The Low Impact Narrowboat: A Design for British Canals

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Summary

Vessels on the inland waterways will need to transition away from dependence on fossil fuels for propulsion and heating/cooling according to the UK Government DfT's Maritime 2050 Strategy. Reducing carbon emissions caused by inland waterways vessels is therefore a priority. The biggest issue facing a transition away from fossil fuels is the cost of energy storage on board (be it hydrogen, batteries or a future super fuel) so the first thing to look at in a modern design is reducing the energy consumption on board. Energy is consumed not only by propulsion, but also by heating, cooling and cooking. Simply replacing fuel systems or converting to electric drive is insufficient: of most importance is to reduce the amount of energy needed for both propulsion and heating via hull design optimisation orientated not just towards low drag, but also reductions in carbon intensive repairs to canal banks and bottoms, plus efficient heating and cooling systems on board. This paper outlines such a design and the process taken to achieve it. Note that designs and technologies referenced are subject to patent and design rights. Photos and Designs Simon Boyde/Cadal Craft Ltd unless stated.

Standard Naval Architecture Terms

A	Mid body immersed area	The area of the mid body section of the hull below waterline
Bh	Beam Hull	The maximum immersed breadth of the underwater hull
Cb	Block Co-Efficient	The ratio between the volume of water displaced by the hull of the boat and a volume of Lwl x Bh x T
Cp	Prismatic Co-efficient	The ratio between the volume of the water displaced by the hull of the boat and a volume of Lwl x A
D	Hull Depth	The maximum height of the hull from T to the sheer line
Fn	Froude Number	Vessel design speed relative to length $Fn=v/(\sqrt{(g \times Lwl)}$
g	gravitational constant	9.81
LCB	Longitudinal Centre of Buoyancy	The distance from the stern of the centre of buoyancy.
Lh	Length Hull	The overall length of the hull from stern to stem
Lhs	Length Hull of model	The overall model length from stern to stem
Lwl	Length Waterline	The length of the immersed hull at waterline at level trim
T	Design Draught	The maximum hull depth below the waterline
h	Water Depth	The depth of the body of water the vessel is passing through
S	Blockage factor	The ratio between A and the cross sectional area of the canal
v	Vessel Speed	Vessel Speed at Full Size
v0	Vessel Scale Speed	Scale speed of a vessel $v0=v/\sqrt{(Lh/Lhs)}$
	Convert m/s to knots	1 knot = 1.944m/s
	Convert knots to mph	1 knot = 1.151mph
	To convert scale speed in m/2 to full scale speed in mph: $v=v0*1.944*\sqrt{(scale)}*1.151$	

Background

The British system of artificial inland waterways systems dates back to Roman times, with Reformation era construction of locks and weirs extending these above tidal areas, and in the eighteenth century the construction of man made channels and trans-country routes. Unlike other European countries these were largely private endeavours with comparatively limited investment resulting in a system of narrow canals - where the locks were built for what became to be known as narrow boats as they were only 7ft (2.1m) wide. While wider locks were built, especially in later canals, early competition from railways resulted in investment being cut back and, with the advent of widespread truck use in the post WW1 era, multiple canal closures. In the post WW2 era activists in the newly formed Inland Waterways Association and others managed to slow this closure process, eventually reversing it, and now the British canal system forms the largest post industrial leisure marine park in the world with in excess of 6000km of navigable rivers and canals extending over the country given over almost entirely to leisure marine use in non tidal areas. This connected canal and river system now boasts higher usage, and now purely for leisure, than during its industrial heyday.

From the advent of the canal age in the eighteenth century narrow boats were horse drawn and were designed and to carry the maximum cargo loads possible in the 72 ft x 7ft size which became standardised over much of the canal network. The earliest boats were all wooden and of course built in traditional ways. When iron hulls became common the late nineteenth century these were closely followed by redesigns permitting early diesel engine fitment in the early twentieth century. All of these hulls therefore had square cross section shapes below the waterline in order to maximise carrying capacity in the same manner as a modern bulk carrier at sea.

Post WW2 the last commercial carrying quite quickly collapsed and a variety of adapted river boat designs became dominant in the early leisure use era. Many of the remaining commercial narrow boats in use were converted to leisure use and in time this type of boat became dominant for new builds on the canals from the 1970s onwards resulting in the modern narrowboat.

Modern Design Limitations

The original commercial narrow boats were built to operate with a 3' (0.9m) or deeper draught (many roughly around the 1m mark). When modern narrowboats were built to mimic the old converted boats of course they no longer needed to operate with such a deep draught, but were normally designed to trim bow up in mimicry of the old boats' floating appearance when empty.

As a result early examples of the modern narrowboat therefore had a stern draught of 3' (0.9m) or higher, and bow draughts of 1'6"-2' (0.45-0.6m), and design draught of 2'6" (0.76m).

Early Modern Narrowboat - note the bow up trim

Photo Ray Kemp

The advent in the 1970s of large fleets of hire boats started to change modern narrowboat design. Poor rainfall in several hot summers starting from 1976 coupled with under investment in canal maintenance due to low usage in the transition period between commercial and leisure use left many canals with low water levels in the crucial summer period.

As a result hire boat companies started ordering boats with much lower draughts and this pattern became standard in later years. This has resulted nowadays with boats being built to design draughts of 22" (0.56m) or even less.

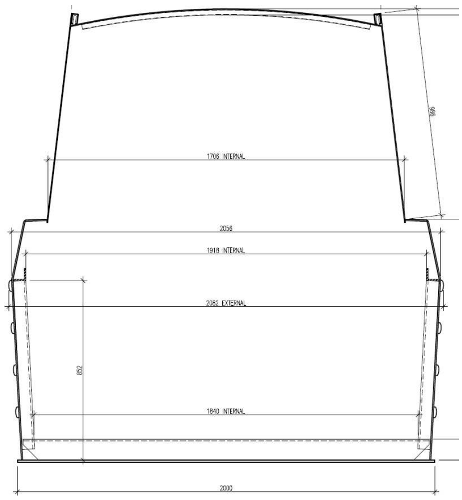
The fashion of trimming these boats so at rest they have a bow up appearance in mimicry of the old trading narrow boats (when without cargo) in fact increases their stern draughts by 6" (0.15m) or more. This is accentuated when the large water tank, typically of over 600L volume, which is always in the bow in such designs, is empty.

Modern standard narrowboat with distinctive bow up trim

The design of such low draught boats has also meant a reduction in prop diameter. Whereas the old boats used props of up to 30" (0.76m) diameter, modern boats will have props at 14-16" (0.35-0.4m) due to the shallow draught. This results in a narrower, higher prop speed, and thus a faster prop wash is the result potentially causing prop stream damage to the canal bottom and sides. In addition the low draught has resulted in boats with poor controllability with resultant canal infrastructure damage when in inexperienced hands.

Design Review

I started this process back in 2014 and started to look at narrowboat designs then on the market. It seemed that the majority clearly have followed the twin routes of low draught and low cost hull construction: built on a 2m wide base plate (selected as it is a commonly available steel plate size), with design draughts when loaded of less than 24"(0.6m) and roughly square in cross section. The reference most used by the buying public strongly recommends low draught (Booth 1999).



Design Richard Wilkinson

I note that concentration within these parameters has been on cost reduction with limited plate bending at bow and stern. The latest designs have design draughts at 20" (0.5m) or less leading to instability in tidal waters.

McGregor and Ferguson (OSTEC 1988, WIT 1993) conducted comprehensive tank testing and full scale trials comparing their new design narrowboat hull featuring a cylindrical bow with a longer bow entry against the common short bow entry standard designs being produced. They found significant reductions in both wave making and pressure with their new design. Their paper included lines for what they considered to be a standard "Traditional" narrowboat design. All their narrowboat designs had square mid body sections. In addition they tested one hull which had a better performance than their favoured design, noticeably without the square parallel mid body section, but this was disregarded in their conclusions due to the disparity in length.

Habben Jansen (Delft 2016) performed a much more extensive computer modelling based study as part of her MSc project which indicates longer lengths, and finer angles, of bow entry significantly reduce drag at low Froude numbers (0.12-0.14 range). She indicates a minimum length of entry of 1.55Bh as a design guideline, and to avoid hollow waterlines in river vessels.

Rotteveel et al (Delft 2014) discuss design guidelines for inland ships in their review paper state the positive effect of a bulbous bow is much reduced on confined waterways. They recommend long stern return lengths to reduce drag and pressure.

Altosole et al (Genoa 2016) show that bow down or stern down trim increases drag in almost all cases. Barrus (Elsevier 2004) gives good information on trim and standard naval architectural parameters. It is clear from Barrus and Altosole et al that level trim is extremely desirable. Moustafa et al (Brodogradnja 2017) give an excellent review of both trim and squat.

Verheij (Delft 2006) strongly recommends a slow turning larger diameter propeller to reduce the speed of the propeller stream, coupled with a horizontal plate or apron below the propeller, in place of an easily blocked propeller shroud, to prevent damage to the canal bottom. He recommends hull design changes to reduce the blockage factor (a ratio between the cross sectional immersed area of the hull and that of the canal) to enable slower return flow thus reducing drag and canal side damage.

Walker et al (DECC/AEA 2011) make clear that the inland waterways are contributors to carbon emissions, albeit not significantly so, and that future boats need to be designed to minimise these.

Boyde et al (Hong Kong BIA, 2020) argue that carbon emissions should not be considered to be purely a propulsion issue, but should incorporate heating and cooking while on board, and use of on board renewable energy, meaning insulation, heat scavenging, heat pumps and solar power should be integral to any low impact boat design.

The UK Government DfT and MCA's Clean Maritime Plan (2019) makes clear that reducing carbon emissions is needed now and no carbon emissions by 2050 is the target.

Parry (2007) gives dimensional parameters to design to which is backed up by the Canal and River Trust with the air draught guidelines for the Standedge tunnel (2016).

Model Testing

From the design review above I decided to create two new hulls in physical model form, based on the recommendations of Verheij, Habben Jansen and Rotteveel et al, with an increased draught and reduced Cb, and test them against modern standard narrowboat hull shapes.

The two new designs (C125 and C150) are similar but with different base plate widths as I wanted to test the effect of this on canal bottom pressure waves. The two additional models (OS750 and OS600) are also similar but with different draughts representing modern narrowboat designs of the 1980s and of now.

These four models were constructed from PLA plastic sections printed on a 3D printer. Each model was 1.5m long, at 1:12th scale, representing full scale hull lengths of 18m. The models lines were made in Rhino 5 and then converted to shell shapes, sectioned into 6 parts each, which after printing were joined together. A single deck was built, which fits to all four models, from which was suspended battery and control systems, as well as a drive system connected to a model ducted Schottel drive unit and rudder, enabling the entire control, rudder, and propulsion systems to be lifted off one model and put onto another so as to provide continuity in terms of propulsion and control systems.

C150 Hull: Base plate beam of 1.5m, double chine hull, 4m long entry 6m long return sections, draught of 0.71m

C125 Hull: Base plate beam of 1.25m, double chine hull, 4m long entry 6m long return sections, draught of 0.71m

OS750: Base plate beam of 2.08m, single chine hull, 2m long entry, 2m long return sections, draught of 0.75m (the 'Traditional" standard narrowboat hull lines from the OSTEC 1988 paper)

OS600: Base plate beam of 2.08m, single chine hull, 2m long entry, 2m long return sections, draught of 0.6m (approximately modern standard narrowboat design)

The propulsion system featured a 40mm diameter model Schottel drive sold for hobbyists. As the same prop and rudder were to be used for all models no effort was made to tune this to hull form.

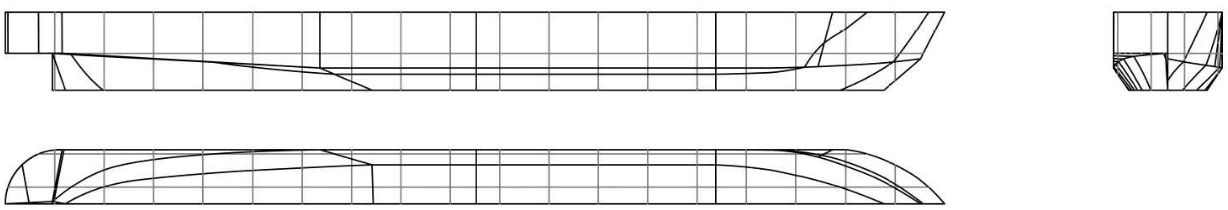
A trough was built 9.6m long which was lowered into a partly filled swimming pool. This was used at approximate depths of 0.08m (representing a shallow canal of water depth (h) of 1.0m at full scale) and 0.12m (h=1.5m) permitting us to test the models at approximate h/T ratios (the ratio of water depth to vessel draught) of 1/0.75 = 1.3 and 2.0. Note that an h/T ratio of 1 in level trim means the boat is on the bottom of the canal.

The models were accelerated to speed outside the trough then steered into the trough from the end opposite to the timing section. They were steered down the trough passing through two timing gates, optical sensors interrupted by the model's transition, situated 1.0m and 5.0m from the end of the trough opposite to their entry. This placement meant that the models completed three boat lengths of transit before the first timing gate, giving full effect to the constrained water channel before our timing started.

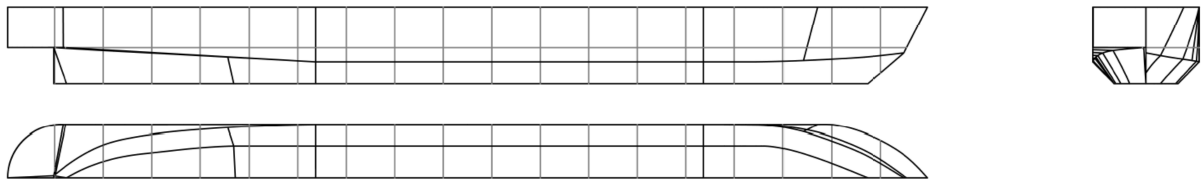
A pressure sensor whose output varies between 0V and 10V over 1m (thus with 0.8V representing an actual depth of 0.08m and a scale depth of 1m) was fitted in the bottom centre of the trough 0.5m before the second timing gate. This placement meant that the stern of the model crossed the pressure sensor before the bow of the model exited the trough

Model details. All dimensions are at full scale. The four models were built at 1:12th scale, therefore 1.5m long.

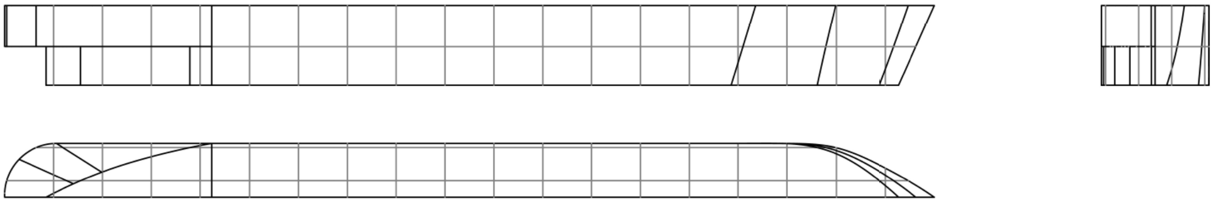
C150 - 18m long with double chine hull, draught 0.71m on 1.5m base plate



C125 - 18m long with double chine hull, draught 0.71m on 1.25m base plate



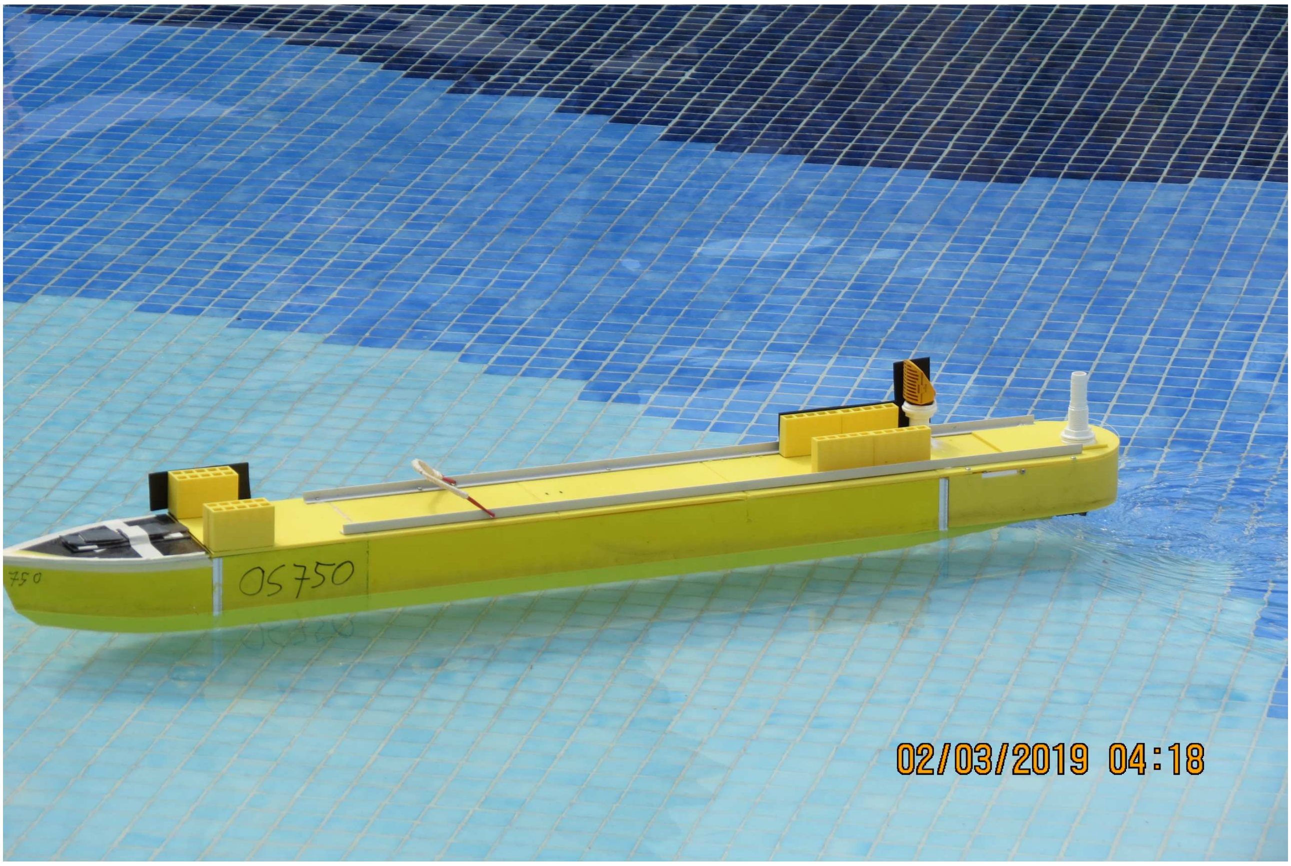
OS750 - 18m long single chine, draught 0.75m as per "Traditional Boat" in OSTEC 1988



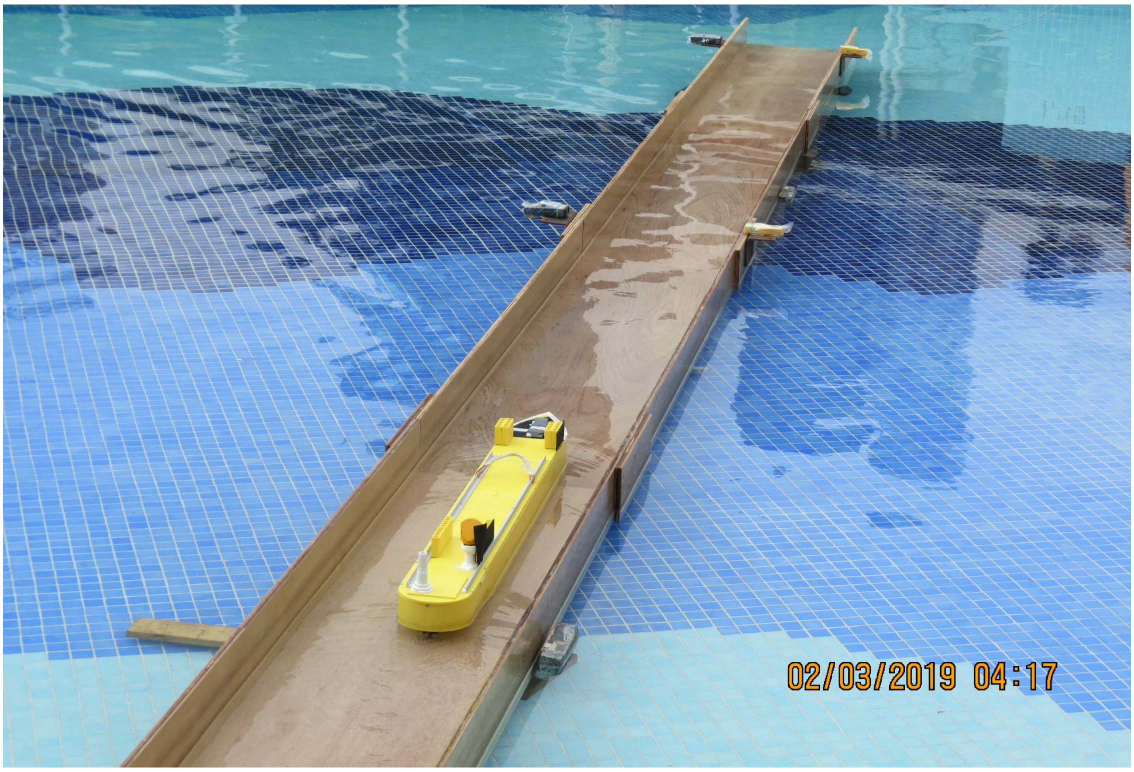
OS600 - 18m long single chine, draught 0.6m similar to OS 750 except for draught

Model Photos

With Propulsion and control deck on

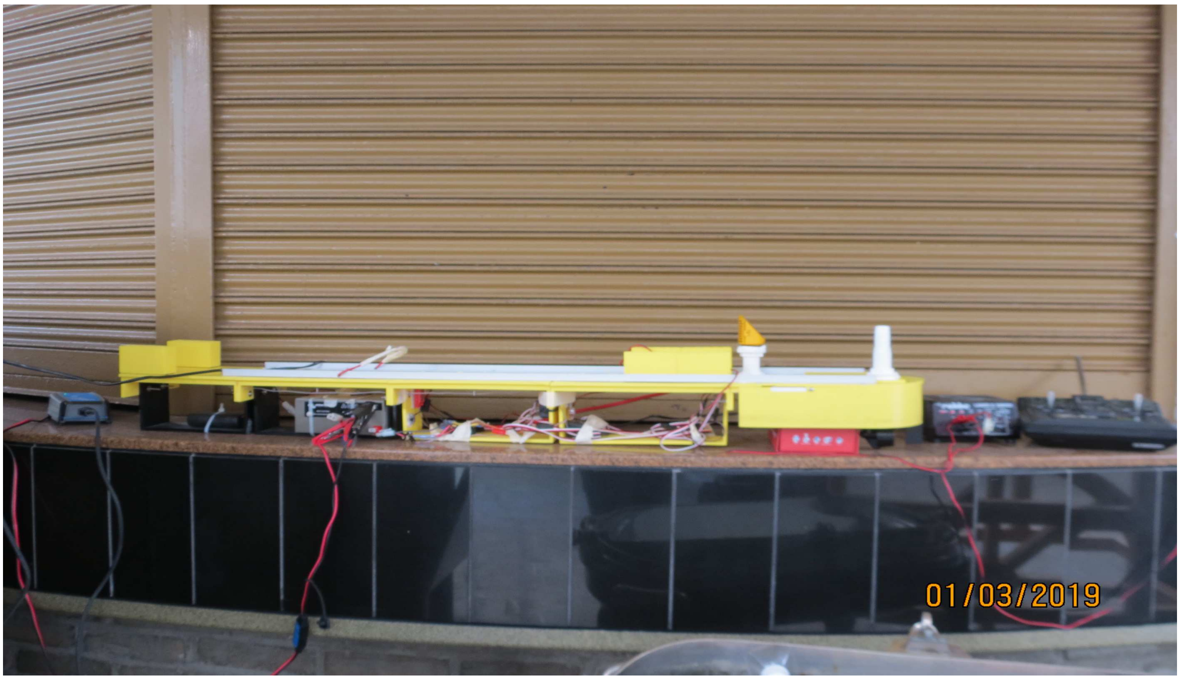


The test rig - hull with deck fitted progressing down trough



The test rig pictured above shows a trough 9.6m long, 0.6m width built out of ply set at the bottom of a partly filled swimming pool. The model is heading away from the viewpoint of the photographer. The two timing gates are clearly visible.

The propulsion deck removed for recharging



Propulsion deck shows battery in the bow, radio receiver in the centre and a stern section with Schottel drive below propped on a box to reduce flex. The entire deck with battery/drive/radio controls was designed to lift off and be placed on any of the four models.

Testing

Testing was done over three days. Consistent low wind conditions featured on all three days. Propulsion battery was recharged each night to ensure the same maximum power was available for all runs. Moveable weights were added and removed as required below representing 2 people standing at the back (100g, 173kg at full scale, placed on the aft part of the deck) and full water tanks (380g, 650kg at full scale, placed at LCB on the C models and at the bow on the OS models.)

Day 1 consisted of open water manoeuvrability tests after the boats were ballasted to the correct draught and trimmed to level with weights added representing full water tanks, in the bow for the OS boats and at LCB for the new C designs. Boats were weighed and the following table established (actual not full scale):

Model Hull	Displacement kg	Draught mm	Block Cb Co-efficient	Prismatic Cp Co-efficient	Manoeuvrability Index
OS600	10.46	50	0.87	0.87	2
OS750	13.07	62	0.87	0.87	3
C-125	10.67	59	0.75	0.85	1
C-150	10.92	59	0.77	0.84	1

Day 2 consisted of multiple runs down the 9.6m trough with the water level in the trough set to 0.08m (approx 1m at full scale). Runs were done for the following conditions

Level Slow: Speed approx 0.26m/s (full scale speed of approx 2mph) with level trim and full tank weights
Level High: Highest speed possible with max power with level trim and full tank weights
Empty High; Highest speed possible with max power with weights representing water tanks removed, and weights added to represent two people standing at the stern therefore representing the maximum bow up trim

In each case three runs were done for each condition for each boat and the middle result used for the results. Speed over the timed section and the pressure wave were taken for each boat, recorded as a varying voltage and sampled 400 times/second.

Day 3 consisted of multiple runs down the 9.6m trough with the water level in the trough set to 0.12m (approx 1.5m at full scale). Runs were done for the following conditions

Level High: Highest speed possible with max power and level trim, full water tank weights
Empty High; Highest speed possible with max power and no water tank weights but added 2 people weights at stern

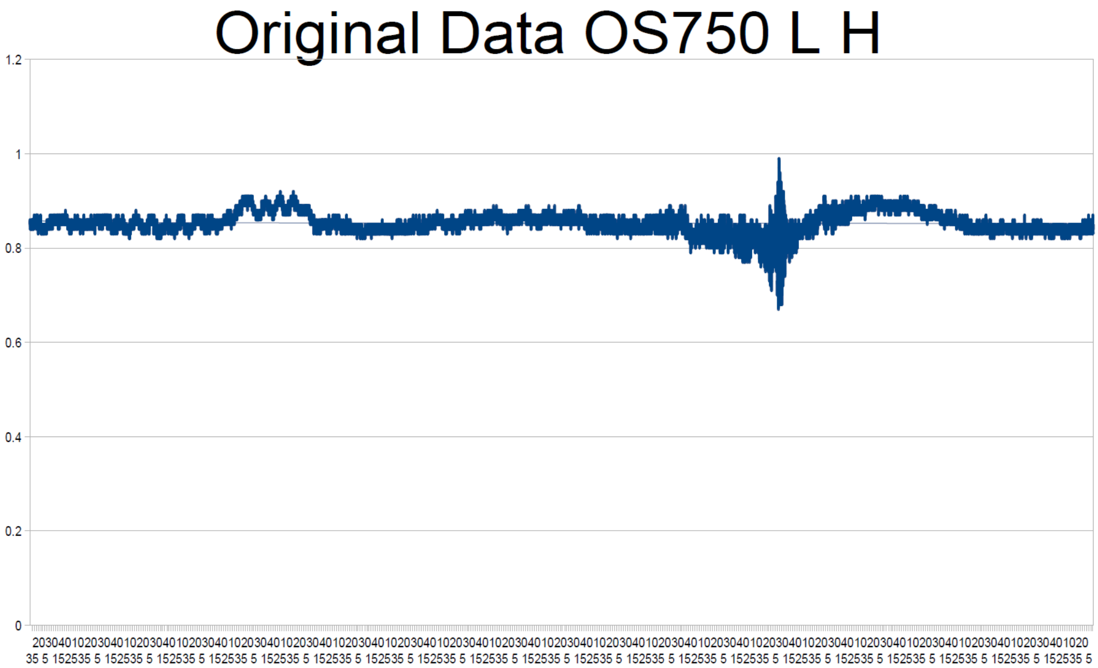
In each case three runs were done for each condition for each boat and the middle result used for the results. Speed over the timed section were recorded for each boat. No pressure data was available for the third day due to logger failure from weather factors overnight.

Open Water Results:

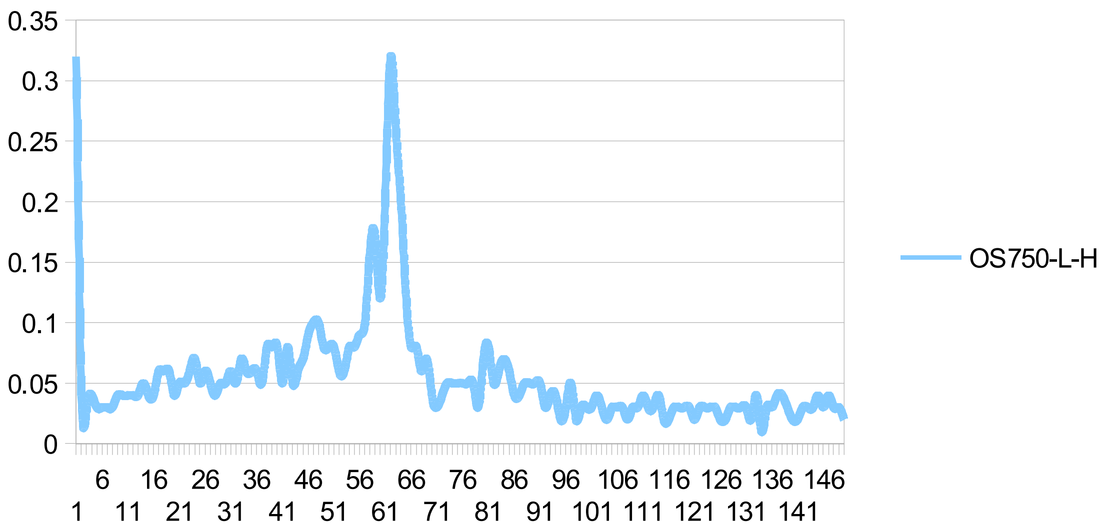
The C150 and C125 models showed similar open water controllability. No obvious difference was seen in directional stability or turning circle. The OS600 model was harder to keep in a straight line, and had an obviously wider turning circle than either of the C125 or C150 models. The OS750 model was better in a straight line than the OS600 model, but had a much wider turning circle than the OS600 or C150 or C125 models.

Canal depth of 0.08m (1m full scale) Results:

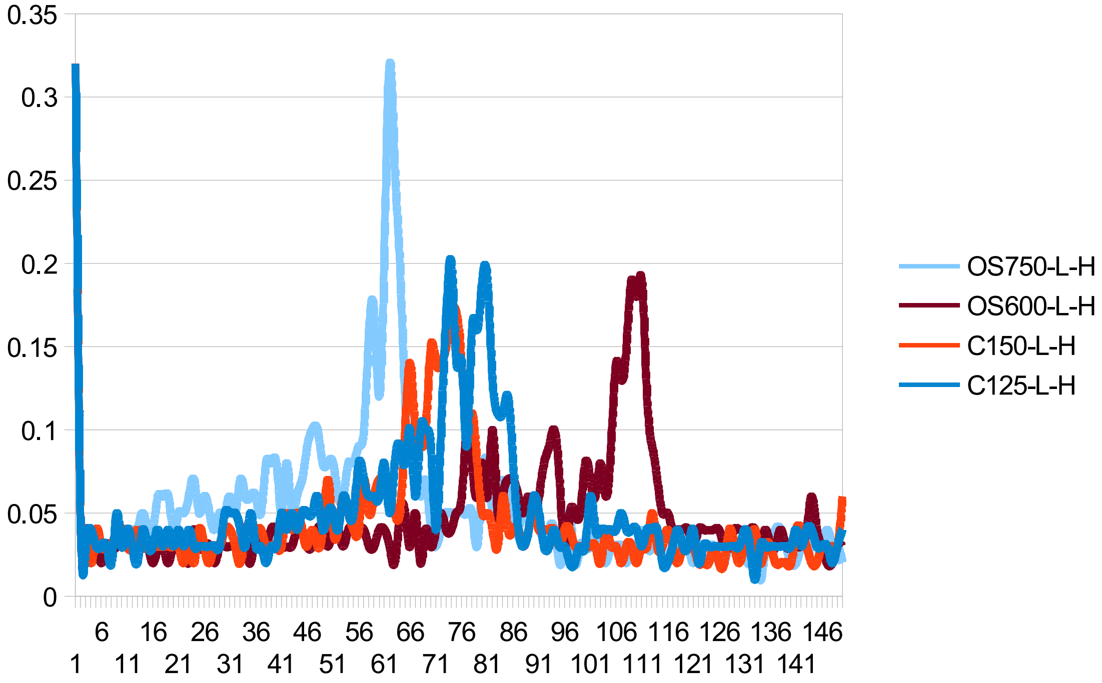
It proved very difficult to compare effectively the pressure waves between the four boats. A sample plot is shown below showing the OS750 in level trim at highest speed possible below. Plot is y=volts, x=time at 400 samples/sec



To make this meaningful the amplitude between highest and lowest value over 0.1 secs (40 sample points) was taken and plotted as below as a sequence of 150 points over 15 seconds covering the peak amplitude. Plot is x=amplitude in volts over 0.1s y=sample plot no from 1-150



All four boats plot of amplitude against each other



This still proved difficult to see defining differences, as different models, due to different hull shapes, show multiple peaks at different parts of their transition. It is noticeable however that the OS750 has the overall highest amplitude, the C125 and OS600 similar peaks, and the C150 the lowest peak

To simplify the results a single number was obtained representing the total disturbance as the area under the graph of each run as plotted above - this therefore showing the energy dissipated into the water as a table for all the runs

0.08m Depth Level Slow	**Disturbance Index**	**Speed (v0) m/s**
OS750	4.28	0.26
OS600	2.92	0.28
C150	1.38	0.26
C125	1.25	0.26
Level High		
OS750	5	0.32
OS600	3.67	0.38
C150	2.52	0.4
C125	3.88	0.38
Empty High		
OS750	4.26	0.31
OS600	2.69	0.36
C150	2.37	0.37
C125	3.24	0.37

As can clearly be seen the OS750 hull performs the worst. It creates by far the largest pressure disturbance and has by far the slowest high speed run.

The OS600 - same hull but with a shallow draught - is better.

The new design C125 hull (long entry and return sections, double chine hull) creates the least disturbance at slow speed.

The C150 hull however performs the best overall - it is slightly faster in both level trim and full load conditions and produces a significantly reduced pressure wave in both these conditions compared to the other hulls, and scores well also in the slow speed run.

Canal depth of 0.12m (1.5m full scale) Results:

Unfortunately the pressure logger was found to be malfunctioning and wet after heavy rain overnight so no pressure data was available from the third day's testing.

The following data was recorded - again the middle run of three runs for each boat over timed section in each trim condition as a maximum speed/maximum power

0.12m Depth	**Speed (v0)**
Level High	**m/s**
OS750	0.38
OS600	0.42
C150	0.48
C125	0.5
Empty High	
OS750	0.39
OS600	0.43
C150	0.49
C125	0.5

The disparities between the OS750 and OS600 hulls are reduced - as one would expect from the drop in the blockage factor. However the OS600 itself does not manage to increase its maximum speed anywhere near as much as the C150 and C125 hulls which perform again much better than the standard designs. It is noticeable that the C125 performs slightly better than the C150 and that all models perform slightly better with a lower load.

Discussion

The results from the tests are of course less rigorous than from a formal tank test: a person is controlling through remote control the free floating models down the trough. To minimise potential variation the same steerer was used for all tests. Runs where the boat was not centred, or required excessive rudder control, or with excessive waves, were abandoned and not recorded.

Originally we intended to run tests at the following speeds:

v0= 0.26m/s (v=2 mph), representing the Canal and River Trust slow speed mode
v0= 0.47 (v=3.5mph), representing the practical full speed possible on British Canals
vmax representing the max speed.

However we found that we could not get any of the models to the required speed in the shallow canal (h=1.0m). The use of the Schottel drive with the ducted propeller may be the cause - the duct simply prevented sufficient flow getting to the propeller with the narrowboat hull shapes ahead., These props are normally installed at the end of a tunnel shape under water, something physically impossible top reproduce on a narrowboat. Alas also, on the day, the construction of the drive and control deck meant that removing the duct around the propeller was impossible without reconstructing the stern area of the drive deck. So we abandoned the v=3.5mph tests.

I expected the C125 model to perform better overall, as indeed is shown in the deeper water tests. However the pressure test results show that this hull shape is dissipating much more energy into the water at lower canal depths - and at such depths the C150 hull is still faster. Differences between the C hulls in the runs in deeper water could be accounted for by the lower Cb ,Cp and displacement in the C125 model.

Both the C150 and C125 hulls show large improvements over the standard modern design OS600 and older modern narrowboat design OS750.

Overall I see a significant improvement of the new models over the old designs, as I would expect from the lower drag shapes, together with enhanced handling.

I am confident therefore that the hull described below, which I have developed based on the C150 shape and experimental results above, will have a significantly lower drag and bottom pressure wake and will cause much less damage to canal banks and bottoms than standard modern narrowboat designs.

Conclusion

The tests above show that changes to the underwater shape can make a significant reduction both to the drag from a narrowboat hull and the pressure waves produced.

Self evidently a double curvature hull shape would be more efficient, and the stern shape could be much improved - but only at a steep increase in build cost.

From the design review there are three principal areas mostly affecting drag and wave making on a canal boat travelling at the low speeds typical of British canals.

Firstly the blockage factor (S), the ratio between the cross sectional immersed area of the hull (A) and that of the canal, needs to be minimised.

Next increasing both bow entry length and even longer stern return length - closely related to the prismatic co-efficient Cp - will help in order to reduce pressure waves.

Lastly the boat needs to be able to travel at level trim - or as close to it as is reasonably possible.

Our tests indicate that a 1.5m full scale base plate width produces a lower pressure wave than a narrower base plate width.

Development

Low Impact Hull

With the results of our testing, and with reference to the design review, a double chine hull has been designed based on the C150 hull (patent pending) and a prototype put into build by Cadal Craft Ltd to test at full scale the conclusions of this paper.

The new Cadal 60 has the following principal dimensions:

Length Hull	Lh	m	18.30
Beam Hull	Bh	m	2.07
Freeboard	F	m	0.80
Design Draft	T	m	0.73
Headroom		m	1.93
Max Air Draught	Ha	m	1.78
Length Waterline (Measured)	Lwl	m	16.93
Hull Depth	D	m	1.53
Design Displacement	Mdes	kg	19,030
Length/Breadth Ratio	L/B		8.17
Block Coefficient	Cb		0.75
Prismatic Co-efficient	Cp		0.81
Cruising Speed (Electric)		knots	3.00
Cruising Speed (Diesel)		knots	6.00
Max Design Speed		knots	7.50
Half Entrance Angle		degrees	22.5

In accordance with the design review length of entry (length of bow) have been made unusually long for this type of vessel at 4m. The length of return (length of stern) is long at 6m. Work was done using Orca3D in Rhino 7 to reduce the Cb of our selected C150 hull type down to that of the C125 hull in our tests, which resulted in a much finer entry and exit, reducing Cp much further.

Using Orca3D multiple Holtrop power predictions were run as part of this process to help fine tune the bow and stern shapes to further reduce drag and displacement while retaining the same mid body section..

Canal Impact

Our use of a deeper draught has enabled us to increase prop diameter, and thus reduce prop rotational speed and therefore prop wash. The addition of an apron under the prop should prevent prop wash and tip vortex damage to the canal bottom.

The hull and superstructure are constructed from mild steel which is 100% recyclable

Stability and Controllability

Draught is slightly higher than the model tests - I found this made a good contribution to hydrostatic stability from our Orca3d iterations. With the much improved under water shape handling should be much enhanced over modern standard narrowboats as evidenced by our model open water tests. Stability is increased and the boat is being constructed to RCD C rather than the RCD D of current standard designs, to enable safe river running.

The double chine hull gives us an area of reducing beam below the cabin floorboards which is used for ballast (steel shot) and for water and black tanks, thus removing the illogical placement of the water tank in the bow which is otherwise guaranteed to make level trim impossible to achieve.

Having validated the hull shape as being of lower drag and a lower canal impact than contemporary builds as outlined in our model tests I am confident that this patent pending hull shape is the right way to go.

It features a hybrid drive enabling electric drive which on a good day will able to be powered almost entirely by the solar panels fitted to the boat; with diesel power for high speed runs on fast rivers and when solar power is insufficient. Future infrastructure developments on British canals may mean that the diesel engine on board can be dispensed with if sufficient canal bank charging points are installed. In the meantime HVO fuel (Hydro-treated Vegetable Oil) can be used with the diesel engine to reduce CO2 emissions.

Energy Efficiency

Following on from the recommendations by Boyde et al in their Low Impact Boating paper, the boat will be fully insulated with double glazed windows. By removing open flame heaters and cookers, we can significantly reduce heat loss through excessive ventilation on board by making all heating and cooking electrically sourced the boat is much more efficient than current designs while being fully rule compliant.

Heating/Cooling/Energy Efficiency

Standard reverse cycle marine air-conditioning systems can successfully extract heat from the water around the boat to successfully a the boat in winter as long as water temperatures exceed 5C.

Research has indicated that it is very unusual for canal or river water to cool beyond this point so we have installed a water sourced heat pump which will operate through a patent pending hull integrated heat exchanger (removing the mud blockage risk) driving low energy fancoils so we heat the air on board, not the cabin sides.

Cooking facilities are induction electric only.

The boat is fully insulated with double glazed windows. By using electrical heating and cooking, thus removing open flame heaters and cookers, we significantly reduce heat loss through excessive ventilation.

Hammond and Price in "Climate change impacts and water temperature" 2007 quote water temperatures for UK rivers showing that there is sufficient water temperature in rivers and canals even in mid winter to make the running of such water sourced heat pumps viable for river and canal vessels as long as the issue with fine mud blocking the heat exchanger can be overcome, which our design will manage.

Cooking facilities are electric only making the boat, on a good day or with access to shore power recharging as recommended by the IWA, independent from fossil fuels if required.

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