ANALYSIS OF YACHT PERFORMANCE UNDER THE IOR RULE: THE RELATIONSHIP BETWEEN GEOMETRY AND SPEED POTENTIAL

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SUMMARY

The International Offshore rule (IOR) provided a handicapping system for racing yacht between 1972 and 1994. During this period great advances in both the materials used in construction and designs specifically to the rule, were made. The popular press discussed, at great length, how loopholes in the rules were exploited to gain a favourable rating. This led to the perception that the exploitation of geometric measurements was leading to boats with poor performance characteristics. This paper aims to address this, firstly through an analysis of the geometric parameters and their evolution through the early part of the IOR era. The paper concludes by undertaking a velocity prediction analysis of a series of boats, a technique that was in its infancy at the time these yachts were designed. The analyses show that the geometric parameters did evolve with time, but not necessarily in line with the understanding behind good performance. Penalties in the rule dictated the direction of design. However, the performance analysis did show that judging yachts based on rated characteristics could lead to misinterpretation, but in general, the performance data aligned reasonably well with assumed performance in specific sailing conditions. The velocity prediction analysis also concluded that the performance of yachts between 1972 and 1981 did increase regardless of the geometric form being dictated by the rules.

NOMENCLATURE

A_s	Aerodynamic side force
AGS	Aft Girth Station
B	Rated Beam
BM	Metacentric height
BWL	Waterline beam
C_f	Coefficient of friction
CGF	Centre of Gravity Factor
D	Rated Depth
DA	Dellenbaugh Angle
DC	Draft Correction
FC	Freeboard Correction
GM	Metacentric radius
HA	Heeling Arm
I_T	Transverse second moment of area of waterplane
L	Rated Length
LPP	Lines Processing Program
LWL	Waterline length
IRC	International Rating Certificate
IOR	International Offshore Rule
MR	Measured Rating
R	IOR rating
R_e	Reynolds number
RM	Righting Moment
RMC	Righting Moment Corrected
S	Rated Sail Area
TR	Tenderness Ratio
TWA	True Wind Angle
TWS	True Wind Speed
VPP	Velocity Prediction Programme
WSA	Wetted Surface Area
∇	Volumetric displacement
μ	Kinematic Viscosity
ν	Fluid Velocity

1. INTRODUCTION

Rating rules are an essential element of national and international yacht and boat racing. They involve the allocation of a handicap that provides a time allowance for boats of different designs, shapes and sizes to race against each other. Rule makers have strived, since the introduction of tonnage rules in the 17th Century, to rate ships. At this time the purpose was port levies to tax trade vessels using a measure of earning potential. This developed into the tonnage rule that rated America who won the first America's Cup race (then the 100 Guineas Cup) in 1851. Since this time rule makers have sought the "holy grail" of a perfect rating system that accurately and universally equates the performance of two different yachts through some measure of their speed potential. Pedrick (1979) describes the evolution of rating rules through to the internationally respected and highly influential International Offshore Rule (IOR). This rule met its demise in the mid-1990s and was replaced with more scientific methods of predicting performance. However, modern rules are still based on basic geometric measurements of the boat. The International Rating Certificate or IRC is now the rating rule of choice for many local club races as well as prestigious international regattas and events. However, the IRC is a closed, unpublished rule. This policy is to prevent the exploitation of loopholes in, or the design specifically to, published rule formulae. However, the role of the yacht designer has always been to maximise performance for minimum handicap for whichever rating rule the proposed boat is to race under.

The IOR rating formulae were openly published in a book of approximately 60 pages, where every measurement made of the hull and sails were combined in a long and convoluted way to calculate the rating of the boat (ORC, 1973). It has been well documented in both sailing magazine articles and technical papers that designers examined the rule variables in an attempt to "beat the rule" (Humphreys, 1976), (Stephens, 1974), (Pedrick, 1979). Much has also been written, particularly in magazines and more recently in online boat design and sailing yacht forums, about the sailing qualities of IOR era yachts and the perception that performance was sacrificed in favour of rating. The hope was that the benefit of the favourable rating would exceed the performance sacrifice. Whether this is true or not is still up for debate.

With considerable input from yacht designers of the IOR era and the help of rating offices around the world, this paper will examine the evolution of yachts through the early part of the IOR era. The data used in this paper comes from a specific class within the IOR rule, the One Ton class. They had a maximum rating of 27.5ft in the period between 1972 and 1983. Designers would aim to achieve this maximum rating with a high performing boat in an effort to win the annual One Ton Cup. The assessment in the paper will employ the use of a Velocity Prediction Program (VPP). Many of the yachts in this analysis were hand drawn by the design houses of the time, building on the understanding of the rule, the experience of sailing the yachts and previous designs, to find the balance between rating and performance. There were 'eureka' moments in the era where a designer would be inspired to try something different with spectacular success. Some of these milestone designs set the trends for future designs and gave hope that there were other areas of the design space to be explored. Given the rules of the time, had the optimum yachts been created, or were there other corners of the design space not yet explored? The creation of digital data from IOR certificates and lines drawings, to enable the performance prediction, must be conducted carefully. The methodology and assessment of the sensitivity of a Velocity Prediction Program (VPP) to the performance prediction of IOR yachts is presented in a paper by Boyd (2017). The current paper will attempt to analyse the relationship between the evolution of the rule parameters as defined on the IOR certificates and the performance of the yachts using the VPP.

2. PARAMETER ANALYSIS

In Mark III of the IOR rule (ORC, 1973), the rating formulae are defined as:

$$MR = \frac{0.13L\sqrt{S}}{\sqrt{BD}} + 0.25L + 0.2\sqrt{S} + DC + FC \quad (1)$$

$$R = MR \times EPF \times CGF \times MAF \quad (2)$$

Equation 1 provides the measured rating (MR) in which L is the rated length, S is the rated sail area, B is the rated beam and D is the rated depth. DC and FC are correction factors for the draft and freeboard, respectively. In Equation 2, the final rating (R) uses MR and includes adjustment factors for the engine and propeller (EPF), centre of gravity (CGF) and movable appendages (MAF). The parameters included in Equations 1 and 2 have been at the heart of nearly all rating rules including the present day IRC.

Length (L) is a very important parameter as it fixes the distance between the bow and stern waves of any ship, boat or yacht. The distance, or wavelength, between the bow and stern is related to the speed at which the waves are travelling. Therefore, a larger distance will provide a greater speed potential, through a reduction of wave resistance (Fossati, 2009). However, yachts spend a considerable amount of time at slow speeds where total resistance is dominated by the frictional resistance of the hull given by the wetted surface area. At low speeds, sail area (S) becomes an important speed-producing factor in overcoming the frictional resistance. The amount of frictional resistance can be estimated using the International Towing Tank Congress (ITTC) 1957 friction equation:

$$C_f = \frac{0.075}{(log_{10}R_e - 2)^2} \quad (3)$$

Where Re is the Reynolds number, an important parameter in fluid mechanics, which represents the ratio of inertial forces to viscous forces within a fluid and is given by:

$$R_e = \frac{vL_c}{\mu} \quad (4)$$

Where, v is the velocity of the fluid with respect to the body, L_c is the characteristic length of the body and μ is the kinematic viscosity of the fluid containing the body. As can now be seen, both the frictional resistance and the wave making resistance, the two largest components of the total resistance of a yacht, are both closely related to the length. As already discussed, the sail area provides the thrust required to move the yacht forwards. When the thrust and the resistance are equal, a constant velocity occurs. This is the basis of the VPP's balance of forces, which will be discussed later. However, speed cannot be determined from length and sail area, only a judgement of speed potential. Even the judgement of length is difficult for the rule makers. What is the characteristic length of a hull?

Beam (B) has been dealt with quite differently over the years by rule makers. Large waterline beam tends to increase resistance due to increased wetted surface area. Large overall beam also increases form stability. The former calling for a rating credit, the latter calling for a rating penalty. The penalty for large overall beam can sometimes be negated by having a high centre of gravity and using crew to provide additional righting moment. Both the waterline beam (BWL) and the rated beam (B) are used in the IOR rule. The latter being the beam at the maximum beam station a distance BMAX/6 below the sheer line.

Depth or Draft (D) provides a benefit to yacht performance in a number of ways, increased keel span improves performance upwind, and the ability to move ballast lower improves stability.

In 1975, Rob Humphreys wrote an article for Seahorse magazine entitled "Rating rules have little bearing on the basic design geometry of an offshore boat" (Humphreys, 1975). The article asks a number of questions related to the One Ton class; "Which way is yacht design progressing? To light or heavy? More or less sail area?" He alludes to the skills of "…the designer to formulate the personality of the boat by qualifying the inherent parameters of the design, the most significant being the length, sail area and displacement". What the IOR rule did was to provide the ability to judge the characteristics of a yacht, developed by a designer, in an attempt to equate its performance with calculated values, which can be related to other yachts.

Humphreys presents this as a graph of sail area, length and displacement using values from the IOR measurement of; $\sqrt{S}$, the square root of the rated sail area, L, the rated length and $\sqrt{BD}$ the square root of the product of rated beam and draft. The latter term approximates the 'bulk' of the yacht or a crude representation of displacement. From this data, Humphreys presented yachts from the 1974 One Ton cup and some other representative designs of the era on a graph of $\sqrt{S}/L$ and $L/\sqrt{BD}$, Figure 1. In terms of the progression of yacht design against rating the trend should be a move towards the upper right corner; increased sail area for length and increased length for displacement.

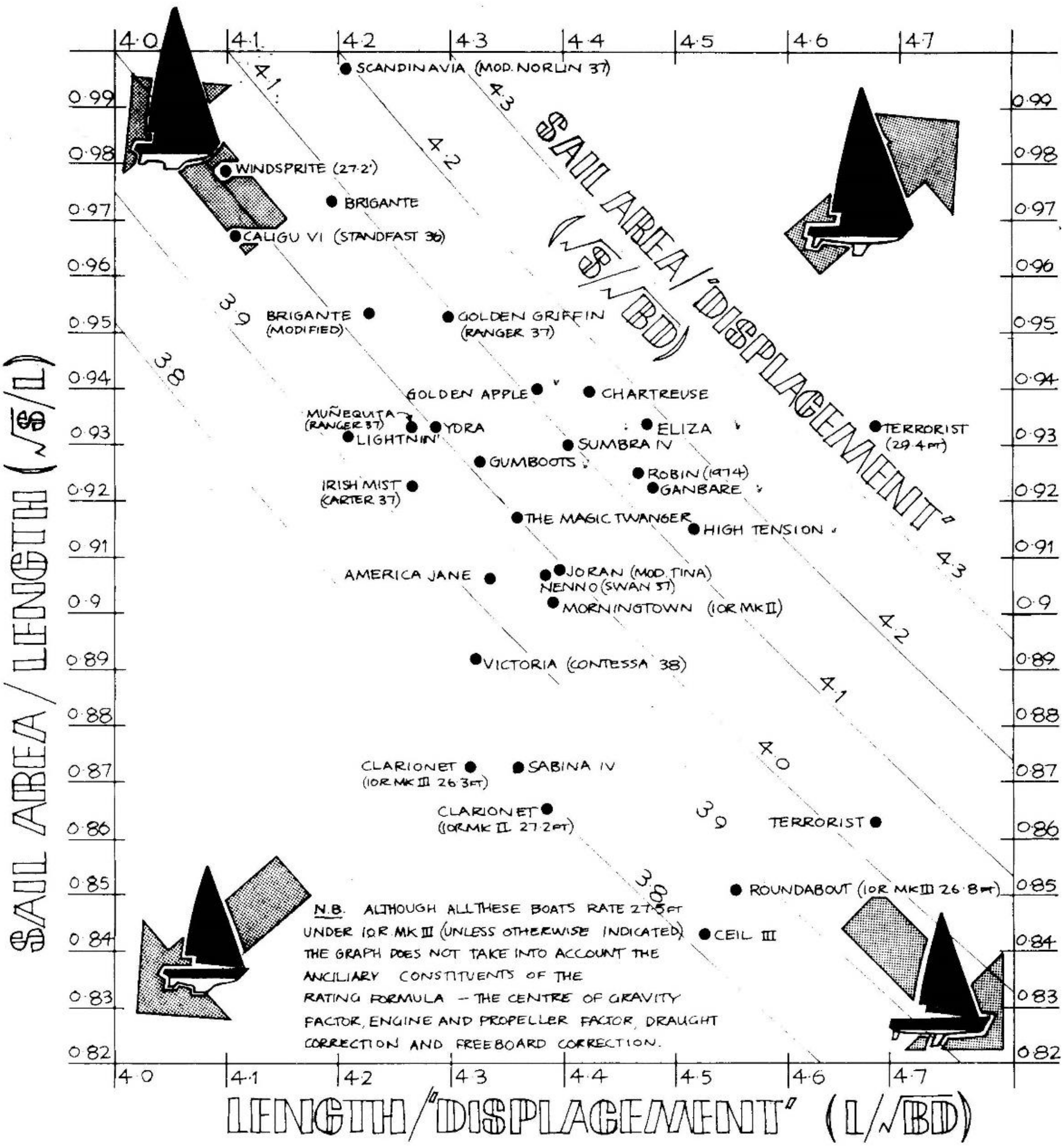


Figure 1 Ratios of Rated Length, "Displacement", and Sail Area in 1974 (Humphreys, 1975)

Humphreys goes on to describe the potential performance characteristics of a number of boats based on the ratios that make up Figure 1. For example, *Chartreuse* and *Golden Apple* both have relatively high sail area for their length and were known to be good in light to moderate conditions. Comparing the two *Chartreuse* has slightly more length and sail area for their displacement and should be faster downwind in heavier conditions. Although these two boats have the same rating, it is assumed that the performance potential of the boats can be distinguished based on their rated characteristics. Much of the commentary relating performance to the rating characteristics in Humphreys' article is speculative in its language. Examples such as "…should be faster….", "…tends to indicate that….", and "….would appear to…." are typical. Of course, this is based on knowledge and experience regarding yacht performance and the three key characteristics of length, sail area and displacement. However, proof of these predictions of performance, at the time, was only evidenced on the race course. There are many examples of commentary on sailing events where the fastest boat did not win, due to crew error, poor preparation or gear failure. This prevents yachts being compared where all is equal except the design.

Humphreys' original analysis was limited to the 1974 fleet and some earlier designs. With the help of various rating offices around the world and the input from a significant number of the designers from the IOR era an analysis can be conducted using IOR certificate data with respect to time. For the purposes of this paper only the 27.5ft rating will be considered which existed as the maximum rating for the One Ton class of yachts between 1972 and 1983. Approximately 60 yachts are included in the analysis. As discussed by Humphreys, progression in design should see yachts move into the upper right corner of Figure 1, which indicated an increase in sail area to displacement ratio. Figure 2 shows how this ratio evolved up until 1981. Initially, post-1974, there was a general increase in the average sail area to displacement ratio, but over the whole period there was a slight decrease. However, one must also consider the very large scatter in this data. For example, in 1977 and 1978 there are two yachts with very low sail area to displacement ratios. In 1977 the data point belongs to *Smir-Noff-Agen*, one of five centreboard one tonners by Bruce Farr for the 1977 One Ton Cup. These boats had a high ballast ratio and a resultant low righting moment. To compensate, she had a relatively small sail area. In 1978 the low value is the Jean Berret designed *Tapacenbal* which had a very long rated length with a relatively small sail area. Contrastingly, the very high value in 1976 is the Doug Peterson designed modified Contessa 35 *Karate*, which was very short but with a very large sail area. Therefore, it is clear that different designers had very different approaches to achieve the required 27.5ft rating.

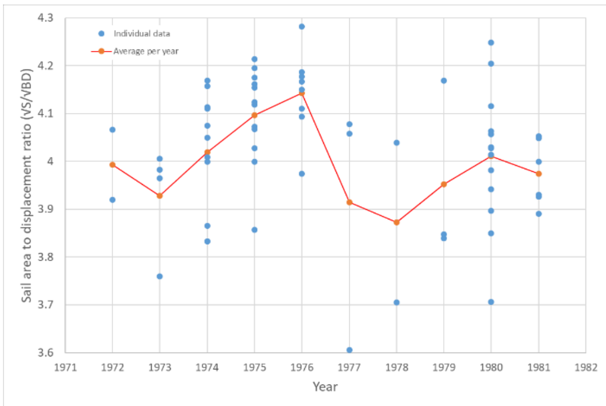
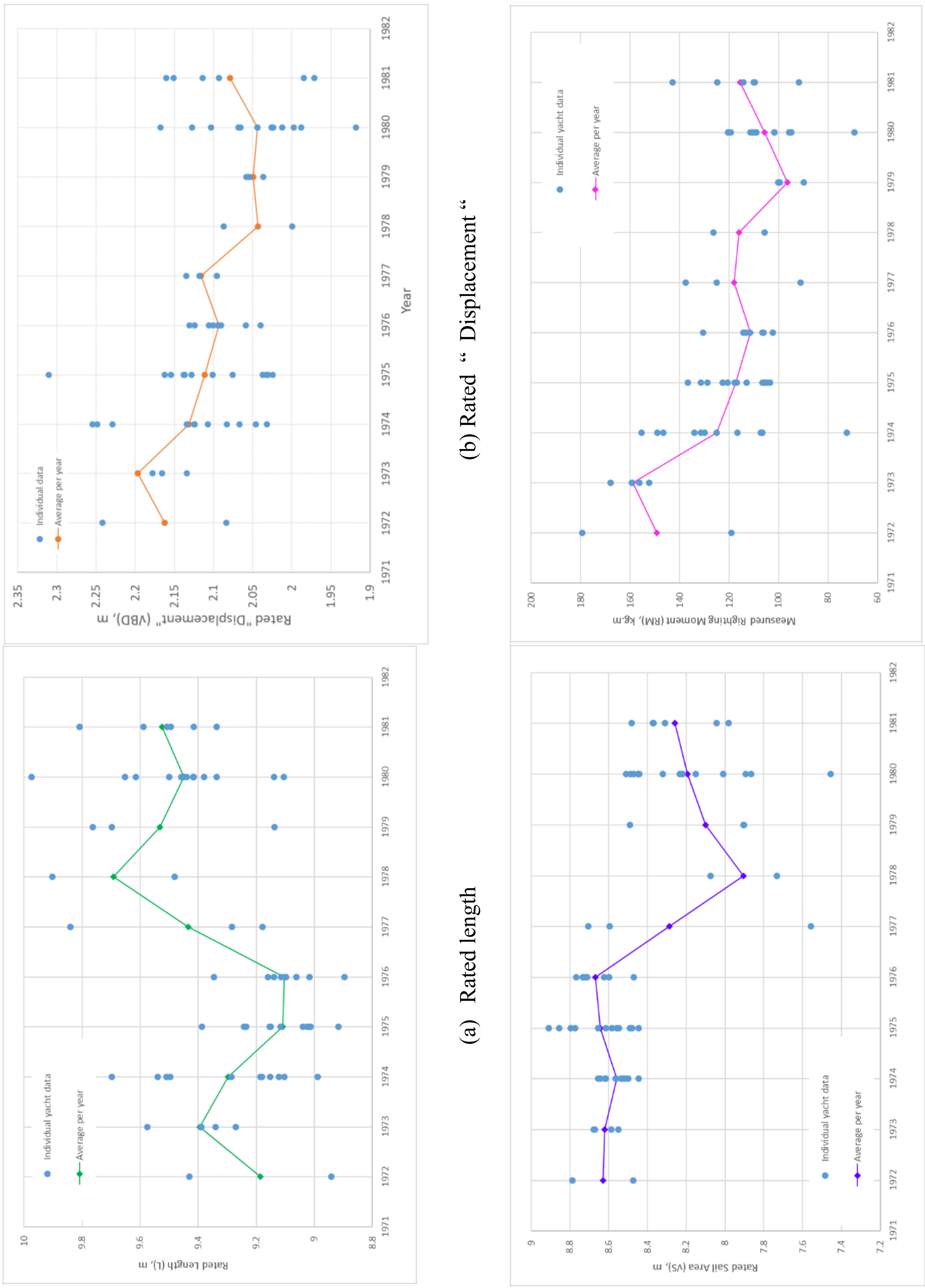


Figure 2 Evolution of the Sail area to "Displacement" ratio over the 27.5ft IOR era

Figure 3 shows the trends in time for length, sail area, displacement and righting moment. It is clear that there has been an increase in length and a decrease in both displacement and sail area. This has moved designs produced later in the period towards the lower right corner of Figure 1. Extracting some of the data from Figure 1 and using the data contained in Figures 2 and 3 a new version of Figure 1 is presented in Figure 4. Here it is clear to see the shift towards longer, lighter displacement and lower sail area yachts. These yachts all have the same rating and if the rating formula was perfect, the performance should be the same, albeit with favourable characteristics for certain conditions. Each quadrant of Figure 4 indicates a perceived performance in certain conditions. Given the discussion by Humphreys, yachts in the lower right corner would be long, light boats with reduced sail area and would need to have a reasonable amount of breeze for them "to make a good account of themselves". Yachts in the upper left corner would favour light winds. The upper right corner would produce boats with downwind performance but tender upwind in a breeze. The lower left corner would indicate a relatively heavy, underpowered cruising yacht. Using the VPP these hypotheses can be assessed using geometry data for the hulls and will be discussed later.

Not discussed by Humphreys is the righting moment. In the IOR rule this was part of the afloat measurements conducted to determine the rating and was obtained from an inclining experiment. The righting moment was used to create a tenderness ratio (TR), Equation 5, which in turn was used to create a centre of gravity factor (CGF), Equation 6. Pedrick (1979) discusses the CGF and explains that the original intention was to ensure that interiors were fitted and that masts and hull scantlings were substantial by penalising yachts that were very lightly built with a low centre of gravity. In his book *Seaworthiness: The Forgotten Factor* Marchaj (1986) discusses the effect of the IOR rating rule on hydrostatic stability. He emphasises that stability is one of the most important speed performance factors. Note: All of the terms in the following equations use imperial units.



(a) Rated length

(b) Rated " Displacement "

(c) Rated Sail Area

(d) Righting Moment

Figure 3 Evolution of yacht IOR rating parameters as a function of time

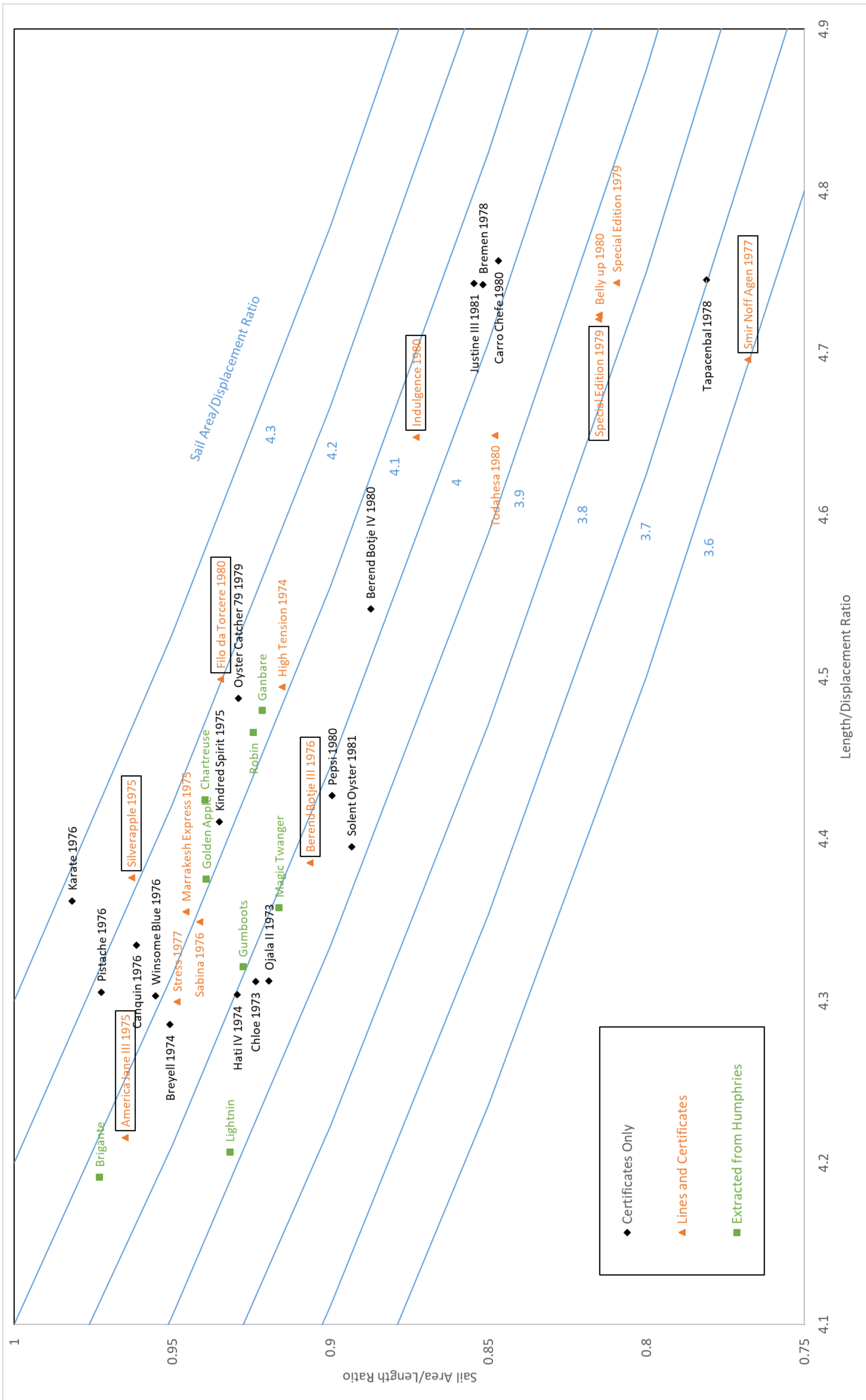


Figure 4 Ratios of Rated Length, "Displacement", and Sail Area from 1971 to 1982

$$TR = \frac{0.97L \times (BWL)^3}{RMC} \quad (5)$$

$$CGF = \frac{2.2}{TR - 5.1} + 0.8925 \quad (6)$$

In Equation 5, L is the rated length, BWL is the measured waterline beam of the yacht and RMC is the corrected righting moment, where the measured righting moment was used for RMC except for non-fixed keel yachts. Equation 5 shows that beam is given considerable importance when calculating tenderness ratio. It can also be seen that Equation 5 is essentially a ratio of form stability and ballast stability.

Marchaj went further by modifying the tenderness ratio using the following two expressions:

$$RM = \Delta GM \sin\theta \quad (7)$$

$$BM = \frac{I_T}{\nabla} = \frac{k \times LWL \times (BWL)^3}{\nabla} \quad (8)$$

Where GM is the metacentric height (a measure of the initial stability of the hull), Δ is the mass displacement and θ is the heel angle, BM is the metacentric radius (the distance between the centre of buoyancy and the metacentre), I_T is the transverse second moment of area of the waterplane, LWL is the waterline length and ∇ is the volumetric displacement.

Taking $0.97L$ as being equivalent to LWL, Equation 7 is the denominator of Equation 5 and Equation 8 can be rearranged for $LWL \times (BWL)^3$ and assuming the $k \approx 0.04$ giving:

$$TR = 22.3\frac{BM}{GM} \quad (9)$$

Using this modified version of TR in Equation 6 for the CGF:

$$CGF = \frac{2.2}{22.3\frac{BM}{GM} - 5.1} + 0.8925 \quad (10)$$

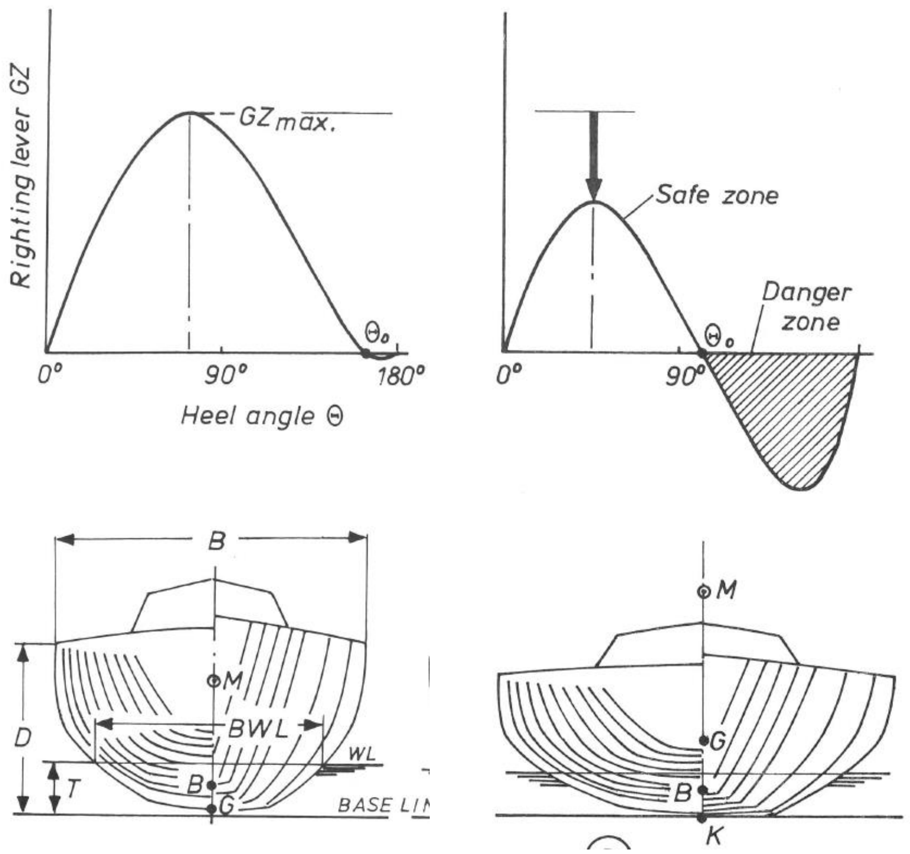
The minimum value allowed for CGF is 0.968 therefore the maximum CGF advantage, using equation 10, is approximately 1.4, given by $BM = 1.4GM$ which indicates that the centre of gravity must be considerably higher than the centre of buoyancy. This penalised a yacht with a low centre of gravity and so designer trends tended towards boats with a high beam to obtain form stability and high centre of gravity to take maximum advantage of the CGF. This was achieved by taking ballast out of the keel and putting it inside the hull. Marchaj (1986) demonstrates, in a set of illustrations, the influence of the increased height of the centre of gravity and the increased beam on the righting lever (GZ) curves. Figure 5(a) shows a narrow beam, low centre of gravity boat has a moderate initial stability (GM) but a large angle of vanishing stability (the angle beyond which capsize occurs). Conversely, in Figure 5(b) the higher centre of gravity and wider beam hull has a greater initial stability but a considerably lower angle of vanishing stability.

This raised the question of whether the IOR rule was driving designers towards unstable yachts. This topic of discussion was further fuelled by the tragic 1979 Fastnet Race. The enquiry that followed pointed at designs to the IOR rule tending towards "… boats of extreme light displacement and dubious ultimate stability…" (Forbes *et al.*, 1979). Figure 3(d) shows that there was a downward trend in the righting moment during this period, with an interesting increase following the 1979 Fastnet race. As discussed by Marchaj the reduction in the righting moment was compensated by a corresponding increase in the rated beam (Figure 3(b)) over the same period. This moves design away from ballast stability towards form stability, and the use of crew to provide righting moment. As shown by the analysis of the relative stability characteristics of the more traditionally shaped Contessa 32 and an IOR half tonner (WUMTIA, 1979) as part of the 1979 Fastnet enquiry (Forbes *et al.*, 1979) the two yachts had very similar initial similarity, given by GM, the metacentric height. However, the more modern yacht had a much lower range of stability. An aspect not measured by the IOR rule.

Figure 6(a) shows the evolution of tenderness ratio, which is essentially a ratio of form stability against ballast stability. Although this indicates an increase in tenderness, were the boats less able to carry their sail area? One measure for sail carrying ability is the Dellenbaugh angle (DA). It provides a ratio of heeling moment to righting moment using the following relationship:

$$DA = \frac{A_S \times HA}{RM} \quad (11)$$

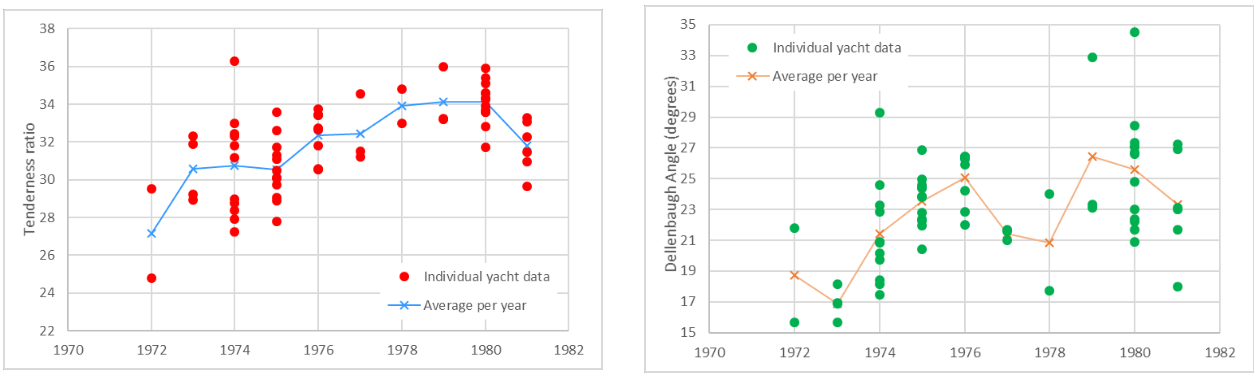
Where A_s is the aerodynamic side fore, HA is the heeling arm and RM is the righting moment. The aerodynamic side fore can be assumed to be the product of the sail area and the wind pressure. At approximately 13 knots the wind pressure is 4.883 kg/m^2 (Skene, 1938). The heeling arm can be obtained from the IOR certificate by assuming that the centre of lateral resistance is 45% of the draft of the yacht (Larsson and Eliasson, 1997). Finally, the centre of effort can be estimated assuming triangular sails and the rig dimensions P (mainsail hoist), E (length of mainsail foot), I (Height of fore-triangle) and J (length of fore-triangle base). Figure 6(b) shows the evolution of the Dellenbaugh angle. It is clear that both the tenderness ratio and the Dellenbaugh angles both show a trend towards less stability, with a marked improvement in the years immediately after the 1979 Fastnet race. Humphreys mentions the yacht *Lightin'* in Figure 1 as being quite heavy for her length implying that she needs a bit of a breeze to get her going. This is somewhat validated by both the tenderness ratio (29.5) and Dellenbaugh angle (15.7°) where she has values that are relatively low and suggest she has good sail carrying ability. However, all of this analysis of data and the use of the understanding of the performance potential of a yacht given parameters of sail area, length and displacement. One question remains from the commentary, particularly in this era of the IOR, did the drive for better rating have a negative influence on performance?



(a) Low Centre of Gravity and narrow beam

(b) High Centre of Gravity and Wide beam

Figure 5 The effect of hull shape and relative positions of gravity and buoyancy on hydrostatic stability (Marchaj, 1986)



(a)

(b)

Figure 6 Evolution of (a) Tenderness Ratio and (b) Dellenbaugh Angle over the 27.5ft IOR era

3. PERFORMANCE ASSESSMENT

The ability to conduct a performance assessment of IOR boats relies on the availability of data. As shown in Section 2, the IOR certificates are a valuable source of data but more is required to complete the analysis. The hydrostatic properties of the hull are required to complete the balance of forces. As presented by Boyd (2017) the VPP is sensitive to reasonably subtle changes to the input parameters of the VPP. Figure 4 presents the available data for the parameter analysis, and also indicates availability of geometry data through the cooperation of the designers of the era. Therefore, only a sub-set of Figure 4 have both the certificate and the lines plan. However, there is sufficient spread in both the rating parameters and age of the boats to attempt to draw some conclusions.

The method of creating the dataset to enable the performance assessment is the same as described by Boyd (2017):

- Digitise the hand drawn lines plans using Maxsurf Modeller
- Extract data from the IOR certificate for righting moment, to establish the vertical centre of gravity
- Define the appendages and weight items (crew) in the lines processing programme (LPP)
- The crew position was standardised as being 680kg, located 2.5m aft of amidships, 0.25m above the deck edge and 80% of maximum beam.
- Extract data from the IOR certificate for rig dimensions and associated sail areas
- The WinDesign4 VPP was run for True Wind Angles (TWA) between 30 and 180 degrees and True Wind Speeds (TWS) from 4 to 25 knots.
- Internal calculations for hydrodynamics were based on the Delft equations (Keuning and Sonnenberg, 1998)
- Internal calculations for the aerodynamics were based on lift and drag coefficients for various apparent wind angles as detailed in the ORC VPP documentation (ORC, 2015)

Seven boats from Figure 4, where both the IOR certificate and the lines were available, were analysed in the VPP. The details of the boats are given in Table 1.

The results from the VPP are presented in Figure 7, showing which boat was quickest in terms of time per nautical mile for the matrix of true wind angles and wind speeds. Also included in brackets is the winning margin in seconds. As expected, at the centroid of the blocks where the individual boats perform well, e.g. Filo Da Torcere at a TWS of 6 knots and TWA of 50 degrees, the margin to the next fastest yacht is quite large, 35.3 seconds in a nautical mile. At the transitions between yachts, the margins become very small.

The results, as presented in Figure 7, will be discussed in terms of each yachts position in Figure 4 and also the understanding of what each quadrant represents in terms of proposed performance as discussed by Humphreys (1975).

Table 1 Details of the yachts examined using the VPP (Rig type M is masthead and F is fractional)

Boat name	Year	Designer	L (m)	B (m)	D (m)	√S (m)	RM (kg.m)	Rig
Silverapple	1974	Holland	8.92	3.42	1.22	8.59	112.95	M
America Jane III	1975	Kaufman	9.12	3.62	1.29	8.80	120.61	M
Berend Botje III	1976	De ridder	9.35	3.50	1.30	8.47	114.33	M
Smir-noff-agen	1977	Farr	9.84	3.43	1.28	7.56	91.24	F
Special Edition	1979	Tanton	9.76	3.62	1.17	7.90	100.28	F
Indulgence	1980	Holland	9.42	3.48	1.18	8.22	120.44	F
Filo de Trocere	1980	Vallicelli	9.10	3.62	1.13	8.51	110.01	F

TWA \ TWS	4	5	6	7	8	9	10	12	14	16	20	25
32	Fi [5.7]	Fi [23.4]	Fi [21.7]	Fi [16.6]	Fi [18.7]	Fi [17.7]	Fi [10.3]	AJ [0.6]	Sm [12.4]	Sm [18.4]	Sm [24.1]	Sm [26.6]
36	Fi [14]	Fi [23.9]	Fi [19.9]	Fi [21.1]	Fi [17.3]	Fi [7.1]	AJ [1.6]	Sm [7.9]	Sm [15.7]	Sm [19.4]	Sm [23.3]	Sm [24.9]
40	Fi [21.9]	Fi [20]	Fi [24.7]	Fi [21.7]	Fi [7]	AJ [2.2]	AJ [0.5]	Sm [12.3]	Sm [17.3]	Sm [19.9]	Sm [22.8]	Sm [23.8]
45	Fi [21.2]	Fi [22.6]	Fi [28.4]	Fi [12]	AJ [1.7]	AJ [1.2]	Sm [7.3]	Sm [15.1]	Sm [18.4]	Sm [18.8]	Sm [20]	Sm [18.9]
50	Fi [36.4]	Fi [44.2]	Fi [35.3]	Fi [11.1]	Fi [1.5]	Sm [8.3]	Sm [12.8]	Sm [15.4]	Sm [16.4]	Sm [17.1]	Sm [18.7]	Sm [21.2]
60	Fi [21.5]	Fi [28]	Fi [8.2]	Fi [1]	Sm [1.8]	Sm [7]	Sm [10.9]	Sm [13.3]	Sm [14.1]	Sm [14.8]	Sm [16.2]	Sm [17.9]
70	Fi [25]	Fi [24.7]	Fi [3.8]	Fi [2.4]	Sm [0.7]	Sm [1.3]	Sm [3.5]	Sm [10.6]	Sm [12.4]	Sm [13.2]	Sm [14.5]	Sm [16]
80	Fi [26]	Fi [17.4]	Fi [2.9]	Fi [1.8]	In [1.1]	In [1.3]	In [0.5]	Sm [4.4]	Sm [10.7]	Sm [12.3]	Sm [13.9]	Sm [15.3]
90	Fi [24]	Fi [25]	AJ [0.6]	Fi [0.7]	Sm [0.7]	In [2.6]	In [2.3]	Sm [0.5]	Sm [4.7]	Sm [10.3]	Sm [14.2]	Sm [16]
100	Fi [18.8]	Fi [28.2]	Fi [5.2]	Fi [2.5]	In [0.3]	In [1.3]	In [2]	In [1.5]	Sm [1.2]	Sm [4.7]	Sm [13.8]	Sm [18.6]
110	Fi [13.7]	Fi [30]	Fi [20.9]	Fi [3.9]	Fi [3.2]	In [1]	In [3.7]	In [3.6]	In [1.7]	Sm [3.5]	Sm [8.8]	Sm [19.7]
120	Fi [6.2]	Fi [28.2]	Fi [15.1]	Fi [13.4]	Fi [4.6]	Fi [0.2]	In [0.9]	In [2.8]	In [1.9]	In [0.8]	Sm [6.4]	Sm [15]
135	Si [20.3]	Be [0.6]	Fi [16.5]	Fi [5.8]	Fi [7.4]	Fi [6]	Fi [1.3]	In [0.5]	In [2.3]	In [0.7]	Sp [1.1]	Sm [4.9]
150	Si [31.2]	Si [15.6]	Be [0.8]	Fi [3.8]	Fi [4]	Fi [2.4]	Fi [5.7]	Fi [1.6]	In [0.3]	In [1.5]	Sp [0.2]	Sm [0.4]
160	Si [26.3]	Si [25.9]	Si [13.2]	Si [0.9]	Fi [8.5]	Fi [7.9]	Fi [4.3]	Fi [5.2]	Fi [0.9]	In [2.1]	In [1.2]	Sp [2.2]
170	Si [13.7]	Si [26.6]	Si [20]	Si [7.4]	Fi [7.1]	Fi [14.3]	Fi [9.7]	Fi [8.2]	Fi [1.7]	In [2.4]	In [2.4]	Sp [0.4]
180	Si [6]	Si [30.5]	Si [24.3]	Si [5.2]	Fi [5]	Fi [7.2]	Fi [11.5]	Fi [9.8]	Fi [2.5]	In [2.8]	In [3.9]	In [1.3]

Si	Silverapple	Fi	Filo Da Torcere	In	Indulgence	AJ	America Jane III
Sp	Special Edition	Be	Berend_Botje _III	Sm	Smirnoffagen		

Figure 7 VPP results showing the quickest yacht [margin of victory in seconds] for one nautical mile for each TWA and TWS combination

3.1 LIGHT WINDS

In this study, light winds are represented by a TWS of 5 knots. As presented in Figure 7 two boats dominate in terms of performance in light winds, *Filo de Trocere* and *Silverapple*. According to Humphreys (1975) yachts in the upper left quadrant of Figure 4 would favour light winds. Interestingly, from Figure 4, *America Jane III* should be the most dominant light airs boat. Figure 8 shows the seconds per nautical mile both upwind and downwind against *Filo de Trocere*. The yachts that are predominantly in the upper left quadrant of Figure 4 do well. *Indulgence* performs particularly well and this is surprising as she has third smallest rated sail area (Table 1). At the end of the 1970s, there was a move from masthead rigs to fractional rigs. Indulgence had a long boom and this resulted in a large mainsail area. As a result, she has the largest sail area given the rig dimensions. This highlights the dangers of using the rated values to infer performance.

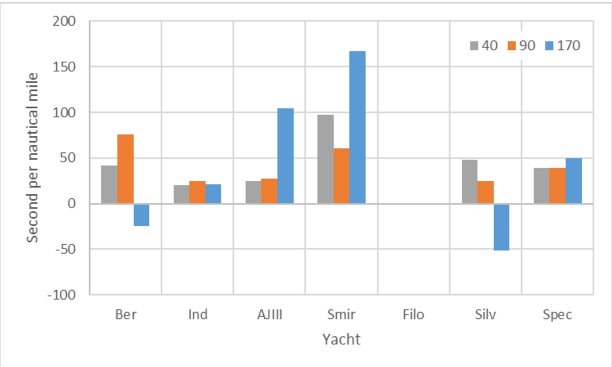


Figure 8 Difference in seconds per nautical mile for TWAs of 40°, 90° and 170° against Filo de Trocere at a boat speed of 5.5knts

Figure 9 shows the comparison of the ratios used in Figure 4 but using actual Sail Area (from known rig dimensions), displacement and waterline length (from Maxsurf model). The relative position of the yachts have significantly changed. However, *America Jane III* is still located in the light wind dominant upper left quadrant.

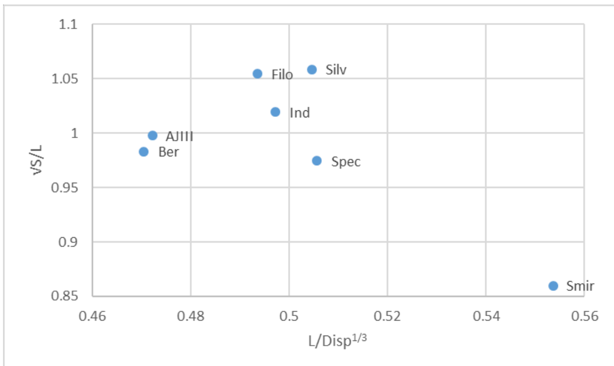


Figure 9 Comparison of Length/Displacement and Sail Area/Length ratios using measured data

A yacht design parameter discussed by Humphreys (1975) is prismatic coefficient, a measure of the fineness or fullness of the bow/stern. Larsson and Eliasson (1997) present a curve of optimum prismatic coefficient for a given hull speed obtained by differentiating the Delft residuary resistance curve with respect to prismatic coefficient for each speed. From this curve in light winds, the prismatic coefficient should be low, approximately 0.5 for a Froude Number of 0.3, which equates to approximately 5.5 knots boat speed for these sized yachts. The Prismatic Coefficient (C_p), from the Maxsurf models, is shown in Figure 10 for each of the seven yachts. It clearly shows that *America Jane III* does have the lowest value, but is still not as competitive. At low hull speeds the major contributor to resistance is due to friction and this is directly related to the wetted surface area (WSA). Figure 10 also shows the variation in WSA obtained from the Maxsurf model. *America Jane III* has the largest value and this will have a significant effect on light wind performance. The WSA also shows that *Filo de Trocere* and *Silverapple* have the lowest values further cementing their light wind performance advantage.

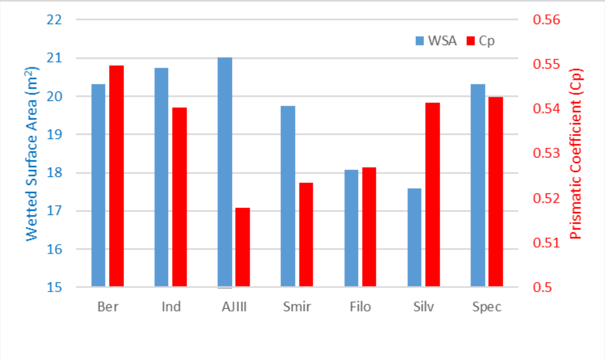


Figure 10 Comparison of Wetted Surface Area and Prismatic Coefficient

3.2 HEAVY WINDS

As boats move towards the lower right quadrant of Figure 4, they should excel in higher winds. One boat stands out in this quadrant, the Farr designed *Smir-noff-agen*. This boat type was conceived as long, light displacement, centreboard yachts with a small sail area. Farr dominated the 1977 One Ton Cup using a common design with small variations, finishing 1st, 2nd, 3rd and 5th. *Smir-noff-agen* finished 3rd. The One Ton Cup was held in Auckland, New Zealand, renowned for heavy winds and therefore the design's position in Figure 4 is justified. The modest WSA shown in Figure 11 is less important in heavy winds due to the increased speed, which increases the wave making resistance. Wave making resistance is calculated in the VPP using the Delft equation for residuary resistance (Keuning and Sonnenberg, 1998). Figure 12 shows that *Smir-noff-agen* has the lowest value of wave making resistance at a boat speed of 8 knots, mainly driven by the low displacement and long length.

When sailing in heavy winds sail carrying ability becomes important for which the Dellenbaugh angle is a good measure. Figure 12 shows a comparison of Dellenbaugh angle and *Smir-noff-agen* does have the best sail carrying ability of the fleet. This is further reflected in the VPP data with *Smir-noff-agen* having the smallest heel angles (Figure 13). The VPP for this analysis does not utilise reef function. Instead, the sail area reduction for reefing is conducted in specific sail sets, representing the No1, No.2 and No. 3 genoas. Analysis of when sails are changed shows no measurable difference between yachts.

Filo de Trocere has the highest Dellenbaugh angle suggesting a tender yacht. Relative to others she is located closest to the upper right quadrant of Figure 4 suggesting good downwind speed but tender upwind in a breeze. The good downwind performance appears in Figure 7 with *Filo de Trocere* continuing to dominate as TWA and TWS increases.

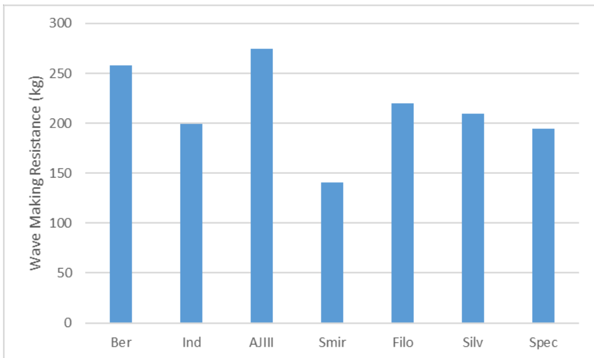


Figure 11 Comparison of wave making resistance at a boat speed of 8knts

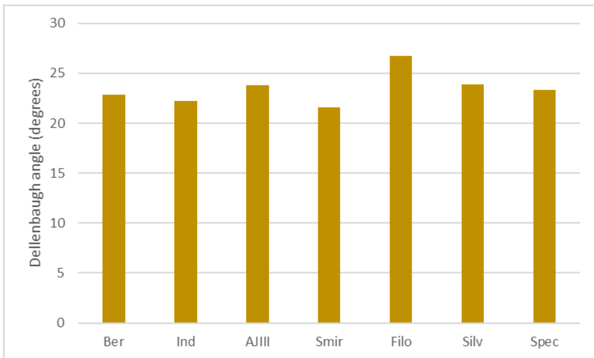


Figure 12 Comparison of Dellenbaugh angle

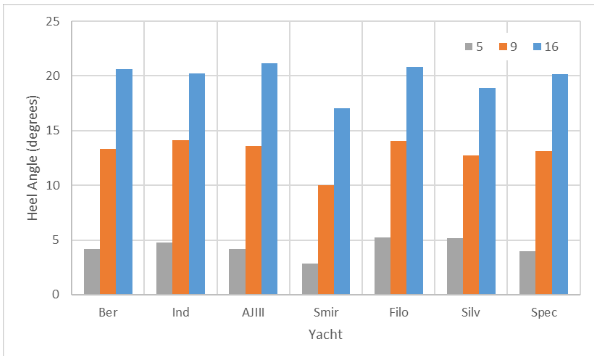


Figure 13 Comparison of heel angles for 5, 9 and 16knt TWS

4. PERFORMANCE EVOLUTION

The VPP analysis has allowed a detailed examination of the geometric characteristics of the yachts to determine what influences performance. It was shown in section 2 that rating rule and geometric parameters evolved during the early IOR era. But, the question remains, did these parameter changes have a positive or negative affect on performance. Although the current VPP analysis only has a limited number of yachts, they are spread across the era and are significant in their own rights. Table 2 shows the recorded achievements of each of the yachts, which demonstrates that regardless of the results presented in this paper, they all were successful. As stated previously, this analysis does not account for the competence of the crew, the natural variance in wind and waves, the unexpected equipment failure or human error. Any of the above can either enhance or mask the performance at any given event.

Table 2 Recorded achievements of One Ton yachts

Boat name	Achievements
Silverapple	1975 OTC (retired damaged); 2nd1976 SORC
America Jane III	3rd 1975 OTC; 3rd 1976 OTC; 3rd 1976 SORC
Berend Botje III	High Tension 36 (proto 2nd 1975 OTC)
Smir-noff-agen	3rd 1977 OTC;
Special Edition	9th 1979 OTC;
Indulgence	2nd 1979 OTC, 6th 1989 OTC; 3rd 1981 OTC
Filo de Trocere	1st 1980 OTC;

However, as the VPP data is available from this research, Figure 14 shows the change in seconds per nautical mile upwind from *Silverapple* in 1974 to *Filo de Trocere* and *Indulgence* in 1980. It appears that there was an improvement in performance. At this time, upwind sailing was very much the focus of performance. Figure 15 shows the same result but for downwind. The results show a large scatter, but in heavy winds, there was also an improvement with time. This result brings into question the negative commentary that the IOR rule resulted in slow boats. Performance improvements seen here do not take into account improvements in sail materials, rig development or hull construction. All of which would have further enhanced performance of the more modern yachts in this study.

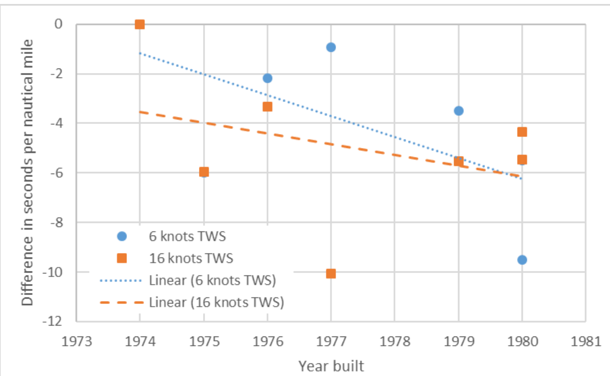


Figure 14 Performance evolution during the 27.5ft IOR era in terms of second per nautical mile upwind

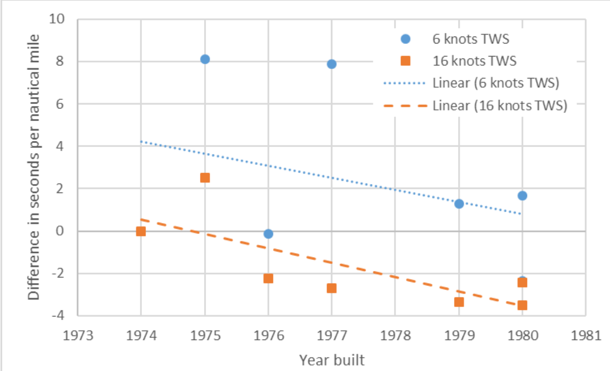


Figure 15 Performance evolution during the 27.5ft IOR era in terms of second per nautical mile downwind (TWA = 140°)

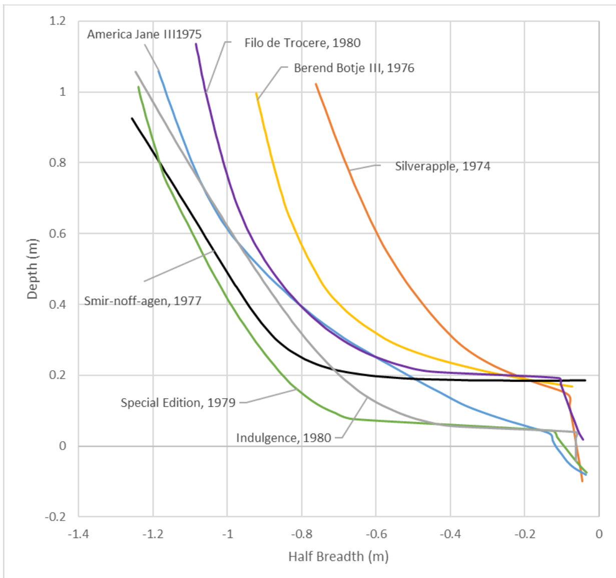


Figure 16 Comparison of the half breadth section shapes at the Aft Girth Station (AGS)

Ron Holland and Doug Peterson designs were often referred to as "pin-tails", a characteristic shape at the stern caused by pinching the hull near to the aft girth measurement point. This was done to shorten the rated length (L) for a rating benefit. The resultant waterlines looked almost symmetrical forward and aft. This shape favoured upwind performance and is often credited with causing some of the undesirable motions downwind. The rapid change of hull shape as it approaches the aft girth station, the region where the rudder would be located, causes flow separation from the hull. This places the rudder in a region of chaotic flow hampering the efficiency of the rudder. During the early One Ton era, designers such as Bruce Farr, sacrificed upwind performance by making the aft end fuller promoting good performance off the wind. Figure 15 shows that performance downwind was improving during this era. Figure 16 shows the half breadth section shape at the Aft Girth Station (AGS). It is clearly shown that *Smir-noff-agen*, *Special Edition* and *Indulgence* all have much wider aft sections justifying their downwind heavy weather dominance in Figure 7. Conversely, *Silverapple*, a 'pin-tail' is very narrow at the AGS. This move towards wider sterns creates a more all-round performer, with less focus on upwind speed than was previously fashionable/desirable.

5. CONCLUSIONS

As concluded by Humphreys (1975), the IOR rule allowed the advancement of design, as the designer had free choice as to the values of sail area to length and length to displacement ratios. This means that the IOR rule is not as type-casting as it is often described. However, some characteristics are typical of the IOR era.

Extending the work by Humphreys, this paper has shown that there was an evolution in design through the early IOR era, but the rule may have limited where it could go. The use of just rule based parameters, from the IOR certificates, of rated sail area, length, breadth and depth has been shown to be slightly misleading when used to judge speed potential.

The digitisation of the lines plans has allowed additional data, not previously available, to be examined in terms of speed potential. Particularly for light winds, parameters such as prismatic coefficient and wetted surface area highlight why some boats do not perform as expected according to the four Humphreys quadrants.

The use of the VPP has allowed the designs to be compared with respect to speed rather than speed potential. The results demonstrate that the performance of yachts through the early part of the IOR era did improve in performance. It also showed that performance downwind became more important and this is reflected in the widening of the aft ends and the general move towards the right of Figure 4 with either good downwind performance in the upper right or heavy wind conditions in the lower right. Overall, the VPP confirmed, in general, the performance assumptions made by Humphreys (1975) with respect to the quadrants of Figure 1.

One important conclusion is that the performance improvement between early and late IOR era boats was not all due to money spent on sails and exotic hull materials. The naval architecture was also improving. The geometry of the yachts, during the era, evolved to have better performance, a finding that would not be possible without the use of the VPP and its underlying data. Although the IOR era of yachts has now passed, this paper is relevant to all classes of yachts. Given the geometry of yachts designed and the formula against which they are rated, the methodology presented here allows the evolution of design to be assessed. Provided that the rating rules are available this approach to speed related performance analysis can be applied.

A next step would be to model all the yachts from a single year of the One Ton Cup and hold a virtual regatta, where different conditions can be modelled to determine all round performance. A comparison with the results achieved on the water would identify those boats that had most potential but were underperforming, or those boats that exceeded their potential. However, the scarcity of data means that this is a challenging objective.

6. ACKNOWLEDGEMENTS

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