independently because of a multisensory perception field around the vessel. The ReVolt will also utilize port charts so as not to get caught in sandbanks. Each of these technologies is already available. We are also looking into shore side control centres.

- **How long does it take to charge the battery?**

We found the average port stay for the route studied was 4 hours. ReVolt is designed to be fully charged for departure within this time. The battery has a lifespan of approximately 15 years.

- **How large is the model that is being tested?**

ReVolt – original size: length 60, 23 metres; breadth: 14, 5 metres
Model (1:20): Length: ca. 3 m
Breadth: c.a. 72, 5 cm

- **Could ReVolt technology be used on larger ships?**

Over the medium term we expect many of the technologies used in ReVolt to become more widespread in general shipping. Battery technologies have already been deployed, for example in the vessel *Viking Lady* – a project in which DNV GL was involved. And as battery prices decrease and they batteries become more efficient, we expect their uptake to increase. Some of the parts of the autonomous systems have potential to help crews operate their vessels more safely, for example an automatic system that would watch for potential hazards, check to ensure the crew takes appropriate action and, as a failsafe, initiates course correction.

- **How did you develop the concept?**

We used specialized computer software to design the ship and build a 1:20 model. The ship's parameters were developed using AIS-Data. CFD calculations (Computational Fluid Dynamics) determined the optimal hull form for the route and operational profile suggested by the AIS-Data. We also assessed the hull material, as well as the propeller design, using CFD.

- **If ReVolt travels without captain or crew, how is it quantified legally? Could it be entered by anyone?**

When we developed ReVolt, we concentrated on the technical feasibility of the project. Before unmanned ships come into use, governments would need to develop a legal framework for them. This does not exist yet. We believe that autonomous vessels first would be introduced in territorial waters, where country-specific rules apply.

- **What are the next steps for the project?**

ReVolt has already been built in the form of a 1:20 scale model. We are currently testing its capabilities in open water in Norway. The next step is to test the autonomous capabilities of the demonstrator.

- **Where was ReVolt developed? Were some of the components developed in Hamburg?**

ReVolt was developed by the DNV GL Strategic Research & Innovation team in Norway, where it is currently being tested. The technology used in the ship's design – such as LIDAR, ECDIS and radar – is already commercially available. We combined existing technology to see what is possible and how far we could go with respect to energy efficiency, emissions and safety and still maintain cost effectiveness. We hope that ReVolt can serve as inspiration for ship owners and yards in their efforts to develop new solutions for a safe and sustainable future. DNV GL experts in Germany are also examining concepts and systems for autonomous shipping.

- **Has anybody already shown a serious interest in ReVolt?**

Companies and governmental bodies have inquired about the autonomous operation of the ReVolt. We see maritime batteries as an emerging technology; several installations are in the pipeline. These installations are mainly focused on short ferry connections and for shipping segments with a varying operational profile, for example the OSV (Offshore Support Vessel) segment. With ReVolt we introduced this technology to the coastal traffic segment for the first time.

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Piloting at the 'edge-of-chaos'

Peter McArthur

Background

Many years of research devoted to trying to understand the underlying mechanics of marine hydrodynamics have been rewarded with the publication of a number of papers that attempt to explain both the resultant theoretical principles and their practical application in a simplistic, easily assimilable, manner. Subsequently, my research has benefited from formal recognition and acceptance by the Royal Institute of Naval Architects (RINA) and accreditation by the global hydrodynamic community. Consequently, I am now regularly called upon to investigate 'unusual' occurrences and, where appropriate, give an opinion as to causation. Very occasionally, appointments will prompt questions that require deeper explanations in the field of hydrodynamics, and this article addresses one such event.

For the most part, the maritime community, including pilots, masters and ship-handlers, view water as simply 'water' - a stable, incompressible, immutable and generally predictable medium against which we practise our craft. The truth, however, could not be further from this simplistic perception - as explained by research physicists Anders Nilsson (Stanford University, California) and Lars Pettersson (Stockholm University) in their seminal article 'Water, the strangest liquid' (*New Scientist*, 6 February 2010) and as practically applied to the marine environment in 'Peculiar water, Strange effects' (McArthur, 2011).

During 2010, I was invited by a Harbour Authority to look into a number of intermittent, apparently unpredictable, and irregularly recurring, phenomena relating to very large container ships. For no apparent reason, when under full control of an experienced and competent pilot, these ships would suddenly, and inexplicably, experience a violent and increasing 'sheer' which required all of the pilot skills and the application of all assets at his disposal to effect recovery. Not being a single, isolated, phenomenon, and with no obvious cause, there was naturally some concern as to why this happened.

Upon conclusion of the research, during the report debrief, two fundamental questions were asked: Can you explain what happened? Is there a rule that we can apply in all situations to predict when such an event might re-occur?'

The answer to the first question was a simple 'yes' - although the reasons were complex.

Answering the second question required a little more consideration. First, there is the simple commercial response - "if the event is predictable in all circumstances, then there would be no need for experienced professional pilots" - their job would, very soon, fall to computers which, in the long run, cost significantly less than a professional pilot service. Such a prospect was envisioned over twenty years ago by Dr Odd Falstinen, Norwegian mathematician and theoretical hydrodynamicist.

The second, and fuller, answer is - depending on your perspective - far more interesting, significantly more complex, and requires knowledge not only of ship-handling, bridge management systems and some hydrodynamic understanding, but also an appreciation for *systems complexity* and the mathematical principals that underlie *chaos theory*.

Once understood, it becomes clear that the full answer has implications in many areas that apply to Pilots, Ship Masters and general ship-handlers. Some of these areas include, but are not limited to: law and ship-handler criminalisation; practical management processes; ship-handling training; ongoing professional development; objective competence perceptions; and the need to retain a professional pilot service.

To begin to understand the second answer, one need only accept that water is anything but 'simple'. It does, in fact, exhibit a dual structure (tetrahedral and confused) so that it can exist (and co-exist) in both gelatinous and traditional Newtonian states (see Nilsson and Pettersson, 2010). Water tends to become highly chaotic once disturbed, but can eventually organise to exhibit the complex attributes of natural organic systems.

Complexity theory and principles

Much has been written about 'complexity', and many of the theoretical ideas have been successfully applied in the world of commerce. Complexity theory is particularly useful in describing the increasing confusion surrounding international business markets. No one cause can be attributed to complexity - but in the business world there are three underlying 'drivers': improving communications describing the interconnectedness of all things; increasing internationalisation and the multiple 'problems' this creates; and the increasing dynamic resulting from the range of 'options and choices' available to consumers.

Whilst the application to 'problematic' ship actions may not be immediately apparent, complexity principles are increasingly applied in understanding how order can derive from turbulent, unpredictable and confusing environments (Mason, 2009).

The underlying idea of complexity is that, from absolute confusion, all things tend to self-organise into systems when simple rules are applied (Kelly and Allinson, 1995). These systems can produce unexpected patterns, behaviours or consequences (Goldberg and Markoczy, 1996) and, because of non-linear feedback systems (Stacey, 1996), the interconnection and interdependent system parts (Bar-Yam, 2000) tend to interact with, and adapt to, each other (Meade and Rabelo, 2004).

Complex behaviour is orderly, yet full of surprises, apparently uncontrollable, but not totally chaotic. The rules that generate complex behaviour cannot be managerially enforced and equally cannot be predicted from any one part of the system. One of the most visible and often cited examples of unpredictable complex behaviour is that of huge flocks of starlings creating incredible but beautiful patterns in the evening sky. It only takes one to change position, even slightly, and the rest will follow momentarily in an ever changing aerial display that is absolutely mesmerising.

Nilsson and Pettersson (2010) show that, because of its duality, water is chaotic in essence, but tends towards a self-organised functionality - as suggested by complexity theory. The evidence lies in the fact that mariners are able to identify discernible patterns, pressure features and physical responses when a ship is under the influence of moving water, or when moving through water where, to a greater or lesser extent, the hydrodynamic effects described as 'interaction' might be anticipated.

A second important concept of complexity theory happens when the system parameters change, that is, when a defining or limiting factor alters sufficiently. According to chaos theory, that change need only be very small, and thereafter a 'feedback' occurs in one of two ways:

- **Negative feedback** occurs when the system moves away from equilibrium and a 'corrective' action occurs to return the system to stability. A good example is the domestic central heating system which, once the controlling temperature is exceeded, will act

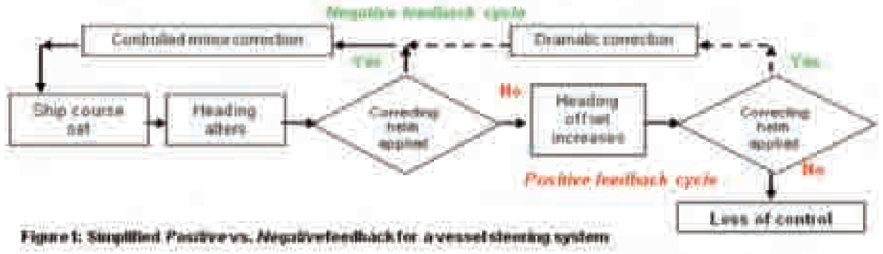

Figure 1: Simplified Positive vs. Negative feedback for a vessel steering system

to re-establish the desired set-value. In the marine environment, there is no better example than that of a ship's helmsman continually adjusting the helm to maintain a desired course.

- **Positive feedback** is exemplified in the 'butterfly effect' (Lorenz, 1963). In short, the butterfly 'flaps its wings' somewhere off the African coast, and sets up a tiny disturbance. There is nothing to moderate that disturbance (no negative feedback) and so it becomes a self-generating system and develops unhindered - achieving the intensity of a hurricane by time it reaches the Gulf of Mexico. This may be an extreme (unproven) example, but it demonstrates the principle.

Chaos Theory

Chaos theory derives from mathematical principles. The equations are fairly straight forward, but their consequences can be quite literally world changing.

Positive feedback tends to be a feature of chaos theory so that, in the real world, once a system turns 'chaotic' the effect grows, perhaps slowly at first, so that it is barely noticeable. Positive feedback, by its very nature, amplifies small changes (McGlone and Ramsey, 1998), pushing the system towards chaos (Doherty and Delener, 2001). It is also a feature of chaos theory that once one system component changes, becoming subject to positive feedback, that system will impact upon others, so that increasingly more areas of the system become confused (see Figure 1: Positive feedback cycle).

Eventually, the whole system will 'break-down', so that a simple correcting measure will no longer be sufficient to re-establish equilibrium.

Initial conditions

There is one final element of complexity and chaos that needs to be grasped, that of sensitivity dependence (Briggs and Peat, 1999). In a stable system, small changes have small effects and will generally be compensated for through the process of negative feedback; but in a complex system, and in line with chaos theory, small changes can grow exponentially, making short term accurate prediction almost impossible (Doherty and Delener, 2001; Holbrook, 2003), and consequently small 'nudges' at the appropriate time can lead to major effects (Wheatley, 1996).

For the knowledgeable practitioner, discernible patterns and clues will indicate which changes to 'nudge' (Morrisson and Quella, 1999) and experience will tell then when to 'nudge' in order achieve the desired effect (Gladwell, 2000). These patterns - known as 'attractors' – have maritime application and relate to what pilots often describe as 'gut instinct' - supported by empirical knowledge gained over many years, plus the handed-down accumulated anecdotes that underlie hard personal experience born out of trial and error. In reality, these 'attractors' cannot claim to derive from formalised, institution bound, tuition.

Practical implications for Pilots and Ship-handlers

Having touched on the theory and concepts of complexity and chaos, the question arises "of what use is this to ship-handling and pilotage?" The answer is 'quite a lot'.

There is a place where complexity, chaos, system interaction and practical experience meet – both in the world of commerce and in the maritime industry - a realm where little is quite what it seems, and all manner of strange things can and quite often do happen.

Chaffney and Smith (2002) refer to this place as the 'edge of chaos' – where conflicting systems are in balance, where knowledge of positive feedback and the judicious application of negative feedback work in harmony to achieve a temporary equilibrium and where, unfortunately, any undue distraction or overwhelming of the principal actor can result in the rapid onset of chaos, deterioration and disaster.

The 'attractor' at the 'edge-of-chaos' has the rather curious title of 'strange attractor' and is the gift of years, trial and error, knowledge, practice and experience. Lewin (1992) describes this place as 'reflecting the area where maximum creativity and innovation happens'.

In the maritime context, I am referring to the act of pilotage. But why should it be so that Holbrook (2003) is able to state that the 'strange attractor' confines within certain boundaries yet, according to Doherty and Delener (2001) such complex chaotic systems cannot be predicted but can, nevertheless, allow change whilst maintaining some order (Frederick, 1998).

Edge of chaos applications and acts-of-pilotage

To understand why the act-of-pilotage can be such a chaotic place to operate, we need only consider the factors pressing on the attention of the pilot. Bridge resource management courses, whilst touching on many of these factors, to a greater or lesser degree, tend to look at individual areas of concern and not the whole picture.

Figure 2 is by no means complete and can justifiably be criticised for being little more than a two dimensional representation of a four dimensional construct (5 or 6 dimensions if you prefer to include human and maritime factors as separate spheres, but this is a matter of choice and makes the point about complexity). Many of the elements, naturally, involve numerous sub-elements.

Taking this as nothing more than the simplest construct, the mathematics is quite simple. There are no less that 45 (or 1024) factors that the average pilot is attempting to balance whilst he is working. Complexity theory says that interaction between factors will always be imperfect and are little better than barely balanced at any instant. Chaos theory suggests when any one factor goes 'wrong' and positive feedback results, others may follow in quick succession, and the situation deteriorates exponentially. It only takes 'one thing in a thousand' to start the downward spiral into chaos - or disaster.

Is it any wonder then that when something goes wrong during an act of pilotage, it happens quickly, without warning and rarely, if ever, can be attributed to a single event? Coincidentally, it may be of some interest that the factors of 'chaos' and 'complexity' and their interaction in confined waterways go a long way to explaining why 'squat' rarely, if ever, perfectly corresponds to calculations or why new-build ships undergoing sea-trials so often fail to perform as predicted by computer modelling and simulations. The reasons for this will become clear shortly.

The more astute reader will realise that the odds are weighted against the pilot who encounters problems 'at the edge of chaos'.

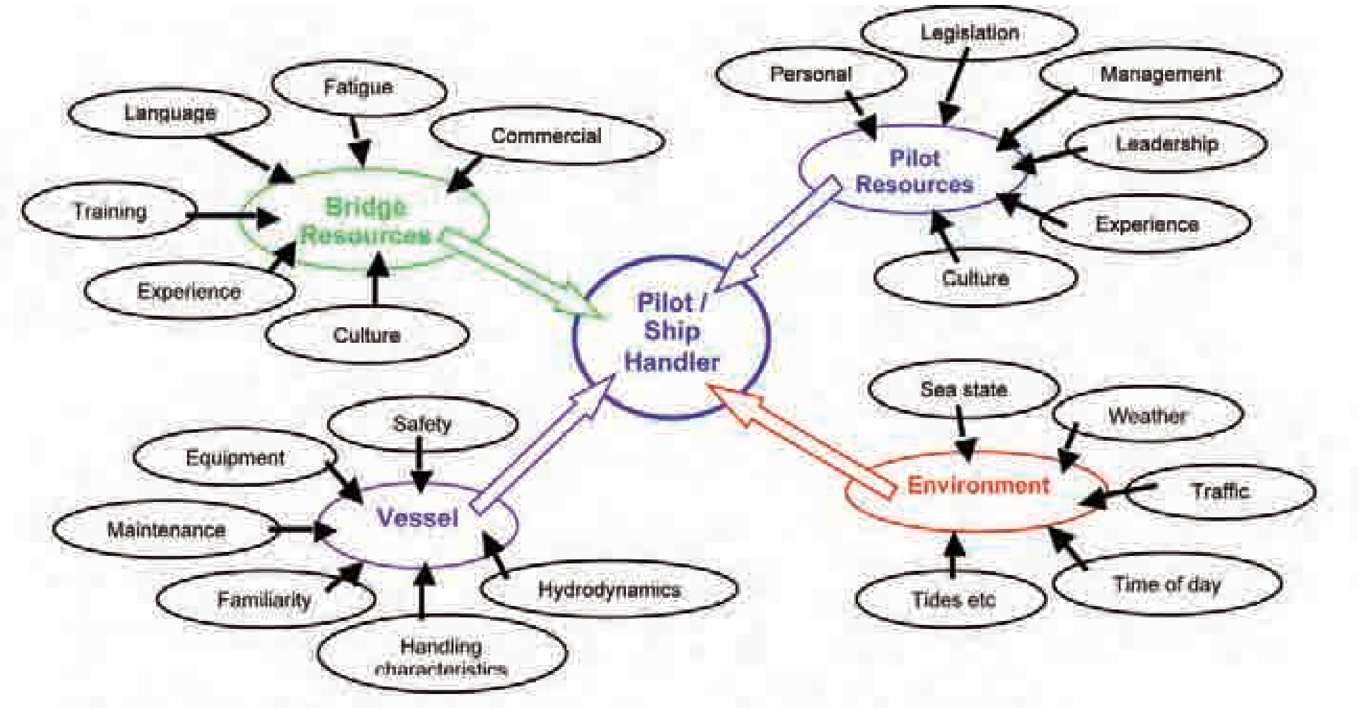

Figure2: Some of the concerns pressing on the pilot operating 'at the edge of chaos'

Furthermore, not all pilots are emotionally, mentally or psychologically suited to operating in this environment. There are, however, factors that can mitigate the risks and pressures:

- **Management Support**

Management support and understanding, rather than criticism, condemnation and a 'blame culture' are an essential component in building confidence to carry out the task. Where the pilot is certain of condemnation or (possible) criminalisation, any willingness to try things out, to push the 'envelope of chaos' and test the bounds of possibility decreases dramatically. Yet pilots are still subject to commercial pressures that require them to work quickly, in all weathers, with a variety of nationalities and cultures and to make sense of it all.

Oliver Williamson (1999) argues for pre-emptive positive mechanisms to support those who work in complex systems by adopting a contingent approach and developing a range of coping strategies. This process begins by carrying out a frank organisational analysis, determining where there are systematic weaknesses – including management attitudes and 'poor leadership' - dealing with them honestly and sympathetically, then developing a robust, integrated and supportive structure that allows pilots to operate with confidence.

Management 'groupthink', an 'us and them' attitude, 'blame culture' and a 'closed mind policy' - when combined with situational complexity – can only exacerbate the likelihood of incidents in such an environment.

- **Legal**

As a lawyer I have particular issues with the way that pilots and ships' masters are increasingly criminalised on an isolated error or a single point of law. Few today, legal or otherwise, can honestly claim to have met a master or pilot who knowingly, deliberately, recklessly or with malice aforethought, endangered their ship or the personnel aboard. In my experience, those who have been involved in incidents, most of which were not explainable – although many could quite easily be attributable to the effects of complexity and chaos - have suffered absolute agonies in trying to understand what happened. The professionalism of such men has always been paramount in their minds, as has the thought that, for reasons unknown, they may have let down their colleagues and profession.

It is easy, after the fact, to dismiss the multitude of conflicting elements that were successfully dealt with, only to alight on a single factor - often only provable after lengthy legal wrangling - then convict a man who did not understand how complexity or chaos played their part in his misfortune. The courts should take appropriate account of the issues by demonstrating some understanding of the principles.

As far back as 1949, the learned Lord Justice Porter commenting on the hydrodynamic related collision between *Queen Mary* and *Curacao*, said that 'the forces of interaction are imperfectly known, but in any situation (at least) some allowance should be made for their coming into play'. Since that statement, ships have become considerably bigger, we understand a lot more about hydrodynamic forces and the effects of interaction, plus we have the added knowledge that chaos and complexity must be considered as part of the causal matrix. Lord Porter's statement, therefore, remains as valid today as it did then.

- **Training**

Having already touched on pilot qualifications, empirical knowledge, experience and the practical implications of 'strange attractors' when working at the 'edge-of-chaos', surely there is some justification in the argument that at this level of expertise the imparting of institutional knowledge offers little value.

In the UK at least there is some recognition of this reality - evidenced by an increasing trend towards pilots training pilots. On the down-side, so long as there is a defensive attitude within pilotage services that 'we don't want others coming in here and teaching us our jobs' there will be industry stasis, with little to be gained from one pilot sharing his experiences (positive and negative) with his fellows. The positive benefits of shared industry knowledge are clearly demonstrable in the world of commerce, and because of the unique attributes and characteristics of each district, pilots should not fear usurpation by their industry contemporaries - some of whom have given many years of their own time to undertake research and promote safety and industry professionalism.

Returning briefly to the mathematical concepts of chaos and complexity and their impact on the marine environment, the more perceptive reader will realise that there is one particular area of training that relies heavily on mathematical constructs: computer simulations and bridge training simulators.

Simulators portray a perfect electronic world constructed from known algorithms that are capable of carrying out unchanging and infinitely repeatable exercises. You should consider, 'does this represent the real world of ship-handling?' Paradoxically, it is the mathematics used to construct the simulated environment that prevents chaos and complexity from being part of the training experience.

Sections 5.2, 5.5 and 5.5.5 of IMO A960(M) on the training of pilots, states that professional training can be 'supplemented' (not replaced) by simulator training - as part of a pilot's continuing professional development (CPD) – but prudently it stops short of suggesting simulator training in relation to hydrodynamic interaction.

Simulators undeniably offer a viable facility - being useful for practising bridge resource management exercises, equipment familiarisation and integration techniques and for enhancing district familiarisation (as stated by IMO A960). Nevertheless, an awareness of their inherent limitations predicates caution if using simulators for practising interaction exercises.

Using the same logic and applying knowledge of algorithmic confinement we learn that where simulators are used to 'reconstruct' an incident - particularly where the results might be applied in evidence to prosecute a ship-handler - utmost caution must be exercised when relying upon a simulated reconstruction. I have actively engaged with some of the world's leading computational fluid dynamicists who generally acknowledge that simulators are not perfect and, no matter how advanced their programming, simulators simply cannot replicate the marine environment with all its chaotic complexity.

Dr Odd Falstinen over twenty years ago pronounced that mathematical algorithms and computational fluid dynamics (CFD) would eventually do away with pilots - suggesting that they would be replaced by computer programmes. Although not a mariner, he is now a respected professor at the Marine Technology Institute in Norway. When addressing the Second International Conference on Hydrodynamic Interaction at Trondheim in May 2011, he made a number of defining statements. Key among these was his conviction that 'computer prediction may be pretty good but it is not, and cannot be, completely satisfactory' and 'there is always likely to be a difference between computer modeling and reality, no matter how good the computers and models are'. Professor Falstinen's argument, like my own, is that simulation takes place in an idealised medium of perfectly performing algorithms. What results is a 'tidy' representation, arising from perfectly performing formulae, portraying a wonderfully predictable world – an electronic utopia. Simulated results will always be perfectly explainable mathematical constructs showing what 'should' happen in a perfectly ordered environment. However, they cannot stand up under the microscope of chaos and systems complexity. Consequently, simulations should never be used to try and convict a ship-handler or pilot.

Prof Odd Falstinen, Keynote speaker, Trondheim (May 2011)

Introducing complexity and chaos into simulator equations does not work. Both (or either) of these factors, operating inside an ideal mathematical world results in uncertainty, confusion, unpredictability and more chaos. Logic fails, the CPU rapidly becomes overwhelmed and the programme ceases to operate.

Conclusion

If chaos and complexity are introduced into a rational system there are no rules that can predict the eventual outcome. Whereas bridge operations and mechanical/electronic systems may be rational and fairly predictable, the same cannot be said of water: where one element tends to chaos and complexity, the whole becomes subject to the same trend. The interacting factors at best balance or, through careful management, are held in temporary equilibrium at 'the edge of chaos'.

Responding to the first question 'can you explain what happened?' my answer was a simple 'yes' - and that was the end of the matter.

To the second question: 'is there a rule that we can apply in all situations to predict when such an event might re-occur'. Hopefully, readers will realise that the answer is complex, involving disparate areas of social science, commercial theory, mathematical principles, hydrodynamic theory, ship dynamics, environmental considerations, local knowledge and personal skill sets. My answer, therefore, has to be a resounding 'No!' But that is not the end of the matter.

Will the effect under investigation re-occur? Possibly. Chaos and complexity theories suggest that it could, but not necessarily arising from the same unique combination of factors.

Perhaps the penultimate word should go to Lord Justice Porter who averred that 'each (hydrodynamic) event can only be explained with reference to those factors prevailing at the material time'.

For as long as the second answer remains unchanged, competent ship-handlers and exceptionally skilled pilots, each having an intimate knowledge of their own district, with all its nuances and idiosyncrasies, will be fundamental to maritime safety. Managers, legal practitioners and well meaning 'educators' who, perhaps unwittingly, undermine that specialist competence, unknowingly enact an immense disservice upon professionals who must, however imperfectly, balance the numerous variables they face.

Yet pilot professionalism prevails and the pilots' unchanging creed remains the maintenance of an unflinching mindset directed towards safety, security, good conduct and the well-being of the world's most congested waterways.

About the Author
Peter McArthur is: an experienced Pilot; a Master Mariner; an experienced Lawyer, expert-witness and advisor to the courts; marine technical consultant; maritime arbitrator; Chartered Marine Technologist.

(A full list of references was submitted with this article, but took too much room to publish. Ed)