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Optimising Ferry Routes*

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Abstract— **In open waters, the skippers of passenger ferries have some leeway to plot a course that balances fuel efficiency, safety, and passenger comfort whilst still maintaining a tight schedule. This paper describes the seeking of an optimal ferry course for a 400t vehicular and passenger ferry. Numerical dynamic optimal control studies based on the vessel's actual operating data, bathymetry and tidal streams showed that depth under keel was important in periods of slack water which fortuitously in this location happens to be adequately approximated by a simple straight line. During times of strong tidal streams, the optimal trajectory improved travel time by about 3.5% compared to the simple hooked curve course.**

I. INTRODUCTION

The city of Auckland in New Zealand, like many coastal cities around the world, prides itself on its maritime heritage and attractive location lying on an isthmus between two large harbours. Consequently marine traffic is intense with international, commuter and recreational vessels plying the narrow waterways. Not unexpectedly there are collisions, some involving fatalities.

The Sealink Travel Group operate a 400 tonne vehicle and passenger ferry shown in Fig. 1 running between Half Moon Bay and Kennedy Point on Waiheke, one of the outlying islands in the Hauraki Gulf. Fig. 2 shows the open sea portion of the 12km passage in protected coastal waters with depths ranging from 2m to 15m.

Fig. 1. The 450 tonne car and passenger ferry, SeaCat.

Rather than a full transport infrastructure system overview such as reported in [1] for a similar operation, or the optimal design of new routes and associated timetabling as reported in [2] or [3] using mathematical programming techniques, in this instance the operating company concentrated on ways to improve operational efficiency and sustainability since the destination was fixed, and the convenient hourly timetable considered too important to adjust unless this study could persuasively argue otherwise.

Given that the running costs are dominated by the fuel costs required to drive the four 450hp diesel engines, a previously commissioned energy audit, [4], recommended to explore the potential of route optimisation taking into account uncontrollable external circumstances such as wind, weather and tides, and also partly controllable circumstances such as vessel loadings, scheduled delays etc. This paper explores the potential for optimising the ferry route.

The outline of the paper is as follows: section II describes the important static and dynamic characteristics of the vessel. Section III considers the problem of establishing an optimal trajectory both with, and without the influence of tidal streams. Section IV weighs the cost of dredging a deeper channel against the costs incurred by detouring during low spring tides. Finally some conclusions and comments regarding the general applicability of the approach are presented in section V.

II. VESSEL DYNAMICS

Any route optimisation program must consider the vessel dynamics; namely how the vessel performs as a function of water depth, load, weather and sea state. This section discusses the principle factors pertinent in the vessel dynamics and energy usage. Marine architects can predict vessel behaviour with tools such as CFD, but experience has shown that a cost effective way to develop a vessel model is via sea trials which was done in this case.

The most important parameter in the vessel dynamics is the water depth under the vessel. As the water shallows, the increased flow of water is accompanied by a reduction in pressure (following Bernoulli's law) causing the vessel to squat particularly at the stern thereby increasing friction due to the increased wetted surface area. The three profiles shown in Fig. 3(a) show the steady-state speed as a function of water depth under average cargo load and average weather conditions for three different engine conditions. What is important to note is that the speed decreases significantly at what otherwise would be considered substantial depths starting around the 8m level. The vessel draws around 2m.

A semi-empirical model of the speed over ground, v, in knots as a function of depth in meters, d, is of the form

$$v = \frac{p_1 d}{p_2 + d} \qquad (1)$$

for the three engine load cases. This model asymptotes to a maximum speed over ground of p_1 as the depth tends to

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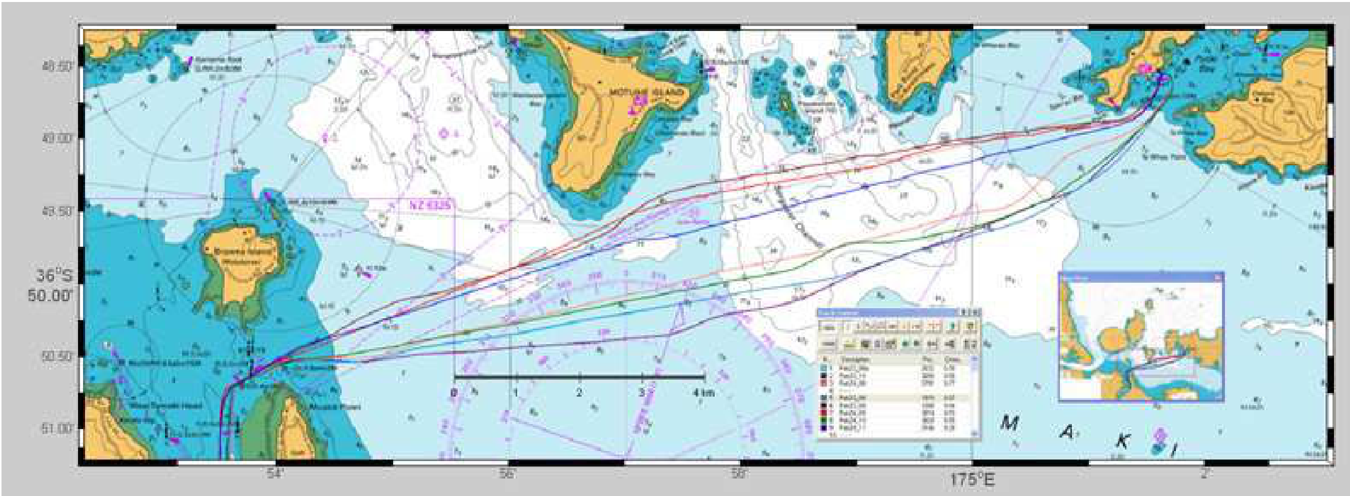


Fig. 2. Various GPS logged trips of the ferry showing the natural separation between eastward (southern tracks) and westward (northern tracks) ensuring that meeting vessels pass *port to port*. Projection Mercator.

infinity. If we include the effect of engine load, L, as a second independent variable, a plausible model structure is

$$v = \frac{p_1(d - p_3 L - p_5)}{d + p_2} + p_4 L \tag{2}$$

and the curves of which are overlayed in Fig. 3(a). The parameters p_1 through p_5 are regressed from this experimental data. The speed/depth dependency is well known to the skippers, although the magnitude might surprise some.

In addition to the vessel squat in shallow waters and subsequent reduction in speed, the engine load also increases on the inner two propellers, and the fuel consumption (in liters/hour) increases as shown in Fig. 3(b). This means that there are two compounding nonlinear inefficiencies apparent in shallow water.

The model for the fuel consumption, $\dot{F}$, in litres per hour as a function of both depth, d, and load L, used in Fig. 3(b) was of the form

$$\dot{F} = -\theta_1 \tan^{-1}(d - \theta_2) + \theta_3 L + \theta_4 \tag{3}$$

which captures the “S” curve form of the data. The parameters of both models, θ, were fitted to the data using nonlinear least-squares regression.

The vessel models presented so far in Eqns 2 and 3 are static and this is deliberate. Unlike the dynamic studies in [5] and [6] aimed at stabilising control to improve passenger comfort in fast (40 knots) ferries, our ferry speed (around 10–15 knots) and harbour sea conditions in this application were such that this is not an issue for this ferry. Fig. 4 shows the dynamic response of the vessel accelerating after the throttles are step changed to 100% when leaving the speed restricted zone in relatively deep water (upper plot) compared to the same throttle step change when accelerating in shallow water (that gradually deepens). A low order model fit to this data gives a dominant time constant for the deep water of 8–9 seconds, while it is over 3 minutes for the shallow water case.

This reinforces that the depth dependent static models are far more important than the dynamic response for this operation.

III. Trajectory optimisation

One of prime goals at the outset of this project was to explore the optimisation potential of varying the route taken by the ferry as a function of bathymetry, cargo loads, tides and tidal streams, wind and sea state. The objective function was to minimise fuel costs whilst maintaining the timetable, although there is some benefit to minimise the travel time as that increases customer satisfaction, and relieves the time-pressure for loading and unloading the vehicles.

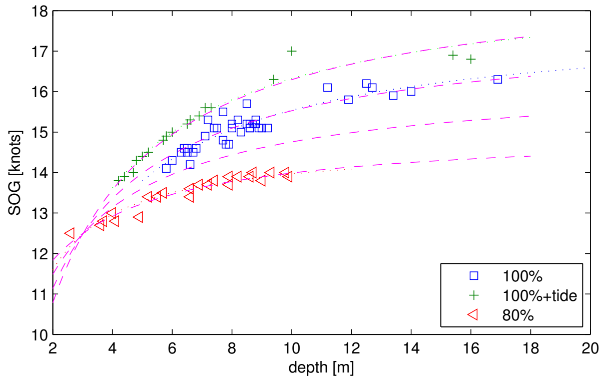
Formally this is a trajectory optimisation problem which can be solved using mathematical programming techniques although in practice considerable insight can be gained by studying a small collection of simple candidate trajectories.

A. Three candidate trajectories

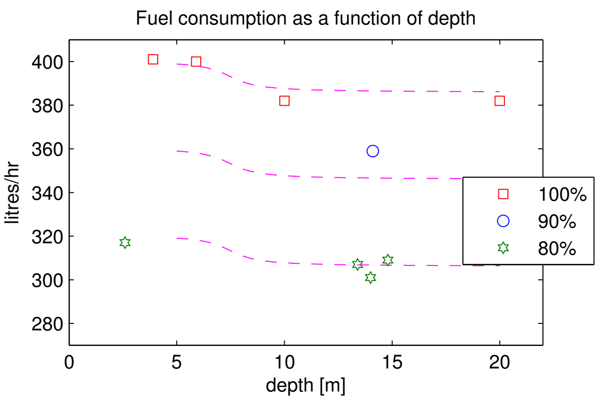
While there is no strict legislative requirement to do so, the vessel masters currently deviate (if any) to the south on eastward runs, and to the north on the return trip running westward as shown in Fig. 2. This has the advantage that they naturally pass other vessels port-to-port, and other skippers know and expect this behaviour. For these practical reasons, we have chosen three candidate trajectories:

1) Nominal (straight line from Musick point to Kennedy point)
2) When travelling East, deviate south (ES)
3) When travelling West, deviate North (WN)

all of which are illustrated in Fig. 5. The curved trajectories in Fig. 5 are obtained by running smoothing splines through the marked waypoints. Clearly the curved routes are longer than the straight-line track, so any efficiencies gained due to tide and depth must more than compensate for this extra voyage length.



(a) The speed/depth characteristics of the vessel at different loads



(b) The fuel consumption/depth characteristics

Fig. 3. The hydro-dynamic characteristics of the ferry Seacat

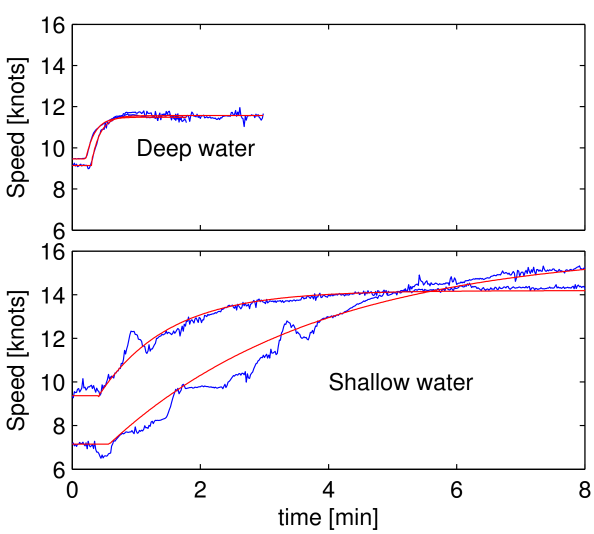


Fig. 4. Dynamic response to a step change in throttle position (for two cases) in both deep and shallow water.

The upper trend in Fig. 6 shows the resulting depth profiles for each of the three trajectories proposed in Fig. 5. Note that all three profiles have (marginally) different lengths. The middle trend in Fig. 6 shows the resulting speed as a consequence of the depth and the average speed for each of the three trajectories. To compute the fuel consumption, we need to first convert the data to a time basis, and include the fuel consumption/depth relation from Fig. 3(b). The results of this calculation are given in the lower trend of Fig. 6 which shows that the nominal straight line path has the distinction of both using the least fuel (148.9 litres), and taking the least time (23.2 minutes). For this geographical location it is simply fortuitous that the straightest path is also the deepest.

The North deviating track is heavily disadvantaged by a shallow area just to the south of an island, while the track deviating south is shallow for most of the passage. The motivation to go north is to try and catch the tidal stream through Sergeant Passage, although as will be quantified in section III-B and illustrated in Fig. 9, this does not have a significant effect and does not therefore compensate for the extra shallow portion.

Clearly for a given trajectory, operating the engine at higher loads uses more fuel, but reduces the travel time. This then is a multiple-objective optimisation problem due to the competing objectives, and we can plot elapsed time/fuel consumption trade-off curves as shown in Fig. 7 for various engine loads from 60% to 110% and for the three candidate trajectories for passages at low tide where the depth nonlinearities are more pronounced.

The trade off curves in Fig. 7 allow the skipper to make an informed judgement regarding the optimum throttle setting. For example at low tide, by dropping from 100% to 80% engine load (throttle), a 13% fuel saving (or 20 L of diesel) for this section is made at a cost of an extra 2.4 minutes travel time. An alternative way of looking at the fuel/time trade-off is to note that the gradient of the nominal trajectory is 8.5 litres/minute, or 8.5 litres of diesel is saved for every minute extra on the voyage.

B. Including tides and tidal streams as forcing functions

The analysis so far assumed a static sea condition and low tide when the differences between the trajectories are

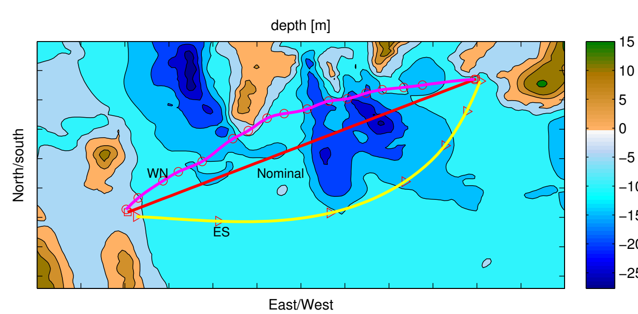


Fig. 5. The 3 candidate profiles: nominal, ES (or south tending when travelling east), & WN (or north tending when travelling west) superimposed on the chart from Fig. 2. (Bathymetric data taken from appropriate charts NZ5325 & NZ5324.)

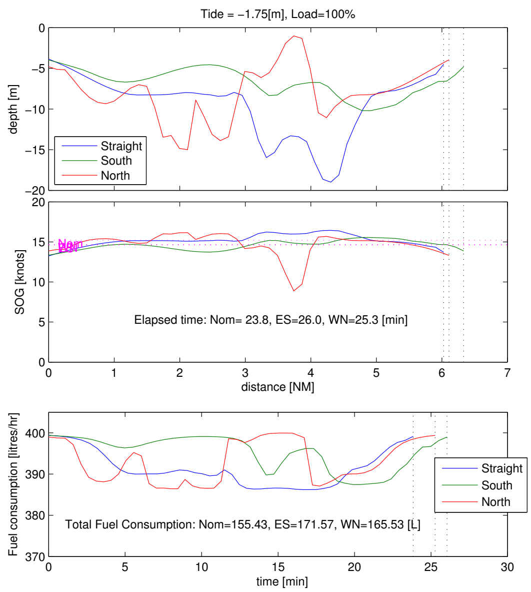


Fig. 6. Depth and speed as a function of distance (upper) and fuel consumption as a function of time (lower) for the three different candidate trajectories.

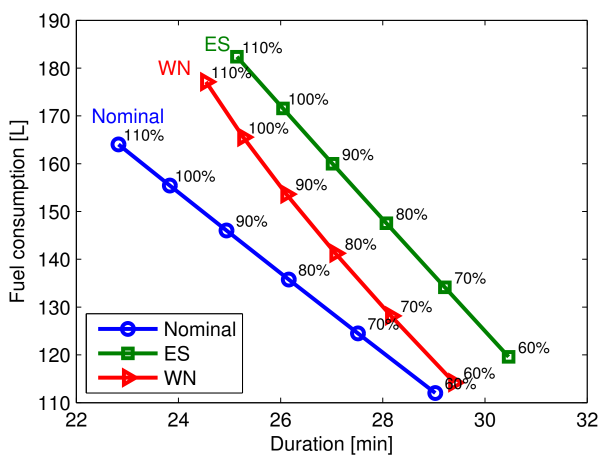


Fig. 7. Elapsed time/fuel consumption trade-off curves.

the most pronounced. However using a dynamic model of the tides from [7], the tidal streams (*horizontal* water movement) due to the vertical tide movement in part using the computational fluid dynamic model from [8] shown in Fig. 8 as external forcing functions; the static vessel characteristics from section II and the dynamic terms from Fig. 4, one can construct a computer model in order to search for the optimum trajectory, in this case using the control vector iteration approach, [9] in a manner similar to the methods reviewed in [10].

For this application, the manipulated variable to be optimised, $u(t)$, is the command to the rudders which is essentially the bearing to steer by. We use a 1 minute sample time which equates to around 23 free variables to optimise over the 23 minute journey. The objective is to minimise the travel time, although an alternative objective function could

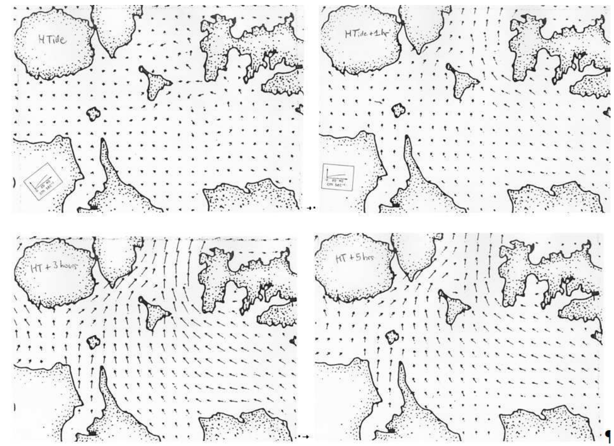


Fig. 8. Snapshots of the ebbing tidal streams around the area of interest. Top row: (a) High tide, (b) 1 hour after high tide; Bottom row: (c) 3 hours after high tide, and (d) 5 hours after high tide. Data after [8].

be the weighted minimisation of the travel time combined with the fuel consumption. This latter objective function additionally penalises shallow water travel when considering Fig. 3(b). Hence we wish to minimise

$$\mathcal{J}(u) = \int_0^{t_f} dt + w \int_0^{t_f} \dot{F}\, dt, \quad \mathbf{z}_0 = \text{start} \tag{4}$$

subject to reaching the destination $\mathbf{z}_{t_f}$=destination where $\mathbf{z}(t)$ is the vessel's location (x, y) at time t, the term $\int \dot{F}$ is the total fuel consumed for the trip, and w is a weighting parameter, possibly zero. The passage of the vessel over ground is governed by

$$\dot{x} = -\,v(x,y,t)\cos(u) - A(x,y,t)\cos(\gamma(x,y,t)) \tag{5}$$

$$\dot{y} = -\,v(x,y,t)\sin(u) - A(x,y,t)\sin(\gamma(x,y,t)) \tag{6}$$

where the speed of the vessel, v, the magnitude, A, and direction, γ, due to the tide and tidal stream are complex functions of position and time actually implemented as large 2D table lookups. The manipulated variable, u, is related to the compass bearing. Movement due to wind is not implemented in this application, and this simplification is verified by sea trials.

Prior to this study, it was postulated by the skippers that a deviation north when travelling east to west (right to left) 3 hours after high tide (ebbing tide) may improve on the straight-line track. However the numerically computed optimum trajectory incorporating the speed/depth dependency, the vessel dynamics, the tide and the tidal streams is given in Fig. 9 which shows a slight 'S' curve, deviating south first, then north (when travelling right to left) primarily in order to remain in deep water. It should be noted that the magnitude of the tidal streams in this simulation is increased by a factor of 2 from that reported in [8]. This is done for two reasons; first the values reported are about half that tabulated in the tidal diamonds given on the official local marine charts, and secondly are low compared to spot measurements taken by the author.

Of course being optimal, this trajectory is superior to the course where the skipper follows a constant pre-computed bearing, where due to the set of the tide, the vessel is pushed sideways (known as 'leeway' in nautical circles). The natural tendency is to correct this sideways drift by constantly adjusting the vessel's attitude to point at the destination target. If this is done (much like a simple proportional controller), the course over ground will describe a 'hooked curve' as shown also in Fig. 9. The optimal trajectory is about 3.5% shorter than the hooked curve. (Without any tidal streams, the improvement is only about 0.1% which is clearly insignificant.) Both are of course preferable to the blind open-loop control strategy of following a constant bearing, which in this case will shortly run aground. The optimal manipulated variable trajectory, i.e. the bearings to steer by are given in Fig. 10, again with the two sub-optimal cases for comparison.

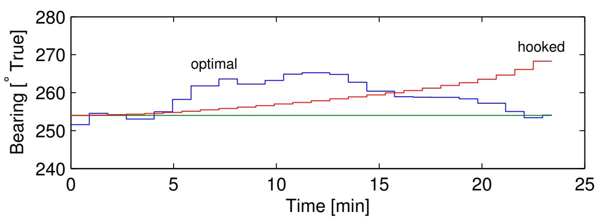


Fig. 10. The bearings to steer required for the optimal, the constant, and the hooked curve trajectories given in Fig. 9.

The case presented in Figs 9 and 10 were for the case with strong flooding spring tidal streams which represents the best opportunities for trajectory optimisation. Fig. 11 shows the range of expected performance improvements for differing tidal streams. Clearly at slack water there is little advantage in an optimal trajectory, while a flooding tide, (negative values of stream magnitude), presents more opportunity than an ebbing tide when travelling from east to west.

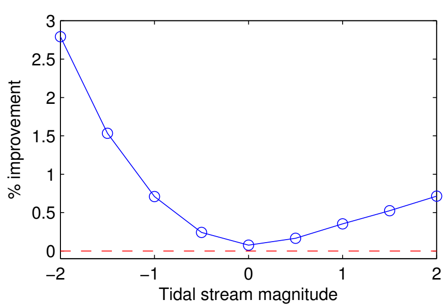


Fig. 11. The percentage improvement in using the optimal trajectory as opposed to the naive 'hooked curve' strategy for different tidal streams.

IV. The need for detouring

A major secondary consideration for ferry skippers is to decide when they must make the considerable detour around an island due to insufficient water through the channel either due to tide, excessive load, wind conditions, or all three as shown in Fig. 12. The detouring incurs substantial delay and requires extra fuel, while the alternative is a possible grounding which, given the muddy bottom conditions, does not damage the ship, but does remove the expensive anti-fouling on the hull.

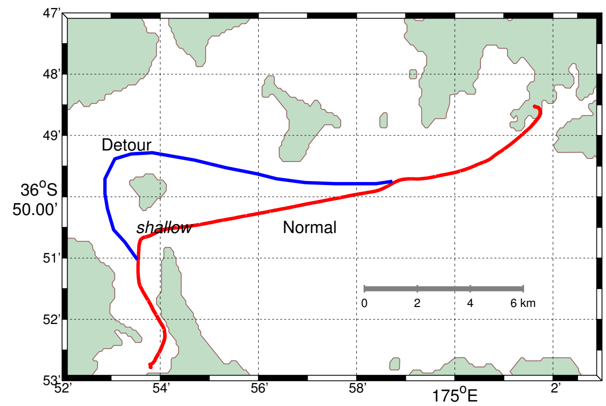


Fig. 12. The detour (upper arc) required at low tide due to shallow water between the point and the outlying island.

It is not necessary to detour at every low tide, just those spring lows that happen to fall at the relevant time of the sailings as shown in Fig. 13(a) for 2010. The number of detour sailings per year as a function of the cut-off depth is given in Fig. 13(b) given that the vessel potentially makes about 5200 sailings per year (1 per hour every day). The additional fuel cost is also plotted, but what is not quantified is the cost associated with the delays and subsequent customer dissatisfaction. A remedy to avoid the need for detouring is to dredge the shallow area. However the quote received for this operation was above NZ$2M, which clearly unless supported by the council and/or harbour authorities, is not economically viable.

V. Conclusions

The selection of an optimal ferry route is complicated by balancing passenger safety and comfort, saving fuel, and maintaining a regular operating schedule. In the operation described in this paper, during slack tides, the optimal trajectory taking bathymetry and vessel dynamics into account was practically indistinguishable from the straight line course. During periods of high tidal stream flow, the optimal trajectory as shown in Fig. 9 was better by about 3.5% in travel time compared to the hooked curve. Admittedly this is only a modest improvement given the complexity of implementing the optimisation algorithm in commercial operation. However the course over ground is straighter when following the optimal trajectory, and this is considerably safer when operating in congested waters. It should be noted that the external hard constraints, (the timetable constraint or hitting land), are not active at the optimal solution.

Deviating north (when travelling westward) or alternatively south (when travelling eastward) are both sub-optimal and one pays a penalty in terms of time and fuel. When considering the optimal straight path, dropping the engine load from 100% to 80% over the open portion of the trip

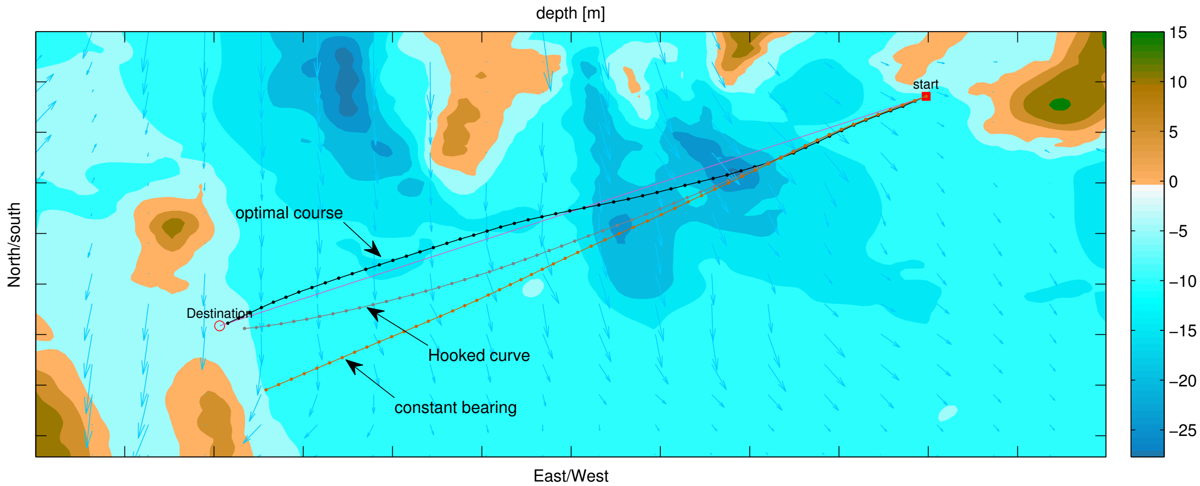
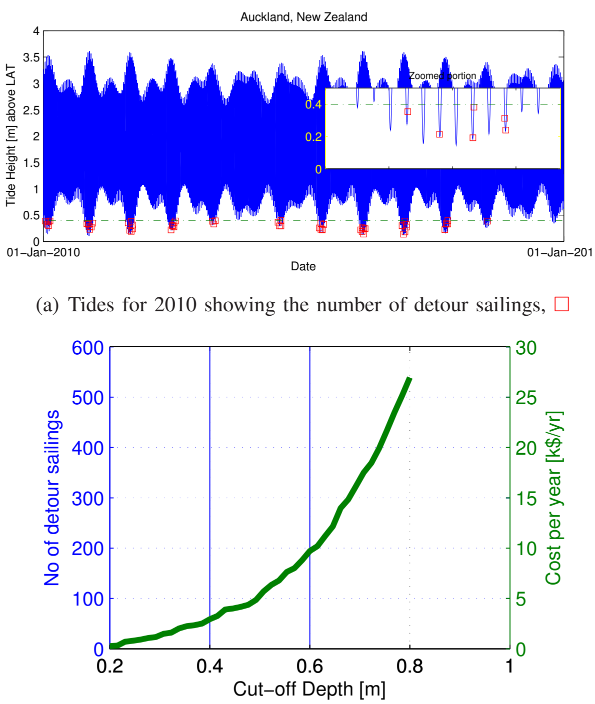


Fig. 9. The optimal trajectory across the open passage section (from right to left) assuming a flooding tidal stream 3 hours before high tide. Also shown for comparison is the constant bearing course, and the 'hooked curve' course.



(a) Tides for 2010 showing the number of detour sailings, □

(b) The number of detour sailings as a function of cut-off depth, and the associated fuel cost per year

Fig. 13. The cost of detouring to avoid the shallow water passage

saves 20L of fuel, but adds 2 minutes to the nominal 45 travel time. The economics of this trade-off depend on the speed of the turn-around at the jetties. An alternative view highlighting the speed/fuel consumption trade-off is that for every minute extra on the voyage, one saves 8.5 litres of diesel. The Brown's Island detour is costly but dredging does not offer a suitable payback.

This particular optimisation problem is necessarily tailored to specific circumstances, notably New Zealand costal waters using a black-box dynamic vessel model. Nevertheless, the optimisation approach taken is quite general and could be applied to a wide range of vessels. The economic success or failure of would then depend on the quality of the dynamic models, the magnitude of the environmental variations (tide and tidal streams), and the length of open-sea path allowing a wide range of route possibilities.

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