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A Vessel Navigational Behaviour Model for Assessing Waterway Capacity

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ABSTRACT

We have designed and built a detailed simulation system for modelling vessel navigation and traffic flows in a network of waterways. The simulation system includes the following models: the navigational network model, the traffic flow model, the vessel movement model and the vessel navigational behaviour model. In this paper we will focus on the vessel navigational behaviour model. We are able to simulate realistic navigational behaviours which depend on the type of the vessels, on the physical location and on the traffic situation. The model is calibrated and validated by three sets of real historical radar data collected from three different time periods. Using this model, we are able to analyze the traffic flows under various identified scenarios and conduct traffic capacity studies of the Singapore waterways.

Keywords

Navigational Behaviour Modelling, Waterway Capacity, Model Calibration and Validation

1. INTRODUCTION

There are many busy waterways around the world. Marine traffic increases each year in many parts of the world and is expected to increase significantly over the next few decades. This may result in congestions and the increase in the risk of collisions in certain traffic hubs. The direct consequence is a longer time to travel through waterways with high density of vessels. This will reduce the competitiveness for the busy port cities in favour of places with smooth traffic flow. It will thus be very important to be able to assess whether the waterways available are able to sustain the increased traffic forecasted.

The waterway capacity is a complex problem which may be considered from different aspects. A meaningful and useful definition that provides the understanding of what a waterway does, supports the needs of all waterway users, and is applicable worldwide [2], is yet to be universally accepted. In principle, the capacity of a waterway can be considered in two ways: physical dimensions and navigational throughput. The dimension, e.g., width and depth, defines a single vessel capacity threshold. The throughput is a dynamic measure of waterway capacity and can be considered in terms of (a) the number of vessels passing though per unit time (b) the vessel waiting time (c) vessel turnaround time [3]. This definition of capacity appears in the Permanent International Association of Navigation Congresses (PIANC) channel design guidelines, as well as International Maritime Organization (IMO) [1] and International Association of Lighthouse Authorities (IALA) [4] risk management initiatives.

In reality to assess the throughput of a network of waterways is not an easy task because of the dynamics of such a system. The vessel mix (vessel lengths, vessel speeds) in a waterway may change

with time. The geometry and physical environment may be different at different parts of a waterway. All these may affect the navigational behaviour of vessels. The vessel mix, the environment and the navigational behaviour will all have impact on the traffic flow rate. Therefore to assess the throughput for marine traffic planning and management purposes, simulation is a proven useful tool [5, 6].

The Straits of Singapore played host to about 130,000 vessels in 2009. These include containerships, general cargo ships, oil tankers, chemical tankers, ferries, cruise ships and many more. Some vessels are ocean-going vessels where they come from other continents or ports. They visit Singapore for various purposes like cargo loading/unloading, getting repair or maintenance services and/or getting supplies. Then they leave for other ports. Some vessels may go to an anchorage before visiting a terminal/shipyard, whereas others may do so after visiting a terminal/shipyard. There are also vessels making more than one visits to anchorages or terminals for different purposes. Some vessels simply pass Singapore without stopping.

We have designed and built a detailed simulation system for modelling vessel navigation and traffic flows in a network of waterways. The simulation system is very flexible and may be reconfigured in many ways to simulate the different traffic scenarios on different networks of waterways. The model will capture the vessel speeds during their journeys, the travel times vessels take to complete their trips and the number of times vessels need to take actions to resolve potential conflicts with other vessels throughout the navigational network. These results will help identify congested waterways and increased risk of collisions.

Using this model, we are able to analyze the traffic flows under various identified scenarios and conduct traffic capacity studies of the Singapore waterways. The simulation system includes the following models:

- Navigational Network Model
- Traffic Flow Model
- Vessel Movement Model
- Vessel Navigational Behaviour Model

The navigational network model represents the network of waterways the simulated traffic flows will use. The traffic flow model shows where the traffic flows are. Traffic flow is formed by a set of vessel trips to be made by vessels. A vessel trip is represented by an origin-destination pair. The vessel movement model is a model of a vessel's movements in the navigational network from its entry till its exit. From the time a vessel enters the navigational network to the time of its exit, a vessel may make one or more trips. Each trip is a journey specified by an origin-destination pair. The vessel navigational behaviour model simulates the movement behaviour of a vessel when it moves through a waterway. In this paper we will focus on the vessel navigational behaviour model. This model is able to simulate a vessel's decision in choosing its speed, course under different traffic conditions. It will navigate a vessel automatically through its given route to its destination point. We calibrated and validated our model against historical radar data.

In the rest of the paper, we will discuss about the related work in Section 2. The vessel navigational network model is presented in Section 3. It is followed by the calibration and validation approach in Section 4. Conclusion is in Section 5.

2. RELATED WORK

Previous studies include a simulation model for Panama Canal presented by Golkar et al. [8, 12]. They stressed in detail how a comprehensive simulation system was constructed by different model components. However, the details of each model components were unclear and the system effectiveness was not provided.

Osaka University's SMARTS (Ship-with-a-captain MARine Traffic Simulation system) [9, 11, 13] is a multi-agent model to simulate marine traffic in Osaka Bay and Tokyo Bay of Japan. It can automatically create marine traffic flow according to the statistical data to drive the simulation runs.

Hasegawa et al., the system inventors, applied a fuzzy expert system to navigate vessels through waterways. The model was used for marine risk assessment and navigation rule evaluation. They showed that the alternative rotary route plan is more dangerous than the standard regulation by IMO. In addition, they showed that the adoption of a virtual radar system can improve safety.

Kose et al. [10] presented simulation of marine traffic in Istanbul Strait. Their simulator made several assumptions: vessel arrival time is uniformly distributed; each vessel enters the strait from every entrance once; vessels are forbidden to overtake each other; constant separation distance among vessels are maintained; the designed speed for vessel in the strait is set to be 10 knots; transiting traffic cannot be interrupted by local traffic; all vessels are transiting (i.e., no dwelling). With simulation output, they found that the waiting times for two particular entrances were not impacted with 36% increasing of strait capacity.

BMT's Dymitri [7] is a time-stepping model in which a number of vessels in the simulated area move along prescribed routes and manoeuvre according to a set of rules. The rules determine when and how to change course and when to slow down or increase speed, thereby providing rudder and engine commands to each active vessel. Navigational risks are evaluated at every time step; then avoidance manoeuvres (slowing and/or steering) are suggested to operator for human decision. Their forecasting model is able to provide an enhancement to the operator's decision-making abilities.

Fan and Cao [14] presented a capacity model where the throughput of a waterway is calculated from the average vessel size, average vessel speed, average separating distance between vessels and the probability of each type of vessels appearing in the waterway. However, different parts of a waterway may see different average speeds due to the physical environment or other factors. The average speed of vessels based on the whole waterway may not be a good estimate for the capacity calculation.

Brockfeld et al. [15] presented a procedure for the calibration and validation of microscopic simulation models. They show that calibration of microscopic simulation models involves numerous parameters for tuning, resulting in a very time consuming process for validation. Their calibration results showed that there is error of 12% to 17% in terms of gap distance between every vehicle-pair.

3. THE VESSEL NAVIGATIONAL BEHAVIOUR MODEL

The vessel navigational behaviour model consists of four components including three sub-models, the free travel model, the overtaking model and the slow down/speed up model, as shown in Figure 1. It is a time-stepped model. At each time step, a vessel will try to detect potential conflicts with other vessels and plan for its movement until it reaches its destination.
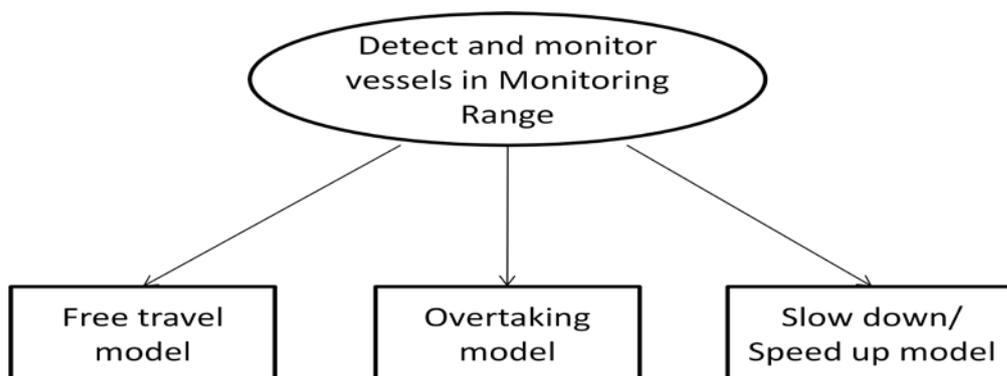

Figure 1: Vessel navigational behaviour model.

3.1 Detection of Potential Conflicts

Possible collision scenarios include: catch-up, head-on, and crossing conflicts.

Each vessel has a size defined by its length and beam width. A *vessel domain* is usually used to separate this vessel from others with safe distance. We use a rectangle with the size of 3 (configurable) times of vessel length and 3 times of beam width to represent its domain. Other definitions have also been proposed, for example half circle in [7]. At all times, a vessel should make sure that necessary actions are taken so that its domain does not overlap with the domain of another vessel.

In a medium or large size simulation model, there may be hundreds or even thousands of vessels navigating through the waterways at any time. In order to save computational time, a vessel should avoid checking against all other vessels for potential conflicts. In our model, each waterway is divided into a number of segments. Only vessels that will be in the same segment of a navigational channel or in two neighbouring segments for a same period of time may incur potential conflicts. So for each vessel at each time step, checks are performed on all other vessels this vessel expects to satisfy this condition. This is computed based on the observation of each vessel's current speed and course. A two-stage test is done in order to reduce the computational time further. The first stage test is to filter out vessels that will not be getting close to this vessel. Vessels failing the first test will go through the second test to confirm whether there is a potential collision.

```
D = Inf;
        [t_a , t_b ] = intersection of two vessels' time intervals in the segment;
        Compute the relative speed v, and relative displacement z;
        Compute the minimum distance d*, and denote the time t*;
        If t* not in [t_a, t_b]:
                Let d* = min( distance at time t_a , distance at time t_b );
        D =  min( D, d*);
Return D>= 3*the length of the smaller of the two vessels.
```

Figure 2: Distance Test

A closest point of approach between two vessels is the minimum distance between them. We first compute the time interval during which two vessels V_1 and V_2 will be both in the same segment (or two neighbouring segments). Given this time interval, the minimum distance of these two moving vessels' centre points is computed as follows. Let $[t_a, t_b]$ be the time interval. Let $v = v_1 - v_2$ be the relative velocity for one vessel to the second vessel. Let $z = z_1 - z_2$ be the relative displacement vector at the initial time t_a. Then the function of distance between two vessels is $d(t) = \| z + v*t \|$. Its minimum value $d*$ can be obtained by choosing

$$t^* = argmin_t \, d(t) = -\frac{z \cdot v}{\| v \|^2}$$

$$d^* = \| z + v \cdot t^* \|$$

Comparing three values of d(t) at time 0, t* and $t_b - t_a$, and checking if t* is in $[0, t_b - t_a]$, we obtain the minimum distance between two vessels for the time interval $[t_a, t_b]$. Also, we obtain the precise time when two vessels reach this minimum distance. This algorithm as shown in Figure 2 enables us to quickly judge if it is possible that the two vessels may get into each other's domain.

The second test in the detection for potential collision is to pre-determine if two vessels' domains would overlap if they continue on their current tracks, given the time interval to look ahead and the current speeds of the vessels. Our algorithm is derived from Separating Axis Theorem [16]. The Separating Axis Theorem determines whether or not two static convex polygons intersect. It projects two polygons onto every axis of both polygons. If these projections intersect on all axes, then the polygons are intersecting. Otherwise, they are not intersecting. In our context, it is not enough to check whether the two domains of the two vessels overlap at the beginning and at the end of the time interval where they are in the same area (the same segment or two neighbouring segments). This is

because during this interval, the two vessels may 'go through' each other. So we extend this theorem to the cases with two moving convex polygons: each convex polygon is given an initial speed and acceleration. The algorithm to determine if two moving convex polygons overlap or not is presented in Figure 3.

For each edge vector of both polygons:

1. *Determine the separating axis, which is the normal of the unit vector of the edge.*
2. *For each polygon: find the dot product between each corner point (with two positions respectively at time t0 and t2) in that polygon and the separating axis; the projection of that polygon onto the separating axis spans between the smallest of those projected points and the largest of them.*
3. *If the projections do not intersect, terminate. That means the polygons are not intersecting. If step 2 was completed, the polygons must be intersecting.*

Figure 3: Detecting potential collision between two moving vessels

3.2 Free Travel Model

During the movement in the navigational channel, a vessel will normally follow a constant speed, called *normal speed*, if there is no potential collision. Based on our analysis of historical radar data, we find that normal speeds for different types of vessels are different. Normal speeds in a wider waterway compared with those in narrower waterways for the same type of vessels are also quite different. To simulate realistic behaviour, the normal speed of vessels will form a distribution. The distributions of speeds for different types of vessels in different parts of the navigational network are simulation parameters.

A vessel will gradually pick up speed when it is starting a journey. Similarly it gradually reduces speed when it is ending a journey.

We simulate the behaviour that if the captain of a vessel anticipates that the vessel is going to turn left (right) in the near future, he would be more likely to navigate the vessel along the left (right) side of the waterway. On the other hand, if the vessel's path in the near future is to go straight, the captain is more likely to navigate the vessel along the middle of the waterway. Usually a waterway is wide enough, multiple vessels may move in parallel.

3.3 Resolution of Potential Conflicts

When a potential crossing conflict is detected, the rule of right-of-way applies. This rule says a vessel should give way to another vessel on its right at the point of conflict. This rule specifies which vessel will take action to resolve the potential conflict. The actions to take include adjusting its speed, either to slow down or speed up. It can only do so between a minimum speed and a maximum speed. The values of the minimum and maximum speeds depend on the vessel type and where the vessel is. We use a location-aware scheme to specify a vessel's permissible speed range. These simulated speed ranges are statistically calculated based on historical radar data. The vessel may also change course or change speed and course.

Overtaking at the current speed is the first choice if a vessel is catching up with another vessel in front except in certain waterways. If overtaking at the current speed is perceived to lead to conflicts, i.e., no safe path is found, the vessel will slow down or choose a combination of changing course and changing speed. After overtaking another vessel, a vessel will turn back to the original path when it can. After a slow down, if the vessel in front is not there anymore, a vessel will return to its normal speed.

4. MODEL CALIBRATION AND VALIDATION

Our vessel navigational behaviour model is calibrated and validated based on real historical data. The input to the simulation model during calibration and validation are the actual vessel arrivals in historical data. To avoid "over-fitting" of the simulation model to one set of data, historical radar data from three periods of time are used.

There are two types of parameters for the calibration of navigational behaviours. The first type is the normal speeds for vessels under different situations. The second is how much effort a vessel will try when it attempts to overtake another vessel before deciding to slow down. This means how much deviation from its current course a vessel is willing to take when overtaking. Parameter values are set such that the difference between the simulation results and radar data is minimized.

Two types of simulation results are compared with the radar data. One is the vessel travel times through the various waterways. This is to make sure the simulated vessels will use realistic amount of the waterway resources in our capacity study. The travel time in a waterway is also an indicator of the degree of congestion in that waterway. The other is the microscopic travel behaviour in each of the waterways. This is represented by the vessel speeds for different types of vessels when they travel through the waterways. This is to ensure we will reproduce any behavior that may be the bottleneck or the cause of bottlenecks in traffic flows. It also makes sure that our simulation will not create any bottleneck which is not in the physical system that is being simulated. So this is done in terms of speed profiles (speed against location along a waterway) through each of the waterways.

As an example of the results of calibration, Table 1 shows the percentage differences in average travel times for different types of vessels through one of the waterways simulated. For each type of vessels,

$$\text{Percentage Difference} = \frac{average\ travel\ time\ from\ simulation\ -average\ travel\ time\ in\ radar\ data}{average\ travel\ time\ in\ radar\ data} \times 100\%$$

It can be seen that the differences are very small. After the calibration, a different set of data is used for validation and we see the percentage differences only increase by about 2% from the results in Table 1.

Table 1: Percentage differences of average travel times for one waterway

Direction	Vessel Type	Percentage Difference
westbound	Bulk carrier	-0.24%
westbound	Chemical tanker	0.01%
westbound	Containership	0.63%
westbound	Freighter	-2.88%
westbound	Oil tanker	0.80%
eastbound	Bulk carrier	-3.73%
eastbound	Chemical tanker	4.75%
eastbound	Containership	-0.67%
eastbound	Freighter	-3.45%
eastbound	Oil tanker	-1.30%

We are able to simulate the behaviours we discovered through the analysis of historical radar data. These behaviours include

(1) For certain types of vessels, speedup behaviour is observed when they are approaching the open sea or the wider Malacca Straits.
(2) For certain types of vessels, they are more cautious than other types of vessels when negotiating the sharp turn in a waterway.
(3) For certain types of vessels, they are more cautious than other types of vessels when approaching an area with heavier traffic.

As examples, Figures 4 and 5 show the speed profiles of two different types of vessels in one waterway respectively. It can be seen that in the same waterway, these two types of vessels behave quite differently and our simulation model can simulate them. In conclusion, our vessel speed control logic and the approach to calibrate the simulation model is an appropriate way to help produce a realistic model for vessel navigation.
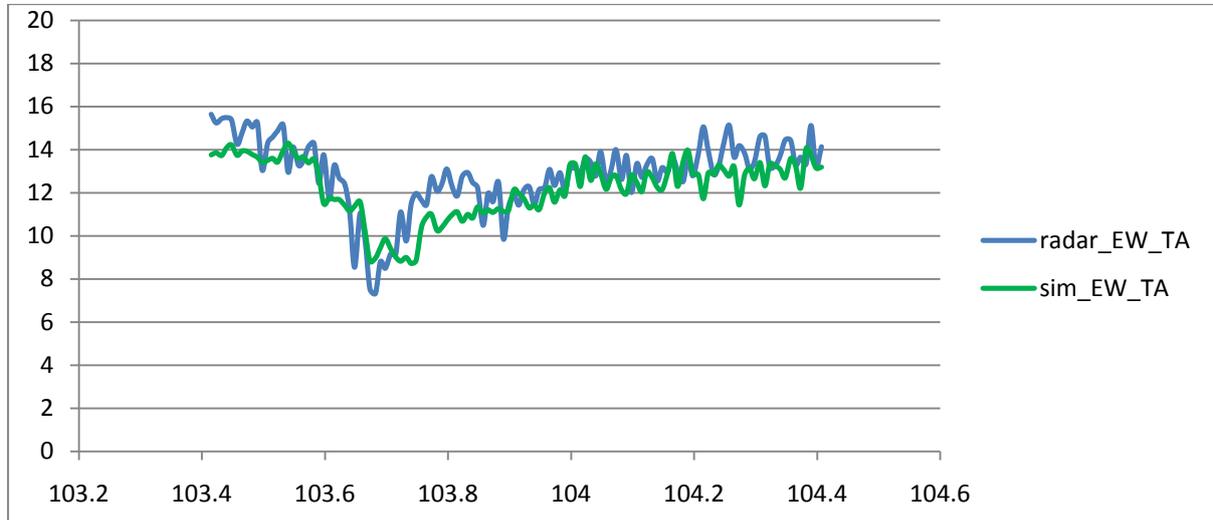

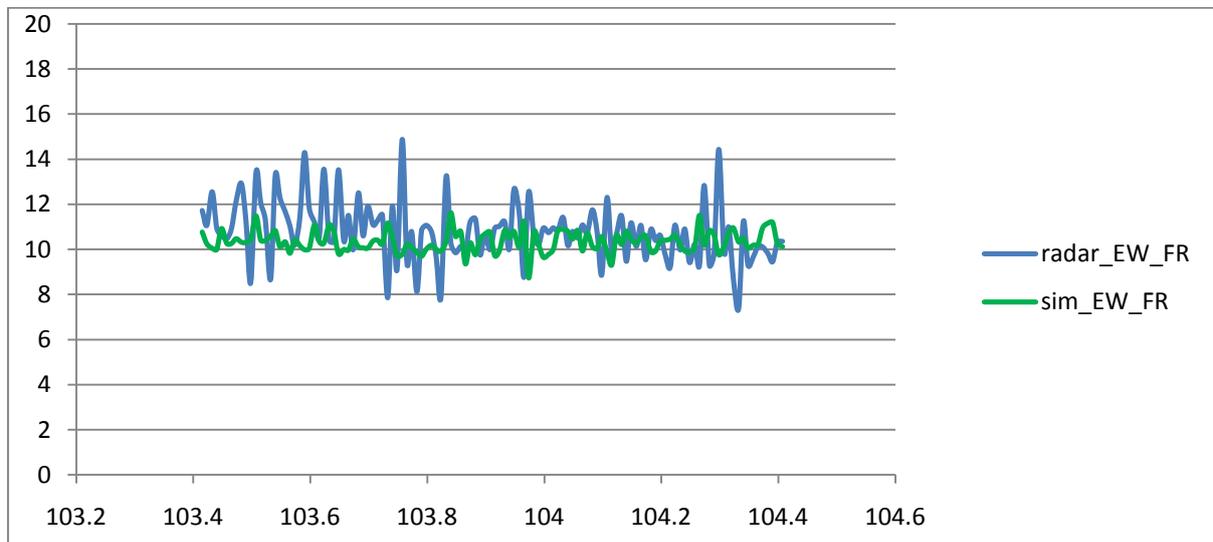**Figure 4**: Speed profile of tanker vessels travelling in east-west direction in one waterway.

Figure 5: Speed profile of freighter vessels travelling in east-west direction in one waterway.

5. CONCLUSIONS

We have presented a vessel navigational behaviour model for the purpose of assessing waterway capacity. Detailed navigational behaviours as controlled by the simulation parameters and navigational logic are simulated. The model is carefully calibrated and validated using three different sets of data collected at different times. We are able to use this model in the capacity study for future scenarios.

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