First International Symposium on Fishing Vessel Energy Efficiency
E-Fishing, Vigo, Spain, May 2010

Trawl-gear innovations to improve the energy efficiency of Australian prawn trawling

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Abstract— **In Australia, efforts to improve the energy efficiency of prawn trawling have usually targeted either "catch increase" or "drag reduction". These seemingly simple notions are actually complex objectives and often interact negatively. Therefore, many attempts to improve efficiency have not produced the desired outcome because identification of the various issues and their interplay remain poorly understood or are ignored. Examples of this include the continuing low efficiency of contemporary otter boards, and the difficulties often experienced using fine-diameter, high strength netting.**

The inputs that affect the performance of key components in a prawn trawling system and their influence on energy efficiency are discussed and specific opportunities to improve energy efficiency are described. They include; a five-net trawling system, which can improve swept area performance by 12% compared to commonly used quad-rig; correct size-matching of otter boards to trawl nets, which can increase swept area performance by 10%; the newly designed Batwing otter board, which conceivably can reduce otter board drag by as much as 70%; and the concept of a double-tongue, square-mesh trawl.

Keywords – prawn, trawl, otter boards, batwing, efficiency

I. INTRODUCTION

In 2008-09, Australian prawn production reached 23 000 t and was valued at just over A$297 million [1]. Landings from commercial prawn-trawling contributed 83% of this production, with the remainder being derived from prawn farming. Most prawn fishermen use multi-net trawling systems; towing two, three, or four trawls simultaneously, and they target a variety of penaeid prawn species located on or close to the seabed. Maximizing the area of seabed swept by the trawl-system per unit time is therefore important to successful prawn trawling.

The socio-economic goal for prawn trawling fisheries is to generate greater profit and community benefit from a given level of sustainable catch. A significant approach to that goal is to minimize resource inputs and environmental impacts so that a maximum amount of business revenue is available to be distributed as net benefits to the community. In all systems, both manmade and natural, it seems that resource efficiency is the result of the appropriate application of complexity, diversity and intelligence. Therefore we can expect that as fishing businesses become more resource efficient they will become more heavily characterized by these features.

In prawn trawling businesses, the natural resources and services that influence the generation of revenue are fuel, time, prawn behavior, and ecosystems (Figure 1). Only fuel usage and time are under direct control of these businesses, and both are factors intrinsically connected to business operating costs.

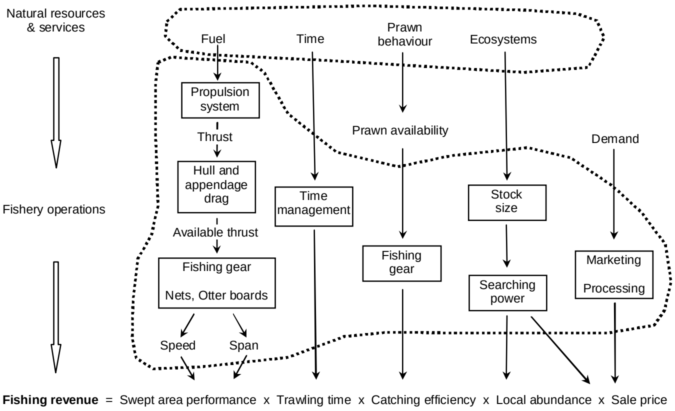


Figure 1. The operational structure of prawn trawling and associated inputs and outputs in context with the generation of revenue.

Within the operations of the fishery, these businesses are afforded a complex array of opportunities to improve the efficiency of resource access and utilization, through swept area performance and catching efficiency of the fishing gear, the ability to search for viable abundances of prawns (searching power), the utilization of time, and product development.

In this context, the application of appropriate fishing gear technology can play a direct role in the swept area performance and catching efficiency of the trawl system, and generate improvements in energy efficiency. Relevant identifiable initiatives in this area include the use of:

- High-order multi-net trawling systems
- Optimal otter board and trawl size for a given vessel thrust
- High-performance trawling components.

II. HIGH-ORDER MULTI-NET TRAWLING SYSTEMS

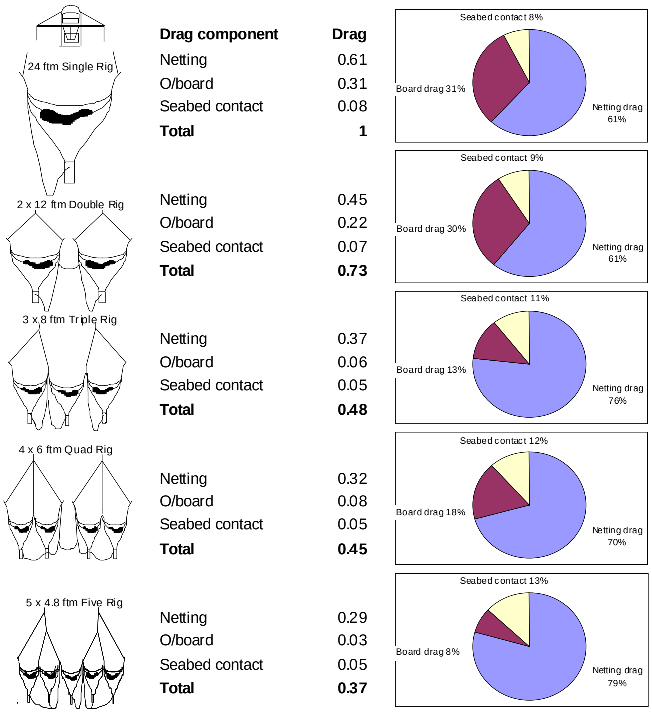
In Australia, the historical progression of technology in prawn trawling has included the adoption by fishermen of multi-net trawling systems. This started with the replacement of a single trawl by two smaller trawls in the early 1970’s, followed by adoption of three- and four-trawl systems in the late 1970’s and early 1980’s [2]. By the late 1980’s, there was widespread concern about overfishing in many Australian prawn fisheries, and in response a suite of regulations were introduced to reduce fishing effort. In some of these fisheries, these regulations limited the allowable number of simultaneously towed trawls to two. Over the last 5 years, however, as the health of prawn stocks have improved, the use of higher order multi-net trawling systems has been allowed back into some fisheries, with balancing measures to hold fishing effort constant [3].

By increasing the number of nets towed simultaneously in a prawn trawling system, the total drag of the system is reduced substantially because both otter board area and twine area are reduced (Figure 2). The drag advantages of multi-net systems were estimated by Sterling [4], based on a number of assumptions that approximately reflect the operation of contemporary prawn trawling gear in Australia:

- The hydrodynamic drag of a trawl is proportional to headline length$^{1.47}$
- The drag of the ground chain is proportional to its length, and in the case of a trawl with a 22 m (12 fathom) headline length, is equal to 10% of the trawl’s hydrodynamic drag
- The hydrodynamic drag of a pair of otter boards is 0.5 times the hydrodynamic drag of the trawl to which they are connected
- The plowing drag of the otter board is equivalent to 10% of its hydrodynamic drag.

Figure 2 indicates that triple- and quad-rig trawl-systems have less than half the drag of a single-net system with the same total headline length. Multi-net trawling systems can be further expanded to incorporate an even higher number of nets, for example the five-net system. Field tests by Sterling [4] showed that this trawl system was 10% more efficient in terms of area trawled per unit of fuel consumed compared to a contemporary three-net system.

Noteworthy also is that a large proportion of the overall drag of a prawn trawling system is associated with the drag of trawl netting, from just over 60% for single- and two-net systems to almost 80% for the higher order systems where many trawls are connected together. This suggests that using finer diameter twine to reduce netting drag could have a very significant impact on the overall drag of the prawn trawling system. The potential gain is even higher than first impressions because the size of otter boards required by the system to spread open the trawls (and the resulting otter board drag) is directly governed by the drag of the trawls. Therefore fine-diameter twine, properly implemented, could realize a reduction in both netting drag and otter board drag; seemingly making it the most powerful energy efficiency factor in prawn trawling.



Drag component	**Drag**
Netting	0.61
O/board	0.31
Seabed contact	0.08
Total	**1**
Netting	0.45
O/board	0.22
Seabed contact	0.07
Total	**0.73**
Netting	0.37
O/board	0.06
Seabed contact	0.05
Total	**0.48**
Netting	0.32
O/board	0.08
Seabed contact	0.05
Total	**0.45**
Netting	0.29
O/board	0.03
Seabed contact	0.05
Total	**0.37**

Figure 2. The drag benefits of multi-net prawn trawling systems with estimated drag breakdown between significant components. The total headline lengths for all systems are equal, and the spread ratio of all trawls in all systems is assumed to be identical.

III. OPTIMAL OTTER BOARDS AND TRAWLS FOR A GIVEN VESSEL

Optimizing trawl-system configuration and deriving maximum performance is a complex objective due to the number of performance dimensions involved (as alluded to in Figure 1). The application of the fishing gear most obviously influences swept area performance and catching efficiency. Less obvious, but also importantly, fishing gear also influences trawling time, searching power and product quality. Focusing on only one of these dimensions however still involves many input variables. A way of moving forward towards optimizing trawl-system performance has been to develop a Prawn Trawling Performance Model (PTPM) to predict swept area performance based on descriptors of the trawling system. In its most advanced form, the PTPM also estimates the geometry of the trawl system, all the acting internal forces, and the orientation of the otter boards [5]. Version 1 of the PTPM (Figure 3), a simple form of the model, reveals the broad engineering character of prawn trawling systems, without the capacity of investigating fine-scale details and subtle interaction effects. A complete description of the form and development of the PTPM ver.1 can be found in Sterling [4].

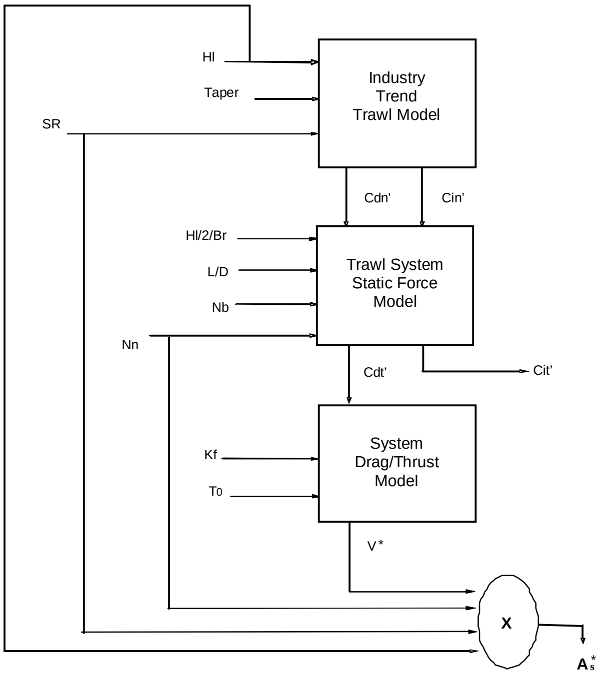
1) Description and use of the Prawn Trawling Performance Model ver.1

The PTPM is a hybrid model containing theoretical and empirical components describing the physical process at work during the operation of a trawl system. It is a deterministic model that does not output any measure of statistical uncertainty. PTPM ver.1 was developed in 1996 by technologists at the Australian Maritime College (AMC) and the Australian Maritime Engineering Cooperative Research Centre (AME CRC), and drew on experimental data collected at the AMC over the previous 10 years. Background studies included an evaluation of contemporary otter board designs, multiple-net prawn trawling systems, trawl design, trawl forces at various spread ratios, and the lift and drag forces acting on otter boards. The measurement of forces was achieved mainly from flume tank tests using specialized trawl and otter board evaluation hardware designed at the AMC.

This version of the PTPM has three main components:

1. The "Industry Trend Trawl Model". A set of empirical relationships that define the engineering characteristics of prawn trawls, being the main building block of prawn trawling systems.
2. The "Trawl System Static Force Model". Two equations that allow the fundamental building blocks of prawn trawling systems to be combined in any number or combination, and then estimate the system's overall drag characteristics.
3. The "System Drag/Thrust Model". Equations that recognize the effect of trawl speed on the drag of the trawl-system and on the available thrust from the vessel. This component essentially matches the drag of the trawl-system to the thrust of the vessel and predicts the resulting trawling speed.

An output of PTPM ver.1 is a swept area performance optimization chart (Figure 4). In this example, the chart is generated for a vessel towing a three-net system and utilizing an engine power of 185kw. The chart shows that the efficiency of engine power utilization, as indicated by the resulting swept area performance (SAR), depends upon correctly matching the size of the trawl in conjunction with the size of the otter boards used and the capacity of the trawler. These results are sensitive to many variables in the trawl-system, for example, otter board design and efficiency, mesh size, and twine diameter, and the PTPM is able to adjust the optimization chart accordingly. Interestingly, the matching of trawls to otter boards and engine capacity by fishermen is usually based on experience and tradition. This produces a likelihood that much fishing effort occurs with fishing gear that is not optimal from a swept area perspective.



$$Cdn' = (1.069 \times Hl^{1.473}) \times (0.306 + 2.83 \times SR - 4.89 \times SR^{2} + 3.14 \times SR^{3}) \times Tapf$$

$$\Omega = 16.36 - 61.37 \times SR + 79.25 \times SR^{2} + 26.56 \times SR^{3}$$

$$Cin' = \frac{Cdn'}{2} \times \tan(\Omega)$$

$$Cit' = \frac{Cin' + \frac{Cdn'}{2} \times Sr \times Hl/\ 2\ /Br}{1 - \frac{(Sr \times Hl/\ 2\ /Br)}{\frac{L}{D}}}$$

$$Cdt' = Nn \times Cdn' + Nb \times \frac{Cit'}{\frac{L}{D}}$$

$$Dt = Cdt' \times V^{2} + Df$$

$$T(V) = T0\,(1 - \frac{V}{2Vd})$$

$$V^{*} = \frac{-\frac{T0}{2Vd} + \sqrt{\left(\frac{T0}{2Vd}\right)^{2} - 4Cdt'(Df - T0)}}{2\,Cdt'}$$

$$Df = Kf \times Cdt' \quad \text{Where } Kf = 1.41$$

$$A_{S}^{*} = V^{*} \times 0.51444 \times Nn \times Sr \times Hl$$

A_{S}^{*}	swept area performance for thrust, T_0 (m^2/sec)
Br	bridle length (m)
Cdn'	trawl net drag parameter (kgf@1knot)
Cdt'	trawl system drag parameter (kgf@1knot)
Cin'	inpull force parameter of net (kgf@1knot)
Cit'	total inpull force parameter of system (kgf@1knot)
Df	friction component of system drag (kgf)
Dt	total system drag (kgf)
Hl	headline length (m)
Kf	ratio of friction and hydrodynamic forces at 1 knot
$\frac{L}{D}$	hydrodynamic efficiency (shear to drag ratio)
Nb	number of otter boards
Nn	number of nets
SR	spread ratio (fraction of Hl)
Tapf	side taper drag factor
T0	bollard pull (kgf)
V	trawl speed (knots)
Vd	maximum (design) vessel speed (knots)
Ω	wingend angle of net (degrees)

Figure 3. Schematic and equations of the Prawn Trawl Performance Prediction Model version 1.

In the hypothetical situation shown in Figure 4, point A is the current operating position for a trawler. It is clearly not where maximum swept area performance occurs on the map;

however, at the position of maximum performance the trawl speed is only about 1.85 knots. This could well be too slow for practical trawling, whereby the fisherman might specify that the minimum required trawl speed is 2.25 knots. Under these circumstances, point B would give the maximum performance available. To operate at this point, the fisherman is required to purchase smaller trawls and larger otter boards and in so doing the swept area performance would increase by 12%. The diagram shows that this operator has made the classic mistake of trying to tow trawls that are too large. If smaller trawls were used in conjunction with the existing otter boards; for example, a 12 m trawl as indicated by point C, the swept area performance would increase by 6%.

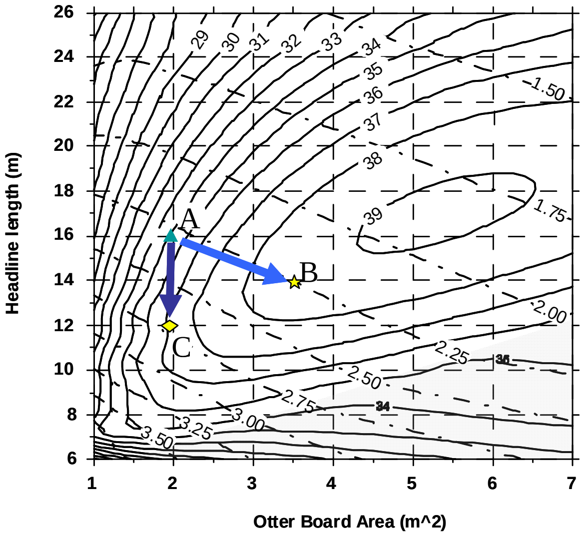


Figure 4. Optimum component matching using swept area performance map. Dashed lines represent towing speed (knots) and the contours represent swept area performance (m^2/s).

IV. HIGH PERFORMANCE TRAWL COMPONENTS

The intrinsic qualities of trawls and otter boards in a prawn trawling system can be improved by changing their structural form. For example, the use of thin, high-strength netting in a trawl or curved foils in an otter board can reduce the drag of these components and improve their efficiency. However, these components also have extrinsic qualities manifested by their size in conjunction with how well their functional role within the overall trawl-system is being achieved. This was highlighted in the previous section, which described the optimization of trawl and otter board sizes in connection with the opportunity of a trawling operation to maximize swept area performance for fixed vessel thrust (and rate of fuel consumption).

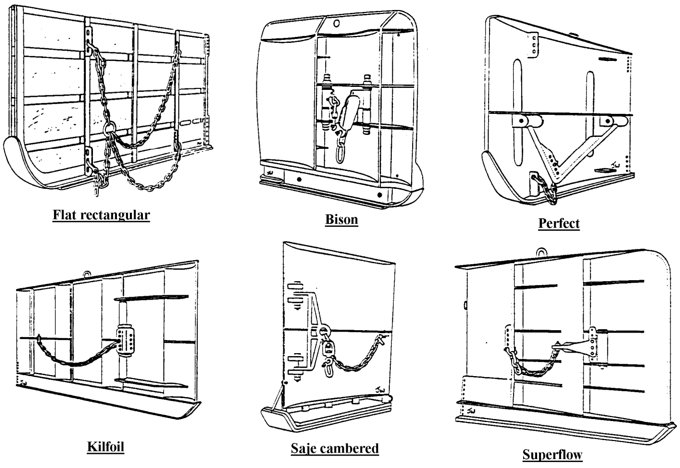
Therefore, in order to have highly effective and efficient trawling components, there is a need to perfect both their intrinsic and extrinsic qualities, and also deal with the reality that at a deeper level there are complex interactions between them. This does not happen by chance, and needs to be a formalized part of our design processes.

In respect to maximizing overall system performance, a more advanced version 3 of the PTPM captures the mechanics of many interactions between component qualities so that all relevant interactions are accurately considered during the optimization of component sizes [6]. Similarly, increasing the intrinsic quality of components through structural refinement is assisted by specifying the relevant context to the design process. The relevant context is the engineering environment for the component that uniquely exists when its extrinsic qualities, as manifested by its size, have been optimized.

A good example of the need for this methodology and the efficiency implications is the case study, in the next section, of the improvement in otter board design occurring for prawn trawling in Australia.

V. INNOVATION IN OTTER BOARD DESIGN

Until the mid 1980’s, flat rectangular otter boards were used almost universally by Australian prawn fishermen, and while their use has strongly persisted through to the present day in some fisheries, in others they have been largely replaced by more “aerodynamic looking” designs (Figure 5). A cursory look at the traditional flat rectangular otter board and the problem of otter board drag can lead one to the belief that large improvements in otter board performance can be achieved simply by incorporating better foil shapes. Many contemporary otter boards have been developed with this narrow objective in mind. An extensive comparison of the six prawn trawling otter boards shown in Figure 5, by Sterling et al. [6], shows that for these otter boards there are only small differences in swept area performance, and several designs were inferior to the traditional flat rectangular otter board (Figure 6).



Drawings by J. Wakeford

Figure 5. Australian contemporary otter board designs [4].

The main reason suggested for the disappointing improvement in otter board performance is that their rigging is not suitable for appropriately controlling angle of attack in such prawn trawling applications. High otter board efficiency comes about by a combination of good foil design and appropriate otter board orientation (Figure 7). The significance of this point is clearly shown in Figure 8 [7]. At angles of attack typically used by prawn fishermen (35 – 40 degrees), the efficiency of the tested otter boards is low – irrespective of the hydrodynamic foil used. At lower angles of attack (eg. 20 degrees), all the otter boards have much improved efficiency, and benefits now appear for the more sophisticated foil designs.

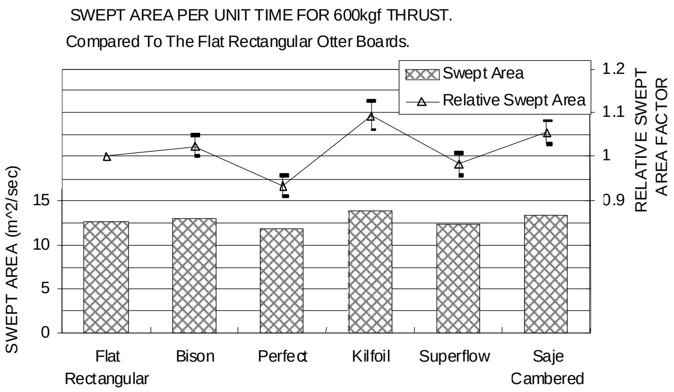


Figure 6. Performance comparison of Australian contemporary otter boards [4].

Some of the modern otter boards used in Australia have plate camber, and slots with shape and position that do produce some improvement in efficiency at high angle of attack [6]. The proposition put here is that further extensive gains can be obtained if the operating angle of attack can also be reduced.

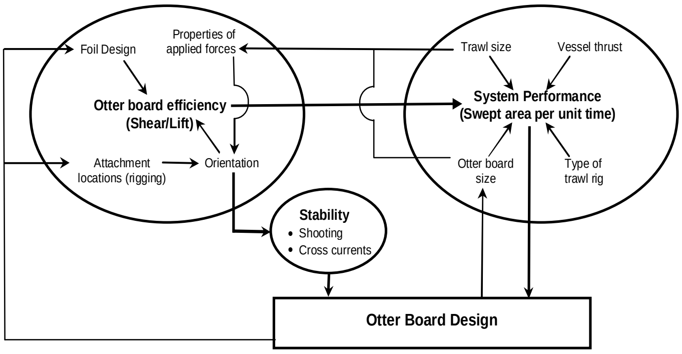


Figure 7. Otter board design and efficiency framework

It is therefore feasible that otter boards can be developed that have 65% less drag than current designs [4]. This improvement is possible because the efficiency of contemporary otter boards for prawn trawling is low (shear to drag ratio less than 1.5), mainly because the operating angle of attack is quite high. Achieving an otter board with a shear to drag ratio of 3 is not in itself an unrealistic expectation since that is still modest when compared to the efficiency of other common fluid-dynamic devices (eg. kites, sails, propellers, aircraft wings). All that is required is devise a way of operating prawn trawling otter boards at a lower angle of attack.

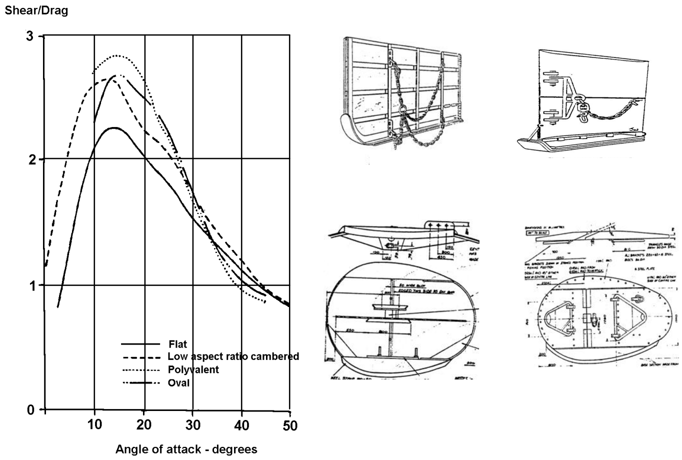


Figure 8. Hydrodynamic efficiency of various low aspect ratio otter boards (adapted from FAO [7]).

The difficulty with this new objective for prawn trawling otter boards arises because of the simultaneous need for good shooting away stability and highly spread trawl operation makes it very difficult to set these otter boards at a low and efficient angle of attack. Figure 7 shows that this comes about because of the interaction between the various factors that affect otter board design, and the factors and pathways that influence swept area performance. The most important feature of the figure is that it shows that a factor affecting swept area performance (otter board size) also feeds back to affect otter board efficiency.

This in essence pin-points the difficulty involved with making significant improvements in prawn trawling performance through otter board design; the dual influences that otter board size has on performance are not compatible. That is, large otter boards produce greater swept area by increasing the span of the gear [4], however, a large span inherently causes the angle of attack of the otter boards to be high when on the seabed, which in turn increases otter board drag. This can be rectified by adjusting the rigging of the otter board to achieve a lower angle of attack while fishing. But this in turn causes the angle of attack while the gear is being shot away to become very low, since the lateral opening of the trawl at this time is low. A low angle of attack during shooting of the gear causes otter board instability. Flume tank trials proved that otter boards that were adjusted to produce an efficient angle of attack on the seabed were impossible to shoot away [8]. To solve this problem a paradigm shift is required in the way prawn trawling otter boards are rigged and the mechanism used to maintain stability. A clearer understanding of the instability problems and being able to model them, means that acceptable otter board designs can be achieved with minimal compromise and substantial increases in swept area performance for the trawl-system.

VI. BATWING OTTER BOARDS

Traditional prawn trawling otter boards have a low aspect ratio (are long and low) and are operated at an angle of attack sufficiently high to ensure they remain stable during all phases of the fishing operation.

An additional issue with using these otter board designs at high angles of attack is the size of the lateral 'footprint' on the seabed. Otter boards scrape the seabed due to a plowing process along its heavy steel shoe (Figure 9), damaging benthic animals and directing some of them into the trawl. At typical angles of attack, the 'footprint' of these otter boards equate to 60% of the otter board's length.

Figure 9. Flat rectangular otter board.

In 2005 a prototype prawn trawling otter board called the "CP1 Batwing" (Figure 10) was constructed and field tested [9]. The innovative features of this otter board were based on recognizing that the difficulties in achieving high fuel efficiency and good stability with contemporary otter boards are due to the longitudinal separation of the towing (bridle) connection point and the trawl attachment points. This conventional arrangement makes it difficult to rig otter boards for operation at low angles of attack. By bringing these connection points to a common longitudinal position, the orientation of the otter board is no longer affected by operational changes in the trawling system; for example, whether the system is essentially closed during the shooting away process or at maximum opening on the seabed during the fishing process. This rigging change produces an otter board that functions in the same way as a tail-less kite on a single string.

Incorporated in the Batwing design, the main ground contact shoe is aligned with the direction of tow and is hinged to the hydrodynamic wing at its trailing edge. This feature is principally designed to put the centre of gravity of the otter board under the towing point, such that the otter board maintains its operational orientation whilst at the trawl blocks and being lowered into the water during the shooting-away process. Another advantage of the inline shoe is that it minimizes plowing forces acting on the otter board, which although known to generate a spreading force, also generate an excessive amount of drag and reduces otter board efficiency.

Figure 10. The CPI batwing otter board

The engineering performance of the Batwing otter board was evaluated over 18 30-minute tows of a chartered prawn trawler. Compared to a traditional flat rectangular otter board, the CP1 Batwing otter board produced 5.5% (4.6% - 6.1% $P<0.05$) higher spread of the trawl net, with an overall reduction in drag of 13% (11.9% - 13.6% $P<0.05$). This means that the new otter boards produced a higher spreading force whilst generating less drag, and are therefore substantially more fuel-efficient. An estimation of otter board efficiency suggests that the shear to drag ratio for the CP1 batwing otter boards was about 2. That is, for the same spreading force, the CP1 otter boards produce 50% less drag than the flat rectangular otter board.

In a second charter, the influence of the Batwing otter board on catches of prawns and other species was assessed from 64 30-minute tows. The trawl connected to the CP1 Batwing otter boards had a 90% decrease in the catch of sessile benthic animals compared to the net spread by flat rectangular otter boards, because of low seabed disturbance of the inline Batwing board shoe. The Batwing otter board was also associated with an average 10% reduction in the prawn and scallop catch. It is hypothesized that these reductions were due to reduced herding of these species into the path of the trawl by the new otter boards because they have a much smaller lateral projection. Given that this explanation is true, the catch difference should be diminished for most commercial circumstances where higher order multi-net trawl systems are used, because the lateral span of the otter boards are a smaller proportion of the total span of the entire trawl-system.

The latest and most refined version of the Batwing otter board (Figure 11) incorporates a flexible sail for lower drag without loss of spreading force (shear), and to more optimally position the centre of gravity for improved shooting away stability [10]. Another advantage of the sail is that construction costs can be substantially reduced to produce a more cost competitive otter board design. This otter board is currently the subject of an implementation project in Queensland, and is expected to produce a fuel reduction of 20-25%. Steps to commercialize this product are also currently underway.

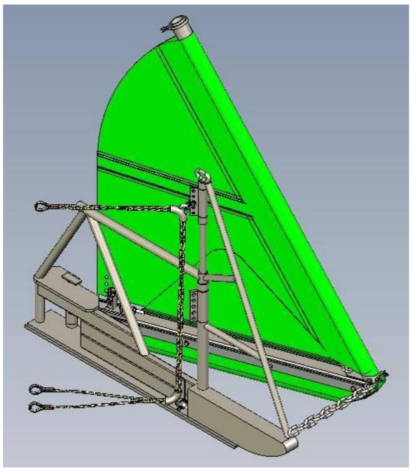


Figure 11. The CP2 batwing otter board.

VII. INNOVATION IN TRAWL DESIGN

1) *High strength netting*

A logical initiative for improving energy efficiency is to develop trawl designs that use high strength netting constructed from finer diameter twine. A major impediment to this initiative is the substantially higher cost of high strength netting, which can be up to a factor of 8. In the long run though, given that twine diameter can be reduced by 30% with no reduction in twine strength, trawl-system drag and fuel consumption should reduce by a similar percentage and provide a short pay-back period.

R&D to implement Ultra High Molecular Weight Polyethylene (UHMWPE, Spectra and Dyneema) netting into trawls has been occurring around the world for over a decade ([11], [12]). In Australia, some fishermen experimented early on with these materials but with little success. Fishermen reported poor shooting away performance by the otter boards, high bycatch meshing rates, and general dissatisfaction with the softness and entangling nature of these materials. Lowe [13] compared the performance of prawn trawls constructed from 1.0 mm diameter, twisted, Spectra netting to 1.79 mm diameter, 30 ply, polyethylene netting, given that they were deemed to have similar strength. In a flume tank, the Spectra netting reduced the drag of a model trawl (no otter boards were used) by about 42%; similar to the measured 45% reduction in twine diameter. However, there was no significant difference in drag between full-scale Spectra and polyethylene trawl-systems (using flat rectangular otter boards) at sea. The spread ratio of the Spectra net was 86%; 14.5% higher than that for the polyethylene trawl. At this very high spread ratio it appears the associated increase in otter board angle of attack and drag, counteracted the drag saving from the Spectra netting.

Over the last 2 years there has been increased adoption of a range of reduced diameter materials by the Australian prawn trawling industry. Success is now being experienced by quite a few fishermen. Outstanding R&D challenges are to document the important knowledge that has been accumulated by fishermen and others with experience using these materials, conduct field trials with optimal gear to establish the maximum benefit for the industry, and to perfect the procedures required for successful implementation of high strength netting into prawn trawling.

To meet this challenge a project entitled, “The methodical introduction of high strength netting to the prawn trawling industry in Queensland”, was created. The work program has the following four components:

1. Measure the relative strength of various netting materials suitable for prawn trawling
2. Assess the relative wear resistance of various netting material types
3. Conduct a detailed drag and flow study for various materials and trawl construction techniques, using the flume tank
4. Conduct sea trials to measure the benefits of optimally using high-strength materials in prawn trawls, and also document the pitfalls.

The principle initiative of the project is to use the PTPM to ensure optimal matching of otter boards to the low drag trawls. This will control the most commonly reported problem with adopting high strength netting; shooting away difficulties and little drag benefit, presumably caused by badly matched otter boards.

The project has currently reached stage 3, with flume tank tests currently being devised to measure the relative drag characteristics of the selected materials and explore various issues/claims promoted by the netting suppliers. Table 1 shows the materials selected for the evaluation and the results of measuring their principle dimensions.

TABLE 1. DESCRIPTION AND SPECIFICATION OF THE NETTING TYPES TESTED

Retail name	**Construction (Labelled description)**	**Measured twine diameter (mm)**	**Measured centre of knot stretched mesh size longitudinal X lateral (mm)**	**Measured knot size longitudinal X lateral (mm)**
C.F.S. 24 ply Polyethylene	400 denier twisted 24 ply single knot	1.68	52.1 X 49.71	5.24 X 4.32
Van Beelen Spectra	1.0 mm twisted single knot	1.00	53.7 X 51.95	3.5 X 3.1
Hampidjan Dynex	1.0 mm braided double knotted	1.26	50.25 X 42.05	6.8 X 3.3
Ultracross Dyneema	1.1 mm braided knotless	1.28	51 X 51	1.9 X 1.9
Euroline Premium Plus	1.0 mm braided single knot	1.38	52.06 X 49.51	5.12 X 4.12

Table 2 shows the results from Sterling [14] for stage 1 of the project. The tensile strengths of the five selected material types were determined for standard-mesh orientation, T90, and square-mesh orientation. Despite the reduced twine diameter of the high performance materials, they all had similar or greater strength than the traditional polyethylene netting for the diamond-mesh samples (Standard-mesh and T90). For the Spectra and Euroline materials the strength was about the same as polyethylene, but the mesh strength of the two Dyneema materials (Dynex and Ultracross) were about 3 times higher.

TABLE 2. MEDIAN FAILURE LOAD AND EXTENSION FOR THE DIFFERENT NETTING TYPES. THE RESULTS FOR THE HIGH PERFORMANCE MATERIALS ARE ALSO EXPRESSED AS A PERCENTAGE OF THE RESPECTIVE 24 PLY POLYETHYLENE RESULT

Netting Type	**Standard-mesh**	**Standard-mesh**	**T90**	**T90**	**Square-mesh**	**Square-mesh**
Commercial brand	**Failure Load (kN)**	**Extension at Failure (mm)**	**Failure Load (kN)**	**Extension at Failure (mm)**	**Failure Load (kN)**	**Extension at failure (mm)**
C.F.S. Polyethylene 400den 24ply	1.12	113	1.18	135	0.155	29
Van Beelen Spectra 1.0 mm	1.34 (120%)	32 (28%)	1.58 (134%)	45 (33%)	0.14 (90%)	11 (38%)
Hampidjan Dynex 1.0 mm	3.39 (303%)	35 (31%)	3.13 (265%)	51 (38%)	0.45 (290%)	20 (69%)
Ultracross Dyneema 1.1 mm	3.70 (330%)	32 (28%)	3.55 (301%)	32 (24%)	1.47 (948%)	26 (90%)
Euroline Premium Plus 1.0 mm	1.00 (89%)	63 (56%)	1.31 (111%)	86 (64%)	0.15 (97%)	15 (52%)

For the three single knot materials, T90 samples were 5% - 30% stronger than the respective standard-mesh samples. For the double-knotted Dynex and knotless Ultracross Dyneema the strength of T90 samples was the same as the respective standard-mesh samples.

Knot construction had a substantial effect on the strength of the square-mesh samples. The single-knot materials (Polyethylene, Euroline and Spectra) all had similar loading when the knots started to slip and substantial distortion of the meshes started to occur. The double-knotted material (Dynex) was substantially stronger and had a load at knot slippage that was about 3 times higher, while the failure load for Ultracross was 10 times higher than the single-knot cases. For the square-mesh Ultracross there was no distortion of the mesh what-so-ever and the ultimate failure was breakage at the gripping points of the tension machine.

Figure 12 shows the specially developed equipment and methodology used for stage 2 of the project. The relative wear resistances of the materials were determined by simultaneously subjecting a panel of each material to an equal 40 minute abrasion treatment.

For the Euroline material (premplus), two panels were subjected to the wear treatment - one panel had the “rough side in” (rsi) and the other had the “rough side out” (rso). The rough character of the premium plus material relates to the raised feature of the knots, which uniquely is always on the same side of the netting panel, therefore making one side of the panel feel rough and the other feel smooth. It is proposed by netting suppliers that the smooth side is less vulnerable to wear, causes less damage to the catch, and is associated with less netting drag if the smooth side of the netting is on the inside of the trawl. All these assertions were tested by the research project.

Figure 12. Application of wear treatment simultaneously to six netting panels. Top left - view of wear application wheel holding 6 net samples inside an empty grit slurry container. Right - milling machine used to rotate the wear application wheel. Bottom left - view of grit slurry container during the wear application process.

The results from Sterling [15] are shown in Figure 13. The wear treatment produced an average strength reduction across the materials of about 60% (40% residual-strength), although the Van Beelen Spectra material, was effectively destroyed by the treatment and had zero residual strength. The Spectra material was supplied in the late 90’s for the work by Lowe [13] and has been replaced by a superior product.

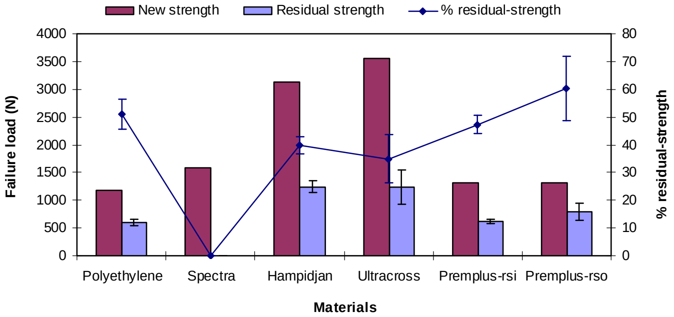


Figure 13. Wear resistance results for prawn trawling netting. Confidence intervals are P<0.1 based on 3 samples taken from a single worn netting panel.

There was little significant difference in % residual-strength for the five cases other than Spectra. Euroline Premium Plus appeared to have the greatest % residual-strength, and was significantly better than Ultracross Dyneema (P<0.1). None of the materials, apart from the Spectra appeared to be significantly different (P<0.1) from traditional polyethylene in terms of % residual-strength. There is some indication in the results that the Euroline material might have better wear resistance if the rough side of the material is opposite to the side experiencing the more intense wear treatment. But the result was not significant at P<0.1. There is also a suggestion, which cannot be proved by the current results, that the Ultracross material has a lower wear resistance than standard knotted Polyethylene. Despite the observed lower % residual-strength of the worn Ultracross material compared to worn polyethylene, it was still as strong as new polyethylene, in absolute terms, because of the very high initial strength of the Dyneema products.

2) Pleated-panel trawl

Another possibility for improving the engineering performance of prawn-trawls is introducing design changes that make the trawl easier to spread by the otter boards for a given drag. European gear technologists stated a similar proposition in the early 90's in relation to designing fish-trawls that obtained greater headline height for a given amount of headline floatation [16]. This was a secondary effect associated with their objective to control the opening of meshes in the side sections of the trawl to improve size selectivity of the catch. The European work resulted in the development of a "Y-Design" fish-trawl, while at the same time a "pleated-panel" prawn-trawl was developed at the Australian Maritime College [17]. Both trawls are constructed with square-meshes in the side sections of the trawl body and wings, by adding a novel seam down the trawl's centre-line (Figure 14). It is proposed that in this design, codend and netting drag forces are transferred more directly along the bars of the square-meshes towards the wingends and towing points.

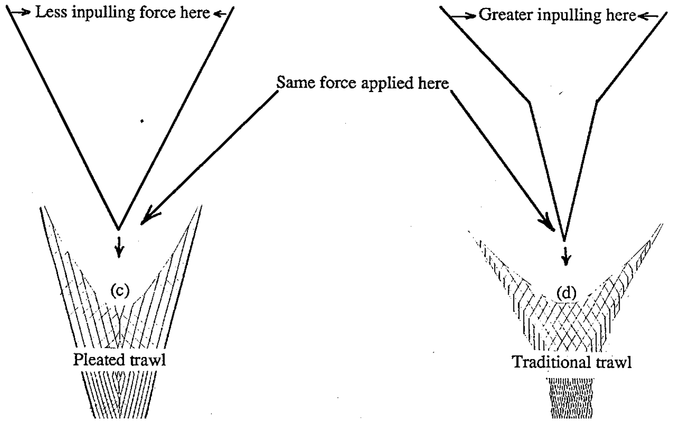


Figure 14. Principle of the pleated-panel trawl, giving rise to a trawl net that is easy to spread (Wray, 1990).

The results of the flume tank tests showed that the pleated-panel trawl was 20% - 40% easier to spread over the range of spread ratios between 75% and 90% (Figure 15). However, this trawl itself had 20% - 30% more drag than a traditional trawl over the same spread ratios, despite having about 10% less twine area. The extraordinary drag result for the pleated-panel trawl has not been conclusively explained, but must be linked to the unique shape of the trawl in operation and the exposure of square-meshes in the sides and wings of the trawl to water flow. The latter produces exposed bars of netting perpendicular to the flow.

The overall effect of greater trawl drag on one hand and less otter board drag on the other hand, due to the trawl being easier to spread, is shown by the estimated swept area rate of the single net system given in Figure 15. This was calculated by Ripon [17] using the PTPM ver.1. There is theoretically a small benefit in using the pleated–panel trawl over the traditional Florida Flyer, but only if the spread ratio is greater than 80%. No full-scale tests in the field have been conducted to test the selectivity or economic performance of the pleated-panel trawl.

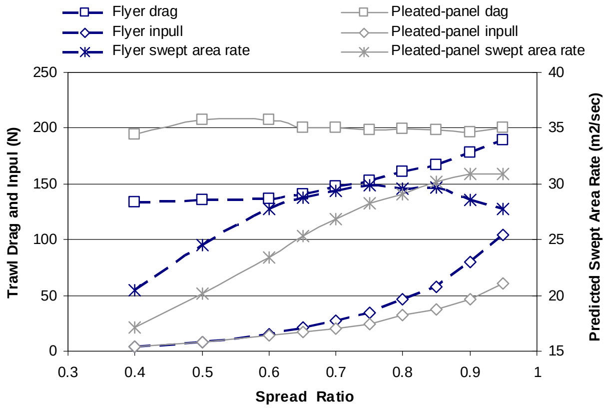


Figure 15 Comparison of various performance parameters for the Pleated-panel trawl compared to the commonly used Florida Flyer trawl.

3) Double-tongue square-mesh trawl

The double-tongue square-mesh trawl is of interest to the authors as it presents an advance on the objectives and outcomes of the pleated-panel trawl experiment (Figure 16). Using a different mechanism than the pleated-panel trawl, the objective is to have another trawl that is also easy to spread, but not be subject to the problem of high-drag side sections with exposed bars perpendicular to the water flow.

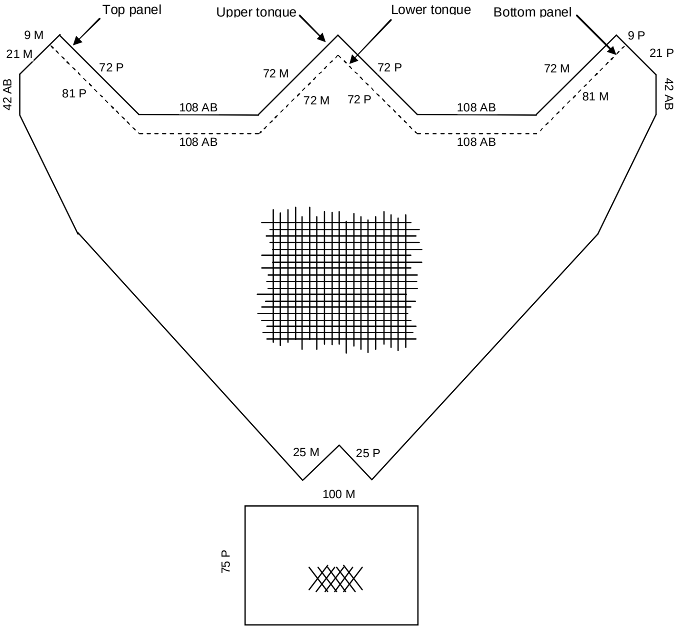


Figure 16. Novel double-tongue square-mesh trawl aiming to produce high energy efficiency and selectivity.

The double-tongue trawl has square-mesh orientation in the upper and lower panels, where the bars perpendicular to the flow are not exposed to that flow; a tongue in both the top and bottom panels; and a taper configuration in the headine and footline that is not dissimilar to a commonly used Australian trawl design, the Siebenhauser trawl. The design concept is that a considerable portion of netting drag is transferred directly along longitudinal bars to a central towing wire via a trawl sled connected to the tongues, rather than the netting drag being transferred to the otter boards through the wings of the trawl. This reduces in-pull forces acting on the otter boards and should reduce the required otter board size to spread open the trawl.

Unlike the pleated-panel trawl, the netting in the side section of the double-tongue trawl becomes diamond-oriented as the square-mesh in the top and bottom panels folds around the sides of the elliptical-cone shaped body of the trawl. The side sections then may not have high drag when exposed to the flow, because the region contains no bars at right angles to the flow. In this way the problems experienced with the pleated-panel trawl may be overcome. The potential benefits of this trawl include:

- Easy spreading
- Low drag
- Good size selectivity

VIII. CONCLUSION

The introduction of new fishing technology to improve the efficiency and performance of prawn trawling in Australia has traditionally been based largely on a trial and error approach. Over time, such an approach can achieve a high standard result, and indeed, prawn trawling systems in Australia are now highly sophisticated, containing modern, high-performance materials and also components that develop large useful forces from complex hydrodynamic phenomenon and provide stable operation in a very dynamic environment. But, trial and error without a deep understanding of the equipment and the problem can ultimately only go so far, and can become a very inefficient way to utilize time and resources to achieve further improvements. Locked up in contemporary prawn trawling systems are inefficiencies that need to be unpacked and solved with a clear understanding of the problem and a good design process. Moreover, the efficient adoption of trawl-gear innovation requires upfront complimentary adjustments of the trawling system to avoid serious negative side effects.

This paper shows how knowledge captured by a Prawn Trawling Performance Model (PTPM) can be employed to significantly and efficiently further advance the energy efficiency of Australian prawn trawling systems. Using a systematic design process, multi-net trawl systems can be successfully advanced to higher trawl numbers; five-rig for example, was introduced and increased energy efficiency by 10%. Correct size-matching of otter boards and trawls in a trawl-system is essential for maximum efficiency, and can increase efficiency by 10%, while improved otter board designs based on fixing entrenched imperfections can increase system efficiency by up to 25%. Optimum adoption of high strength netting can improve efficiency by about 30%, while, innovative trawl designs, such as the double-tongue trawl, can play a substantial role in the quest to further improve the energy efficiency of prawn trawling systems.

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