm model scale, 18.75m full-scale
Reference mast height above DWL 2698mm model scale, 33.725m full-scale
Reference distance of dynamometer centre from tunnel floor 40mm model scale – for centre of effort height calculations, which have not been corrected for this distance, so needs to be added in any VPP calculations.

Test wind speeds associated with nominal dynamic pressures of q = 2.91Pa, approximately 2.2 m/s, which was similar to full-scale apparent wind speeds. This speed was selected to give representative flying shapes using the scaling criteria of the ratio of wind pressure to sail cloth weight.

The model was mounted over a 6-component strain gauged balance with a small gap between its topsides and the floor of the tunnel. The floor was a large turntable that could be rotated to present the model at different apparent angles to the wind.

The model was fitted with remotely operable sail winches with cables led to the control room where the data acquisition system was also sited. The winches allowed adjustments to be made to; gennaker/spinnaker pole height and angle, gennaker sheet, main sheet and main vang, as can be seen in Figure 2. Other adjustments were made manually before the start of a test sequence.

3.3 Test sails

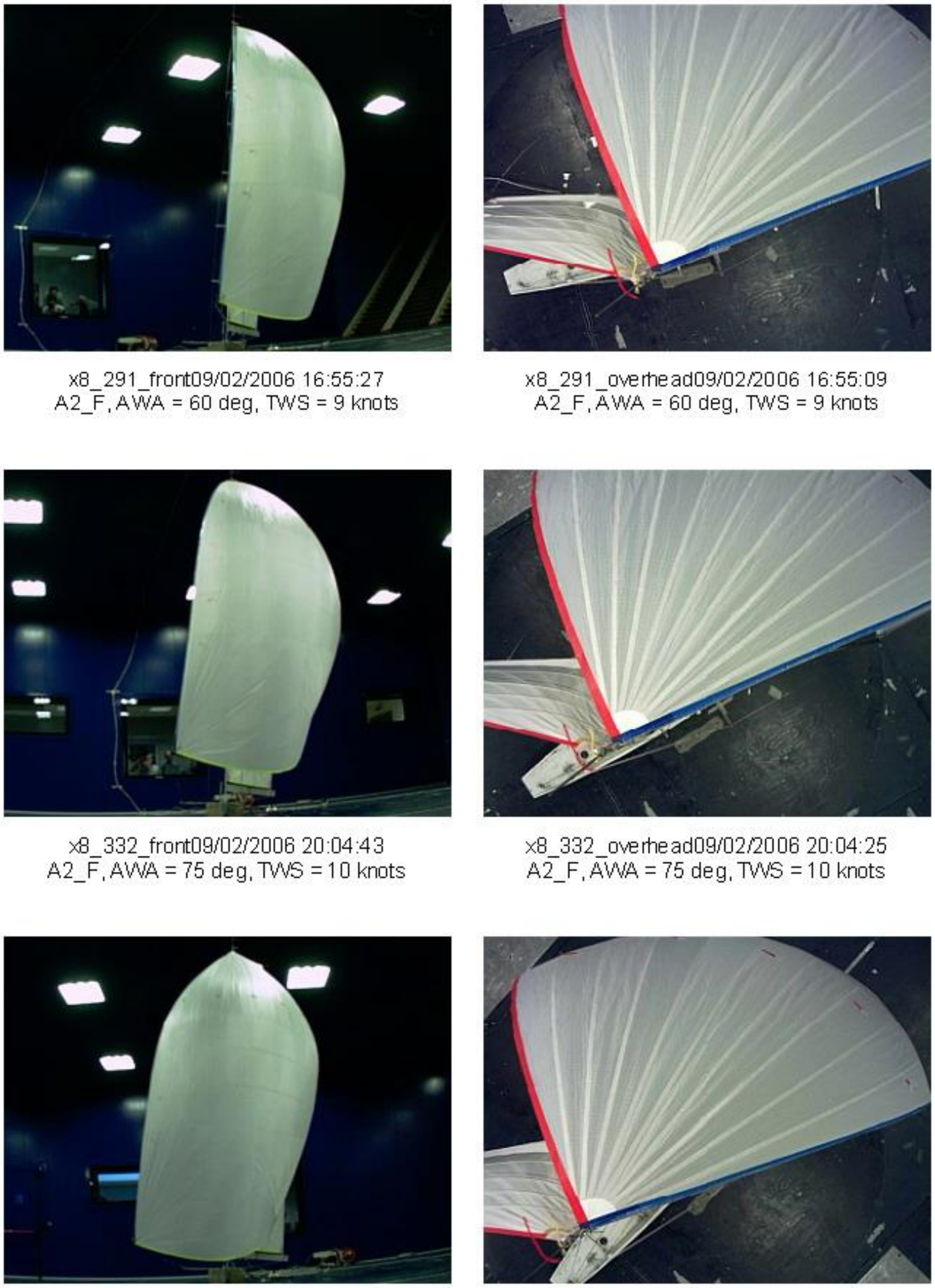
The sails were designed by Luna Rossa's sail team using North Sails' Flow-Membrane software. The model downwind sails were built by Guido Cavalazzi, one of the designers who enjoyed building sails, from the panels derived from the design mould shapes in similar manner to their full-scale construction. The model mainsails were built over a mould in a similar way to their full-scale construction with North Sails' 3DL method.

The sails referred to in this paper are listed in Table 1. The downwind sail type used for racing varied according to the true wind speed, mainly due to the different apparent wind angles associated with optimum downwind speed, as discussed later in this paper. The asymmetric gennakers have the prefix A in their code and the symmetrical spinnaker has the prefix S. Different methods of gybing applied to the asymmetrics and spinnaker, with operational advantages in different wind conditions that affected sail selection when racing.

Each new sail design was allocated a sequential letter and the sails referred to in this paper represent the best designs at the time of the tests together with the design of the original gennaker A3v5 and spinnaker S1. It should be noted that the America's Cup Class rule was revised to version 5 for the 32nd Cup, with an increase in the downwind sail area so new sail designs were developed at the start of the campaign.

Table 1 Sail dimensions

							Model	**Full-scale**
Wind	**Sail**	**Code**	**SLU**	**SLE**	**SF**	**Head**	**Area**	**Area**
condition	**type**		**m**	**m**	**m**	**m**	**m^2**	**m^2**
Light	asymmetric	A1-D	34.50	31.66	18.50	0.05	3.03	473
Medium	asymmetric	A2-F	35.00	31.80	18.42	0.05	3.46	541
Strong	asymmetric	A3-I	34.40	30.04	19.15	0.05	3.40	531
Strong	Original	A3v5					3.45	539
Strong	Spinnaker	S1					3.46	541
Light	mainsail	M1B					1.36	212.5
Medium	mainsail	M2A					1.36	212.5



x8_291_front09/02/2006 16:55:27
A2_F, AWA = 60 deg, TWS = 9 knots

x8_291_overhead09/02/2006 16:55:09
A2_F, AWA = 60 deg, TWS = 9 knots

x8_332_front09/02/2006 20:04:43
A2_F, AWA = 75 deg, TWS = 10 knots

x8_332_overhead09/02/2006 20:04:25
A2_F, AWA = 75 deg, TWS = 10 knots

x8_362_front10/02/2006 10:54:39
A2_F, AWA = 90 deg, TWS = 12 knots

x8_362_overhead10/02/2006 10:54:27
A2_F, AWA = 90 deg, TWS = 12 knots

Figure 2 Images of the A2 gennaker under test at different apparent wind angles

3.4 Test method

The data was measured from the SF dynamometer using the Wolfson Unit Lasso system, which gave a real time display of the sail forces and was used as an aid to trimming the sails to produce the maximum driving force. The data files were analysed subsequently using the Wolfson Unit's WindCorrect program according to the process described in 3.6.

Each sail was tested over an appropriate range of apparent wind angles and the driving forces can be compared in Figure 3. Target driving forces had been obtained from previous test sessions so the sails were adjusted using the remote winches until forces were close to the target. This process could take approximately 5 to 10 minutes and data was then acquired over a period of approximately 1 minute to produce the average sail forces, moments and wind speed. Adjustments were then made in attempts to improve the driving force using the remote controls and real time force display, with acquisitions for mean values at promising settings. This process was repeated a few times within a 10 to 15 minute period before the wind was turned off to check for any zero drift in the dynamometer. Sail trimmers from the team were involved in some of the test sessions to share knowledge about sail settings.

Optimum sail settings of the A2 gennaker are shown in Figure 2, which can be compared with the boat racing in Figure 1, and it can be seen that the spinnaker pole was brought progressively aft as the apparent wind angle increased, bringing more of the gennaker in-line with the bow of the boat. However it can be seen from the fixed overhead camera image that the sail geometry remained similar relative to the apparent wind, with the boat appearing rotated under the sails.

At most angles the drive force could be increased without increasing the heeling moment and it can be seen that in many instances the maximum drive force was achieved at lower values than the maximum heeling moment. Thus the sail trim for maximum drive would produce the best boat speed.

If there were significant increases in heeling moment and heel force this might affect boat speed, due to related hydrodynamic changes in heel and induce drag, but this is only a potential issue with data from tests at 45 degrees apparent wind angle and can be resolved by VPP calculations through the optimisation of speed using the flat function, which reduces the maximum lift and drag with associated changes in driving and heeling forces.

The hydrodynamic characteristics of ACC yacht hulls were for their resistance to be lower at 20 degrees heel than when upright, due to their bow and stern overhangs increasing waterline length when heeled. As can be seen from Figure 14 the yachts tended to sail downwind slightly heeled so the wind tunnel model was tested at 5 degrees heel to represent any flow effect over the sails although at this angle the hull resistance was similar to when upright.

3.5 Windage tests

The windage of the hull and rig was measured without sails and the data was fitted to the VPP windage model, which resulted in drag areas of $Ax = 9.5m^2$ and $Ay = 50m^2$. These data were subtracted from the measurements to derive the sail coefficients, so the VPP calculation included separately the windage and the sail coefficients.

The windage was added back for comparison of the VPP fit with the corrected driving forces and heel moments. The windage has a comparatively small effect on downwind performance since at an apparent wind angle of 90 degrees the hull generates very little lift to augment the driving force and the drag only affects the heel, which is small.

3.6 Sail coefficients

The measured sail forces and moments were corrected to sail coefficients and centre of effort locations by:

- Correcting for wind off end zeros, following each set of runs.
- Transforming the force data into the wind axes in the heeled plane using the IMS velocity vector method, which was a relatively small change for the 5 degree heel used for the downwind tests.
- Subtracting the windage values, which are given in 3.5.
- Calculating lift and drag coefficients based on the total sail area and dynamic pressure from the reference pitot.
- Correcting the coefficients for wall boundary effects and wake blockage effects, taking due account of the induced drag due to lift in determining the separated flow for the wake blockage correction.
- Recalculating the force and moment coefficients in the upright condition at the nominal apparent wind angle and comparing the results from the VPP fit.

The notation on the figures gives for each series the heel angle and apparent wind angle in the horizontal plane, as set on the turntable, i.e. not corrected to the heel plane.

3.7 Sail data

Test results for the basic sail force measurements on the downwind asymmetric gennakers are shown in Figure 3. There is a group of results for each sail that represents different attempts to optimise the trim for maximum drive force and it can be seen that these span approximately 5% at each apparent wind angle, which represents the scope available to the skill of good sail trimmers.

Lift and drag sail coefficients are related to the driving forces and heeling moments and these are shown in Figure 4 and Figure 5. Spline curves were fitted to these coefficients for VPP calculations and the associated VPP curve fit is shown in Figure 3. It can be seen that this fit is matched below the maximum values of driving force from each group of measurements, which was chosen to predict speeds when sailing with off-optimum sail trim.

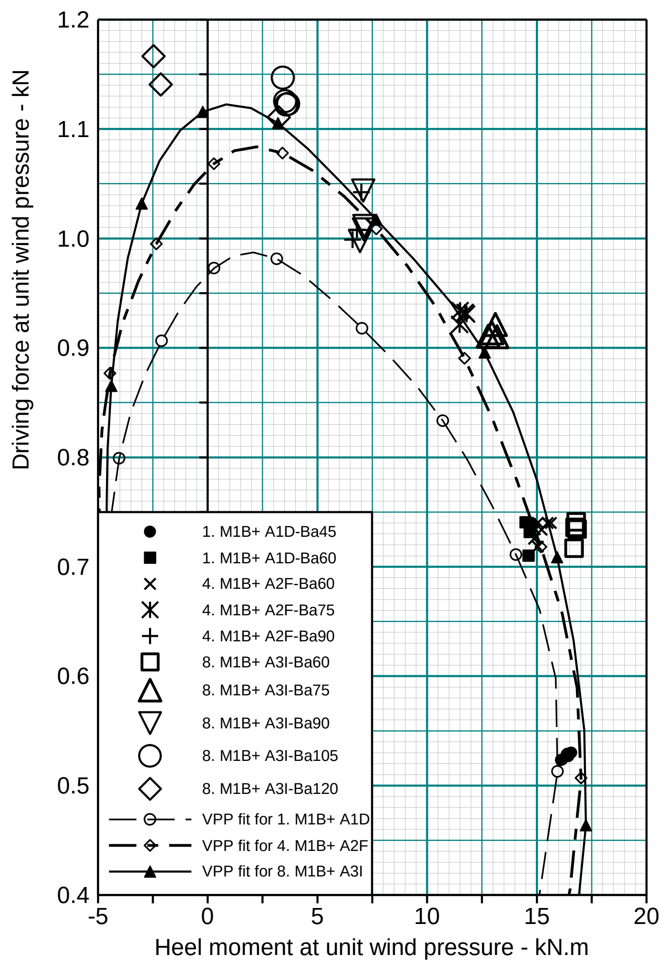


Figure 3 Variation of driving force with heel moment

The data in Figure 3 represents the better sails tested at that time, i.e. A1D, A2F and A3I. The A1-D sail had slightly lower area than the other two asymmetric sails and produced lower forces.

It can be seen from Figure 4 that the lift coefficients were relatively similar for all the sail types between apparent wind angles of 75 to 120 degrees but the A1 sail produced higher lift coefficients at angles of 45 and 60 degrees. The America's Cup Class benefitted in downwind sailing from the allowance of a pole as distinct from a bowsprit used in many sports boat classes. This enabled the gennaker sail luff to be orientated to an optimum angle to the wind at each apparent wind angle with the mainsail accordingly adjusted. The sail geometry therefore remained similar relative to the wind, whilst being different relative to the boat, which accords with the relatively small variation of lift coefficient with apparent wind angle.

The drag coefficients, shown in Figure 5, tended to increase with apparent wind angle and were lower with the A2 gennaker compared to the A3. The relative location of the mainsail to the gennaker changed with apparent wind angle, being most closely coupled with the A1 gennaker at an apparent wind angle of 45 degrees. This geometric difference could relate to the higher lift coefficients produced by the A1 gennaker and the higher drag coefficients produced by the A3 gennaker but the drag also contributed to the driving force at apparent wind angles of greater than 90 degrees so it is possible that the sails were trimmed to produce more drag at these angles.

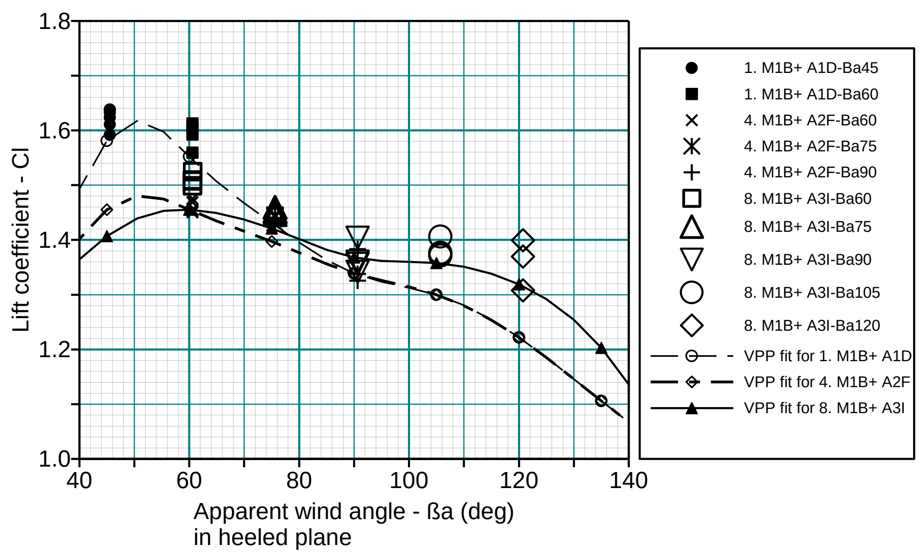


Figure 4 Variation of lift coefficient with apparent wind angle

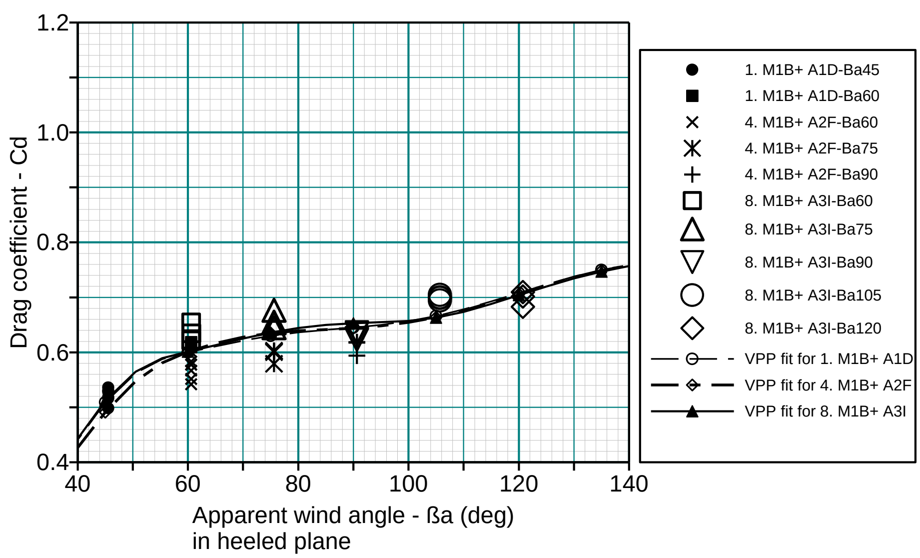


Figure 5 Variation of drag coefficient with apparent wind angle

The VPP fits were adjusted to lower values of lift outside the test data ranges to promote the VPP to iterate to values within the test range.

The centre of effort heights associated with the heeling moments are shown in Figure 6. These have been plotted on a different axis to the lift and drag coefficients to show the influence of heel force. The heeling moment is low at low values of heel force so has little influence on the hull hydrodynamics and sailing performance. The centre of effort height has been obtained from the transverse force to match how the VPP calculates heel equilibrium; however the longitudinal driving forces and pitch moments are considerably higher for downwind sailing at apparent wind angles of 90 degrees and would provide an alternative centre of effort height since the reason for the lower centre of effort height at low heel force is unclear.

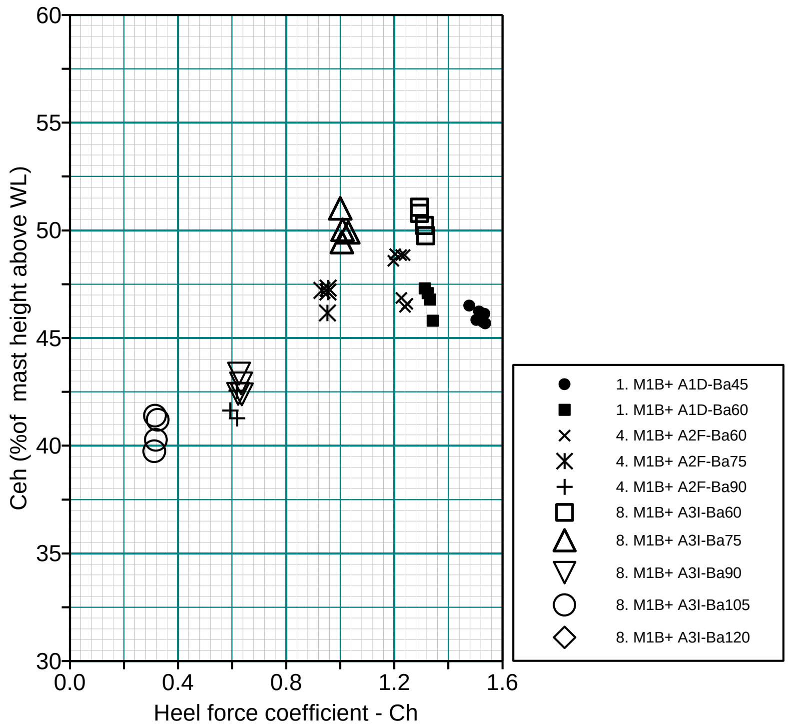


Figure 6 Variation of centre of effort height with heel force coefficient

The wind tunnel was used to compare different sail designs and a large number of shapes were tested, as indicated by the sail code letters. It is therefore of interest to compare sails with significantly different shapes to determine the level of discrimination that can be provided in wind tunnel tests and examples are shown in Figure 7.

The 2006 design of the A3-I gennaker produced approximately 5% more driving force at apparent wind angles of 105 and 120 degrees than the original A3v5 gennaker design from 2005 and similar driving force but at a lower heeling moment at an apparent wind angle of 90 degrees. These are clear differences despite the 5% variations in driving force found during the sail tuning process. The differences found between other sail shapes were, however, smaller but although the designs had different mould shapes their flying shapes were adjusted to produce the best sail forces and may have been similar.

It is also clear that the asymmetric gennakers produced significantly higher driving forces than the symmetrical spinnaker, of up to 15% at the larger apparent wind angles of 120 and 135 degrees.

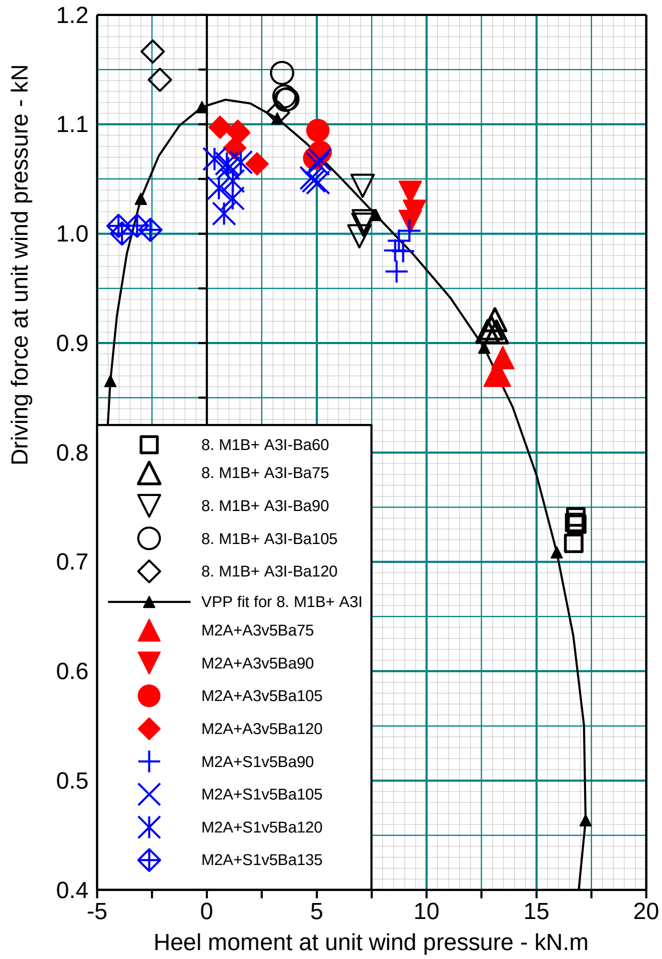


Figure 7 Variation of driving force with heel moment for Spinnaker and Gennakers

4. VPP CALCULATIONS

VPP calculations were performed using the WinDesign WD4 software package developed by Yacht Research International and the Wolfson Unit MTIA, Oliver and Robinson (2008). This program had the facility to input experimental hydrodynamic data for the hull and aerodynamic data for the sails.

The hydrodynamic data for the hull was obtained from tank tests on a 1:3 scale model. This data currently remains confidential to the Luna Rossa Challenge however other generic data on America's Cup Class yachts has been published, e.g. Viola et al. (2012) The hydrodynamic characteristics for downwind performance prediction are, however, relatively simple compared to upwind predictions because downwind heel angles are small so heel and induced drag components are also small compared to the upright resistance characteristics of the hull, which dominate the speed calculations.

The VPP essentially iterates to a force balance between the hull drag and the sail driving force at wind speeds and angles that also match the wind vector triangle shown in Figure 8 using the geometric Equation 1. The VPP calculations take account of the variation of driving force with apparent wind angle shown in Figure 3. The result for downwind sailing always occurs with the maximum sail force coefficient and, unlike in upwind sailing performance prediction, the flattening and reefing functions are not required so the optimization element of the VPP calculations is also not required.

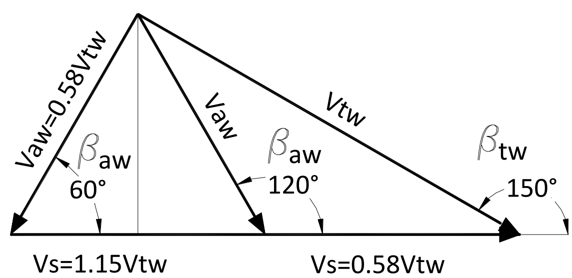


Figure 8 Wind vector triangle for downwind sailing

$$V_{AW} = \sqrt{\left(V_{TW}(Z)\sin(\beta_{TW})\cos(\phi)\right)^2 + \left(V_{TW}(Z)\cos(\beta_{TW}) + V_S\right)^2}$$

$$\beta_{AW} = \tan^{-1}\left\{\frac{V_{TW}(Z)\sin(\beta_{TW})\cos(\phi)}{V_{TW}(Z)\cos(\beta_{TW}) + V_S}\right\}$$

Equation 1 relating true and apparent wind speeds and angles

The aerodynamic characteristics for the sails were obtained from the wind tunnel tests and the inputs required for the VPP were straightforward, being the variation with apparent wind angle of lift and drag coefficients, as shown in Figure 4 and Figure 5 and centre of effort height, shown in Figure 6. The variation of drag with lift was obtained in the VPP calculations from an input of the effective rig height and an associated variation of centre of effort height with lift was also an input. However because the heel angles associated with downwind sailing were small and also the apparent wind angles were large reducing drag had little effect on driving force and the maximum lift produced the fastest speeds. Therefore the effective rig height and variation in centre of effort height did not affect the performance predictions.

A set of lift and drag coefficients were provided as inputs to the VPP for each downwind sail in combination with the mainsail. That is separate coefficients were not produced for asymmetric gennaker and mainsail as is the case when the VPP calculates sail forces from sail dimensions using generic data held within the program. The range of true wind speeds and angles associated with each sail was specified, which ensured that the VPP calculations were based on the same sail selection that was used by the sailors on the boats.

As described in paragraph 3.7 the sail coefficients were set slightly lower than the maximum values obtained from the wind tunnel tests. This was to allow for the sail trimming on the boats to be below optimum since the sailors did not have the benefit of sail force measurements that were available in the wind tunnel. However, to investigate sensitivity, VPP calculations were also performed with a 5% increase in lift coefficient and an associated increase in induced drag. These results are also shown in the performance comparisons given in Section 6 of this paper.

The VPP output is normally given as the speed polars, Figure 9, showing the variation of boat speed with true wind angle for Figure 3 increments of true wind speed. The polars provide a good visual indication of the true wind angles for optimum speed made good downwind and these are marked by square symbols in Figure 9.

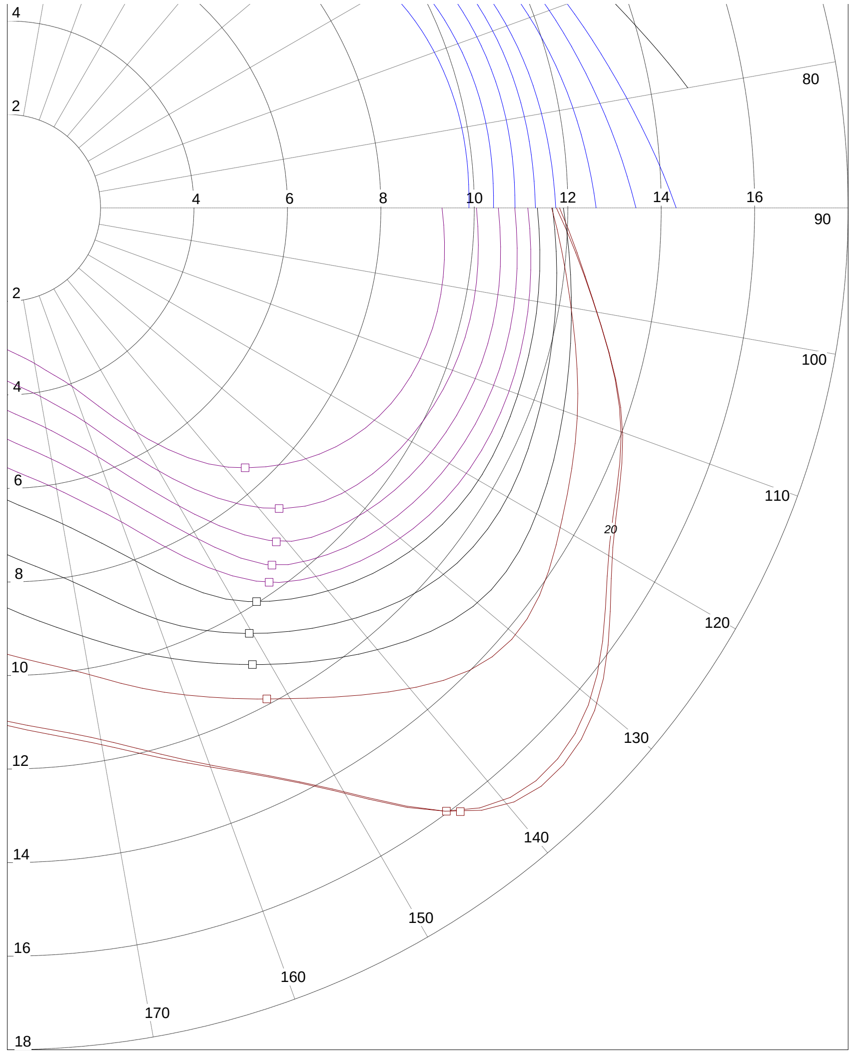


Figure 9 VPP polar speeds downwind

There are, however, other parameters in the VPP output including apparent wind speeds and angles and heel angle, which is important for upwind sailing but is also an indicator of apparent wind angle for sailing downwind. In Figure 10 the speed made good downwind is shown plotted against heel angle for fixed true wind speeds to show both the optimum heel angle and the loss in speed when not at optimum heel. It can be seen that the optimum heel tends to reduce with increasing wind speed but the speed loss is great at heel angles less than optimum than at greater heel angles.

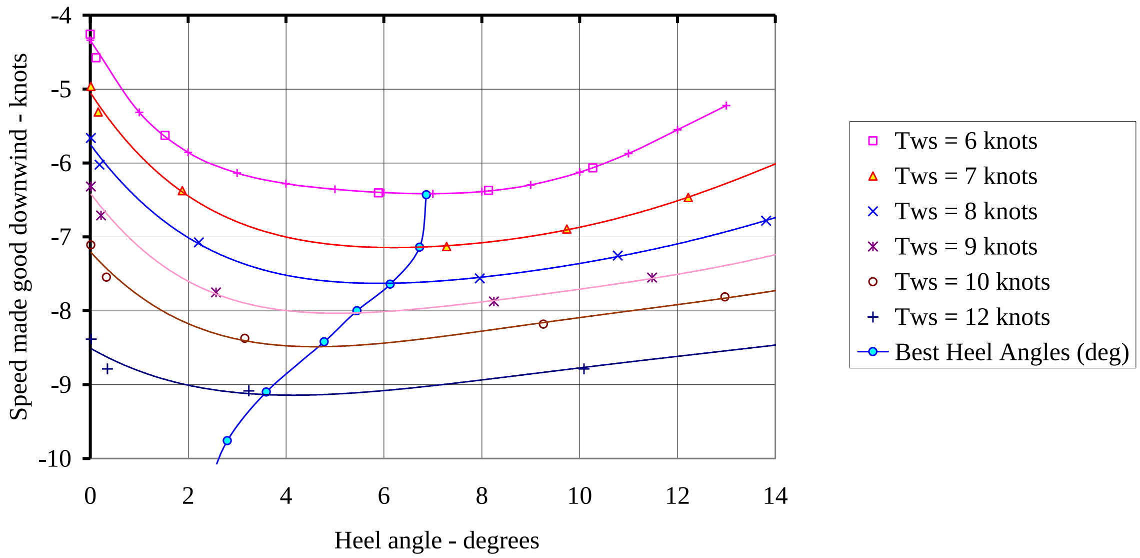


Figure 10 Variation of speed made good downwind with heel angles and true wind speed

5. SAILING TRIALS

2-boat sailing trials were conducted throughout the 3-year campaign but these were limited by a number of factors: e.g. the sailing season in Valencia, periods away from Valencia for racing in "Acts", bad weather with light winds or storms and informal racing with other teams. The trials were conducted for a variety of purposes: e.g. to obtain baseline performance data, to test hull components including fins bulbs and rudders, to test rig components including mast booms and sails, to tune the new boats as they arrived and for crew and race training. Despite the 3-year campaign and a protocol for the Cup that permitted unrestricted sailing, time on the water was a limiting resource for the team and more time would have allowed more development.

Emphasis was placed on upwind sailing performance, since in match racing it is important to get to the windward mark first and control the boat behind, so downwind sail evaluation was limited and sometimes performed in conjunction with other trials, e.g. fin and bulb evaluation. Baseline target speeds and wind angles were developed from sailing trials in 2005 but the data presented in this paper is from trials conducted between April and July 2006. ITA74, Luna Rossa's race boat from the 31st Cup, was sailed against ITA86, their first new design for the 32nd Cup, and approximately 30 downwind sailing trials have been analysed for comparison with VPP predictions based on wind tunnel data. Mausolf et al. (2011) reported on the difficulties of conducting full-scale downwind trials to measure flying shapes on one boat sailed over a three day period. By comparison Luna Rossa's trials were conducted over a much longer period, with greater resources, using 2 boats but with comprehensive performance monitoring equipment to measure speeds and angles. Nevertheless it proved to be a difficult task to obtain definitive measurements of differences to the desired level of accuracy.

The trials were conducted with the boats operated by the sailing team, crewed and helmed by sailors with America's Cup experience and other yacht racing pedigrees. The performance was monitored both on-board and remotely by the performance team using equipment set-up and calibrated with the help of the shore team and the sailing conditions were monitored by the weather team operating from their own boats. The trials techniques had been developed during previous Cup campaigns with input from members of different teams in previous campaigns so it was a well rehearsed process. The results were reviewed following each day's sailing at a STEP meeting, so named because it had originated on steps during previous Prada and Luna Rossa Challenges in New Zealand. So considerable efforts were made to improve the accuracy of the measured data throughout the trials periods.

The trials process involved setting the two boats off on parallel courses for a 6 to 8 minute period, with the crews concentrating to obtain the best relative performance from each of the boats. Measurements of speeds, angles and distances were averaged over this period. The two boats would then swop sides and the trials repeated then, when time and position on the course permitted, the boats would gybe and the trials repeated with the wind on their opposite side giving four separate measurements of sailing performance for each configuration of the boat.

Corrections were applied to the trials measurements to improve their consistency. Wind measurements from the mast head instruments presented particular difficulties for downwind sailing due to; the proximity of the masthead gennaker, the boat's motions, twist in the apparent wind gradient and the low apparent wind speed of approximately half the true wind speed. Normal upwash corrections applied when sailing upwind with the fractional genoas were inaccurate for downwind sailing with masthead gennakers so tests were conducted on the wind tunnel model by observing angles on the masthead wand from an overhead camera to obtain corrections for downwind sailing. However, the masthead wand could be observed oscillating through large angles when the boats were sailing downwind.

Correlations were made between the wind measurements upwind and down, from port and starboard gybes and from weather boats stationed on the course. The relationship between the true and apparent wind speeds and angles must conform to the wind triangle, Figure 8, and this improved during the trials period but discrepancies remained of up to 0.5 knots and 5 degrees. In addition the twist in the wind gradient varied and was noticeable to the navigators on the boats so particular corrections were applied. These issues complicate the correlation between the measurements and VPP calculations.

6. PERFORMANCE COMPARISONS

Comparisons between results from the VPP calculations and measurements from the sailing trials are shown in Figure 11 to Figure 14. The true and apparent wind angles are shown in Figure 11 and a number of points can be noted:

The distribution of measurements represents the wind speeds during the 4-month period of the trials, with preponderance in the 10 to 15 knot range, the sea breeze conditions. Only a few trials were conducted in lighter wind conditions, with little interest in wind strengths below 7 knots as it was the minimum for starting Cup races. There were a significant number of trials in stronger winds of 17 to 22 knots where the spinnaker would be used.

The apparent wind angle increased with true wind speed from less than 60 degrees in light winds to greater than 120 degrees in strong winds whilst the boats were being sailed downwind on courses aimed best speed made good downwind. There were significant variations of 5 to 10 degrees in the apparent wind angle in the true wind range of 12 to 15 knots, which was indicative of the boats being sailed differently from trial to trial. There was also variation in the higher wind speeds but at greater apparent wind angles of the order of 120 degrees.

Apparent wind angles from VPP calculations are shown for both the optimum speed made good downwind and at the trend through the measured true wind angles. The VPP optimum gives a good fit up to a true wind speed of 15 knots although it is associated with lower true wind angles than the trend. Increasing the sail coefficients made little difference to the VPP optimum true and apparent wind angles so it would appear that the differences with the measurements were either due to the trials measurements or the sailing style.

The optimum downwind angles from VPP calculations in a true wind speed of 20 knots, Figure 9, were considerably smaller than those sailed during the trials. This was known at the time of the races but the boats continued to race at the higher angles, i.e. sailing angled closer to the leeward mark. This may have been due to operational or structural reasons, e.g. match racing tactics, sail handling issues when gybing or to lower the apparent wind speed to avoid blowing out the sail. Alternatively there may have been an issue with the VPP but without further races with ACC Yachts in 20 knots of wind the issue remains unresolved.

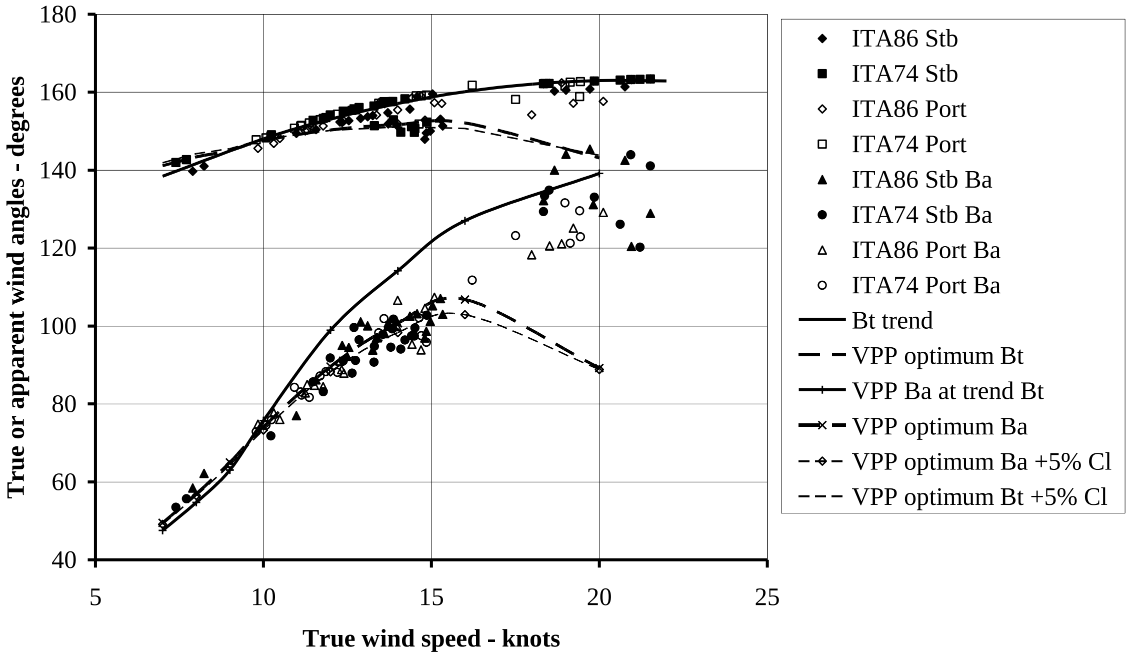


Figure 11 Variation of true and apparent wind angles with true wind speed

The differences between predicted and measured boat speeds are shown in Figure 12, where the baseline was taken as a curve fit through the measured boat speeds. There is less variation in the speed than in the angles, which may be because boat speed measurements are more straightforward than wind measurements.

Comparisons with VPP calculations showed the measurements lying between the predictions at the trend through measured true wind angles and at optimum true wind angles. The predicted optimum in 20 knots true wind speed was a high boat speed, which is associated with the smaller apparent wind angle, shown in Figure 11 and higher apparent wind speed, shown in Figure 13. Increasing the sail coefficients improved the correlation between the VPP optimum and measured boat speeds in the true wind range of 10 to 14 knots.

Of particular note are the low boat speeds in light winds compared to the predictions and the reason for this is unclear. It is unlikely that the hydrodynamic drag was incorrect since it is dominated by friction drag at these lower boat speeds, which can be reliably predicted. There was generally good correlation of speeds and angles at 10 knots true wind so it is unlikely that the sail coefficients were incorrect to the extent required to give the discrepancy in the lighter winds, although it is possible that the sails did not fly properly in the light winds due to the motions imposed by the wave action on the boat.

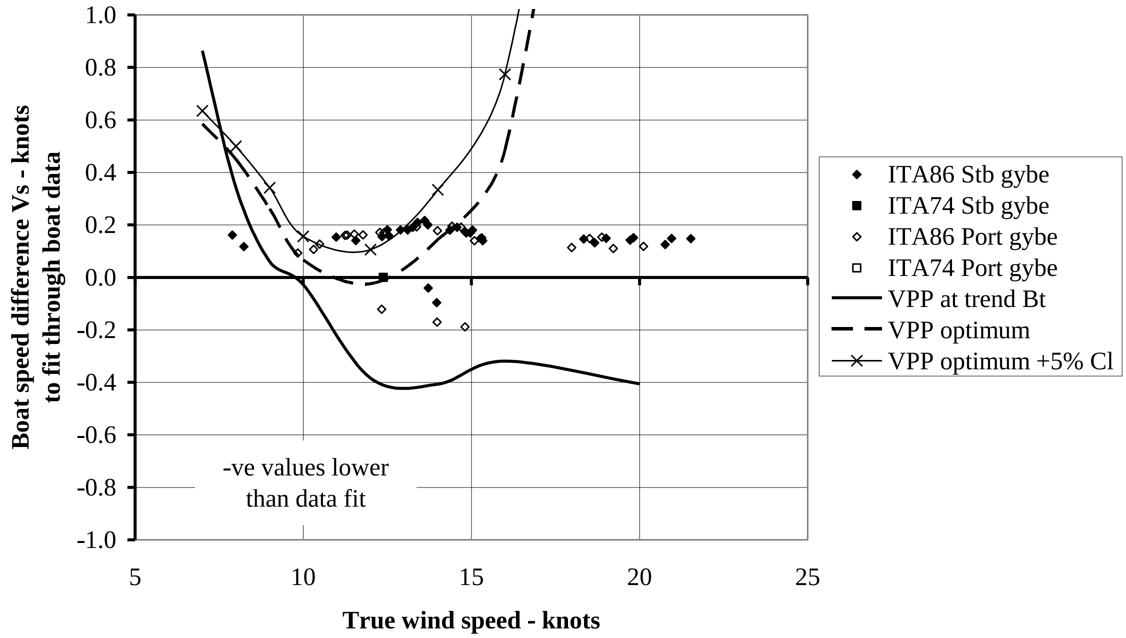


Figure 12 Variation of boat speed differences with true wind speed

Comparisons of the differences between predicted and measured apparent wind speeds are given in Figure 13, where the baseline was taken as the VPP optimum values so there is no curve shown for the optimum as in the previous Figure 11and Figure 12, and it can be seen that there is considerable variation in the measurements at particular true wind speeds.

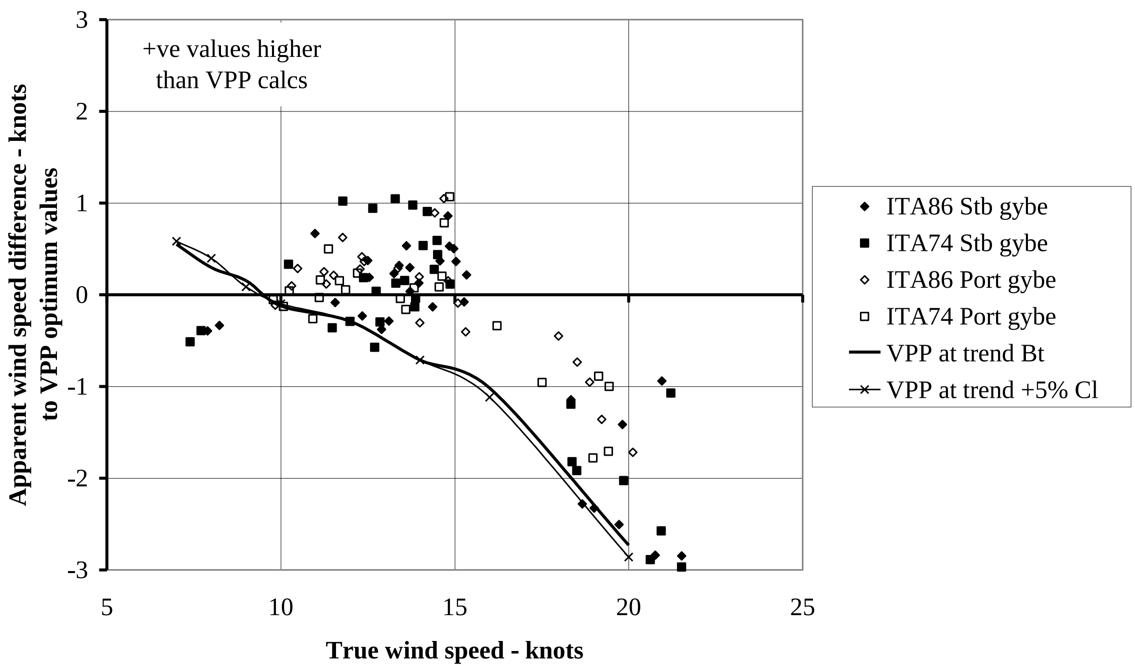


Figure 13 Variation of apparent wind speed difference with true wind speed

The apparent wind speeds were best matched by the optimum VPP calculations up to a true wind speed of 15 knots. As discussed previously the optimum VPP calculation at 20 knots occurred at lower angles and higher speeds than the measurements so the apparent wind speeds obtained from the trend through the measured true wind angle is a better match to the trials measurements for true wind speeds around 20 knots. Increasing the sail coefficients made a relatively small difference to the apparent wind speed although it should be noted that the scale of this figure is much coarser than for the boat speed shown in Figure 12.

The final comparison, given in Figure 14, is of heel angles and it can be seen that the measurements were generally higher than the predictions. Consideration of these measurements can be made together with the VPP output shown in Figure 10 and the wind tunnel data shown in Figure 3. Zero heel moment from the wind tunnel tests occurred at an apparent wind angle of approximately 120 degrees and this is consistent with the measurements shown in Figure 11 in around 20 knots true wind speed.

The higher heel angles in the true wind speed range of 10 to 15 knots are indicative of the boat sailing at a smaller apparent wind angle than optimum, which would also be associated with a smaller true wind angle and this does not appear to be the case from the data shown in Figure 11.

Increasing the sail coefficients in the VPP resulted in a relatively small change to the predicted optimum heel angles.

As in the previous plots the high VPP optimum heel in a true wind speed of 20 knots represents sailing at higher boat speeds and smaller apparent wind angles.

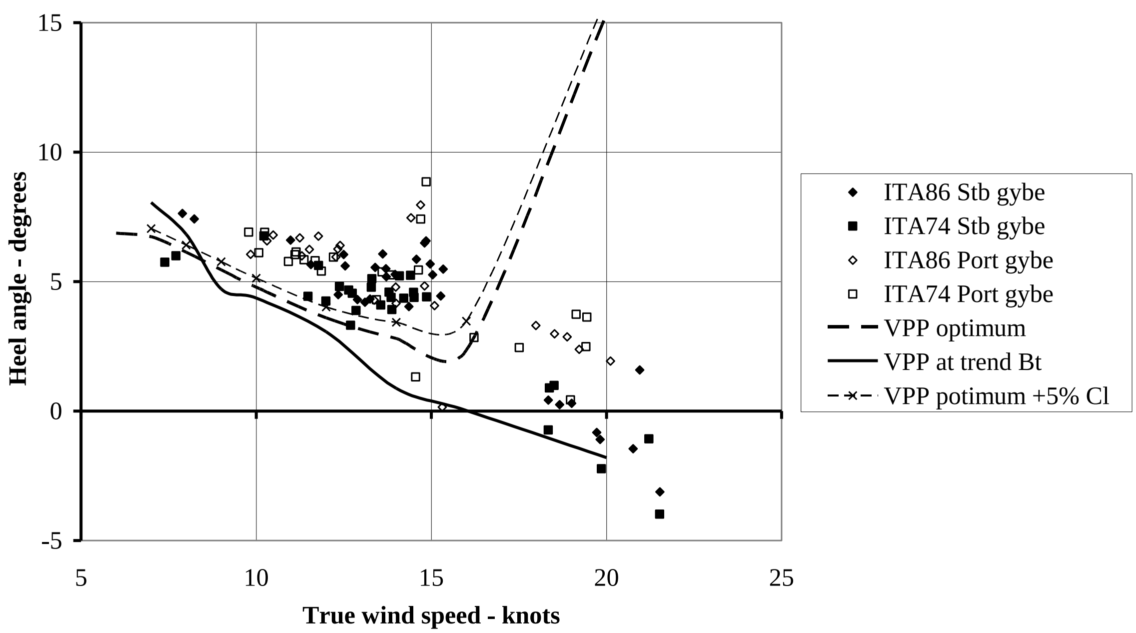


Figure 14 Variation of heel angle with true wind speed

The data in the preceding figures is of measurements of absolute performance from both the boats sailing in the trials. However the important measurements at the time of the challenge were their relative speeds, as shown in Figure 15, because these were used to tune the boats and set up their configuration, including rig, sails and appendages.

Improvements were sought in downwind speed made good of 1m/minute, since this would give an advantage of approximately a boat length on a downwind leg, which could be sufficient to gain an overlap in a match race and take control of the race.

1 m/minute speed difference equated to approximately 2% increase in driving force or reduction in drag but it can be seen in Figure 15 that the speed differences varied by up to 10 m/minute or 20% difference in force. This is considerably greater than the 5% difference due to sail trim found in the wind tunnel, as can be seen in Figure 3. The relative speed differences could be measured with greater accuracy than the absolute speeds and angles shown in the preceding figures so it is therefore clear that significant variations could be attributed to the wind environment and the sailing operation. These are essential ingredients of yacht racing but unfortunately they cloud the analysis of yacht performance.

It should also be noted that each downwind trial was conducted for a different purpose and that the crews' observations, which are not included in this paper, formed an important part of the trials evaluation.

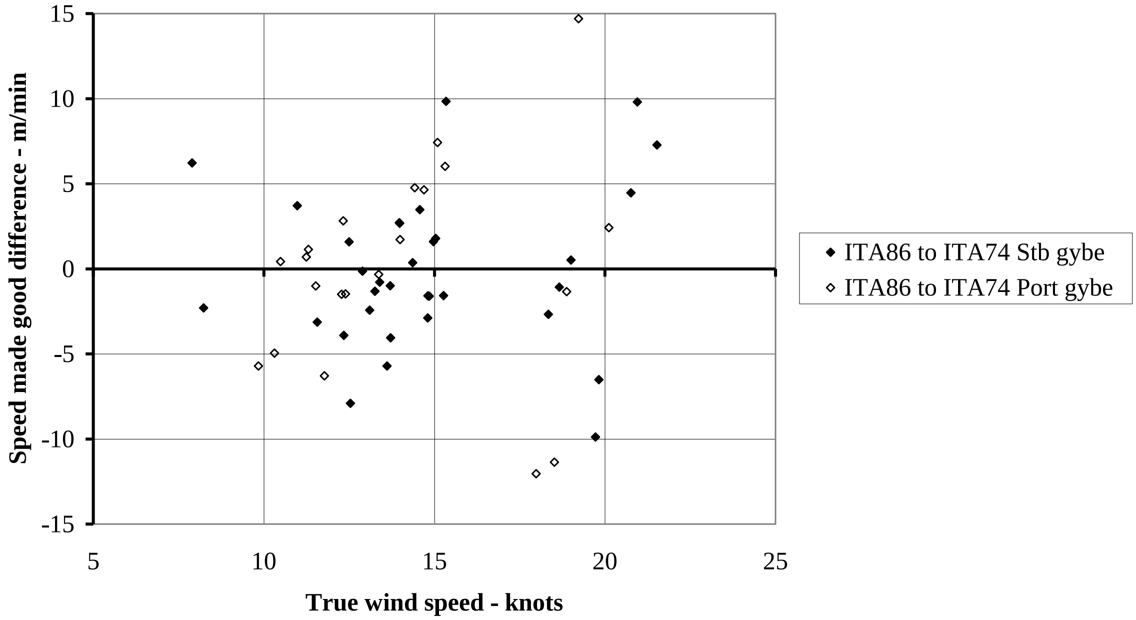


Figure 15 Variation of difference in speed made good with true wind speed

7. CONCLUSIONS

The aim of this paper was to investigate whether wind tunnel tests on downwind sails provide a reliable measure of their full scale sailing performance and it has been shown that there is reasonable agreement between VPP calculations and trials measurements provided performance is compared at related sailing angles and not just the optimum predicted by the VPP. There remains some uncertainty about the accuracy of the trials results that makes it difficult to assess the source of any errors that may exist within the wind tunnel results.

It is clear that adjustments to the sail settings alters their flying shapes, which changes the sail forces by the order of 5% near to the maximum driving force. Wind tunnel tests have provided a reliable method to measure these sail forces with good repeatability.

The forces for a particular sail combination show a reasonably smooth variation with apparent wind angle and with relatively small changes in the lift coefficient, which is consistent with the flying shapes of the sails as viewed in the wind axes.

Significantly different downwind sail shapes produce different forces, e.g. forces from gennakers can be distinguished from those from spinnakers. The effect of smaller shape changes are more difficult to distinguish once the sheeting has been adjusted to optimise their flying shape.

When comparing VPP calculations with sailing trials data the output needs to be interrogated to match measured sailing angles and it is not sufficient to compare speeds from the VPP optimum downwind points. It is also necessary to compare all the output results, including true and apparent wind speeds and angles and heel angle, not just boat speed and wind speed and to ensure that the trials measurements conform to the wind vector triangle.

Trials measurements are difficult even with the best equipment and systems. Variations remained within trials data gathered carefully over a prolonged period even where corrections were applied.

Increasing the value of the sail force coefficients in the VPP increased the predicted boat speed but did not significantly improve the correlation with true and apparent wind angles from the trials. It is unlikely that the source of differences in wind tunnel measurements since the apparent wind angle is set in the tunnel without reference to wind instruments mounted on the model.

Relative differences in downwind sailing speeds from the 2-boat trials, which could be measured with greater accuracy than absolute performance, showed much greater variation than could be attributed to the sail force variations measured in the wind tunnel.

In stronger wind conditions of around 20 knots the ACC boats were sailed at much wider true an apparent wind angles than the optimum from VPP calculations, possibly for operational or tactical match racing reasons and possibly for structural reasons and in lighter winds of around 7 knots the measured boat speeds were considerable lower than predicted.

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9. ACKNOWLEDGEMENTS

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