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Modelling and Simulation for Safe and Efficient Navigation in Narrow Waterways

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This paper outlines the design of a Vessel Traffic Management and Information System (VTMIS) for the Turkish Straits and taking this as an example shows how modelling and simulation may aid safe and efficient navigation of vessels through waterways which are narrow and winding with changing currents and are therefore difficult to navigate and prone to accidents. Ship Handling and Vessel Traffic Flow simulation models and Hyrographic Prediction model are described and the simulation trials conducted under different traffic and environment conditions are discussed to show the role that these prediction and simulation programmes can play in preventing marine casualities in different waterways, which may result in loss of human lifes and property and contamination of the environment.

KEY WORDS

1. VTS. 2. Turkish Straits. 3. Traffic flow simulation. 4. Hydrographic prediction.

1. GENERAL ASPECTS OF SAFE NAVIGATION IN NARROW WATERWAYS.

1.1. *Introduction.* The objective of this article is to demonstrate that modelling and simulation provides to Vessel Traffic Services (VTS) system designers a powerful and practicable means to determine the optimal system composition for the formulation of rules and procedures necessary to minimise the probability of accidents in waterways. It is obvious that the risk of accident can be reduced but never altogether removed. Accidents which occur in waterways typically take the form of collision, grounding, ramming, fire on board or mechanical failures which may result in loss of life and pollution of the environment, in unrepairable damage to cultural heritage, and/or in financial losses.

This paper will discuss ship design, navigation rules and Vessel Traffic Management and Information Systems (VTMIS) which aim to prevent or reduce to a minimum accidents which occur in waterways. In fact the studies reported herein have arisen in connection with the design of a VTMIS for the so-called Turkish Straits which consist of the straits of Istanbul and Çanakkale with the inland sea of Marmara in between.

There are three main factors in the occurrence of marine accidents; ship design, environment and traffic regulations.

The important ship design parameters relating to the vessel control are the engine and rudder performances and the hydrodynamic and aerodynamic behaviour of the vessel. Simulation modelling in this respect is used for studying ship manoeuvring characteristics as affected by geographical and hydrographical conditions and for the investigations in the development of accident risks under different navigation scenarios.

The master's judgment in controlling his ship is, of course, influenced by the data he has about his environment (geography, bathymetry, meteorological conditions and locations of other vessels in the waterway). Some of these data may be obtained by means of the vessel's own sensors but the ones that cannot be obtained must be transmitted to the vessel from shore facilities such as the VTS Control Centre. VTS should also be capable of providing masters with data on environmental conditions prevailing along their course. Since measured data can only be available at a few suitably selected sensor sites modelling and simulation of the key environmental processes is needed in order to provide advice to the masters on the predicted spatial and temporal variabilities of the environment.

Finally, the third factor affecting accident risks relates to traffic regulations in force in the waterway which stipulate priorities for entering the waterway and navigational advice for safe passage taking into account IMO Collision Regulations [1], the size, weight and cargo (hazardous, non-hazardous) characteristics of the vessels which are to use the waterway. In this context and by means of an appropriate "Vessel Traffic Simulator" it is possible to estimate the traffic capacity of the waterway and to determine navigational rules which would assure safe and efficient passage of vessels through the waterway. Before dealing with the details of the topics above, we shall provide the information about the Turkish Straits and its traffic which we used as a model for our studies.

1.2. *Turkish Straits.* The Turkish Straits is the name given to the waterway system connecting the Aegean and Black Sea. It is comprised of the Istanbul Strait, the Strait of Çanakkale and the Sea of Marmara in between. In this paper we will focus only on the Strait of Istanbul, which presents a much tougher problem for VTS design and refer to it as the Strait for brevity. The Strait has a length of about 30 km and an average width of 1·5 km narrowing to a width of 700 metres. The Strait geography is such that a sail plan made for a passage would have at least 12 important turns.

The present day average transit traffic through the Strait is 150 vessels per day. A significant percentage of these vessels carry hazardous cargo (petroleum, chemical products etc.) and can have lengths exceeding 300 metres. Continuous tracking of these vessels is essential, particularly when their masters have little knowledge of these treacherous waters, in order to keep to a minimum the risk of accidents which result in a loss of life and damage to property and the environment. In addition to the transit traffic cited above there are daily some 1500 vessels criss-crossing between the two shores of the Strait.

The Strait has, unfortunately, maintained over many years, the character of being a high-risk waterway; about 40 accidents per 100 000 passages, which is higher than the accident rates encountered in other VTS areas in the world by a factor of about four. The main causes of these accidents are the following: high traffic density, high strength and variability of currents, sharp bends and turns, frequent bad visibility, high density of local cross traffic, and of course faulty judgement by the masters/pilots. When we consider the expected increase of tanker traffic in the coming years the necessity of taking all possible measures, including the implementation of a modern VTS which has the potential of changing the present traffic regime, becomes obvious.

1.3. *The VTS system: Design considerations and system composition.* The design of a VTS system starts with the definition of (a) Priorities, (b) Requirements, and (c) Constraints. For the case of the Turkish VTS the priorities were defined in the following hierarchical order:

1. Protection of human lives,
2. Protection of the marine environment,
3. Protection of the cultural heritage and of property,
4. Safe and efficient navigation.

The primary requirements for a VTS system may be incorporated into two basic groups concerning the qualities of the surface picture generated and the services provided by the VTS system. Quantitatively, the quality of the surface picture can be phrased in terms of the "track integrity time" and "track quality", which specify the average lives of identified tracks within a VTS area, and the type, resolution, accuracy, availability and update rates of the related track and environmental data, respectively. On the other hand, the quality of the services provided by a VTS system, can be rated by considering its effectiveness in reducing the risk of accidents in regard to the state-of-the-art techniques and technologies, their conformity with the international and national rules and regulations, and their cost-effectiveness.

System constraints involve [2] monetary, legislative, legal and technological factors imposed by the national and international authorities, as well as system implementation time constraints.

In view of the defined priorities, the system design work then seeks to achieve an optimal balance between the conflicting factors imposed by the system requirements and constraints, following a methodology which adheres to good design practices and takes into account factors such as modular/open system architecture and evolutionary, phased implementation. The methodology used in designing the Turkish VTIMS is illustrated in the flow-chart given in Figure 1, where the major components of the designed system are shown together with interactions between the various system requirements and constraints which effect the system design. In the following we shall take a closer look to the three modelling and simulation functions represented by shaded blocks in this figure.

The VTMIS system being implemented by Turkey for the three VTS areas of the Istanbul and Çanakkale Straits and the Sea of Marmara is an integral system operated by the Vessel Traffic Control Centres (VTC) of Istanbul and Çanakkale. This system, which was designed under the direction of the authors, uses the most up-to-date technology to provide maximum safety and efficiency of navigation and protection of life and environment as well as maximum effectiveness in minimizing possible damages resulting from marine accidents. Although not shown in the figure, the design also includes emergency services utilizing appropriately equipped vessels and helicopters for fire fighting, pollution control and search and rescue operations which will go into action when accidents occur.

For the provision of an effective VTS it is necessary to collect data continuously about vessels, sea state, meteorological and other environmental conditions. For these data to be collected, evaluated and distributed to all those concerned it is

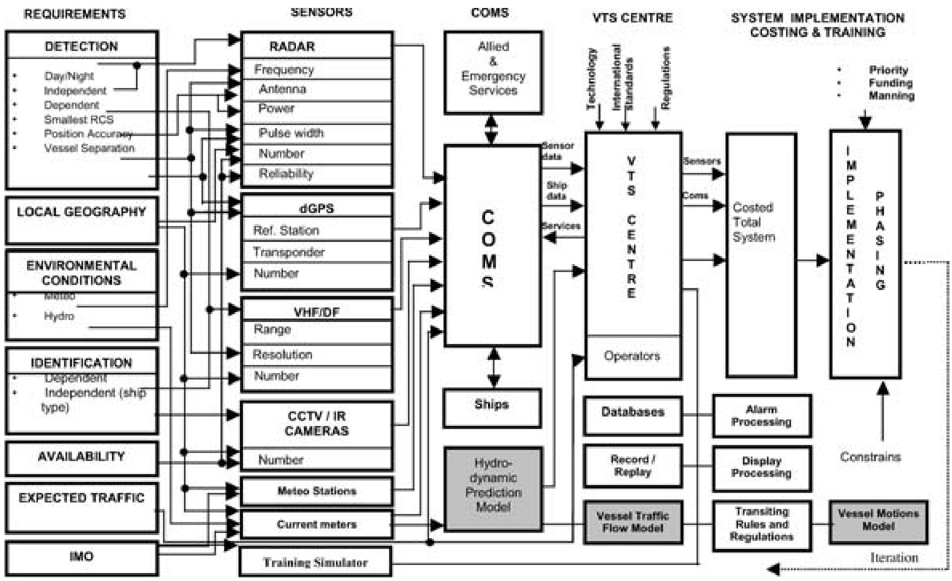

Figure 1. VTS system design methodology.

necessary to have radars, hydrological and meteorological sensors, imaging day/night cameras, dGPS stations and pilot carry-aboard laptop packages (computer and dGPS transponder) which combines GPS satellite data with dGPS corrections and VTMIS traffic and weather data including automatic vessel identifications using AIS technology, VHF and MF/HF communications, VHF direction finders (DF), RACONs and other navigational aids. The configuration of the Turkish VTMIS, depicted in Figure 2, is determined in such a way as to meet all system requirements, comply with all defined constraints and provide 99·9% availability. There are 8 unmanned Remote Sensor Sites (RSS) in the Istanbul Strait, 5 in The Strait of Çanakkale and 3 RSS in the Marmara Sea. Each RSS carries two redundant radars, day/night cameras, meteorological sensors and communications terminals.

In addition to the elements mentioned above, the VTMIS will have an "expert system" (ES) which will be used to provide various vessel traffic services such as vessel passage schedules and safe vessel speeds. The ES is a decision aid for preventing critical navigational situations arising in the Straits. It will advise the traffic controller which vessels wishing to transit will have to wait, their route and speed and what would happen if the advice given were not carried out by the ship master concerned. ES enables the vessel traffic to be managed in complete compliance with the adopted risk minimizing rules and regulations by taking full account of all relevant data, available at the VTC, both of static (such as waterway and ship characteristics) and dynamic nature (such as ship's position, speed, sail plan, cargo, and environmental conditions). The modelling and simulation requirements for the development and operation of the ES can be broken down into the following three tasks.

- "Vessel Motions Model" (VMM) which serves for identification of critical navigational situations and for evaluation of the risk-minimizing transit rules and regulations to be imposed.

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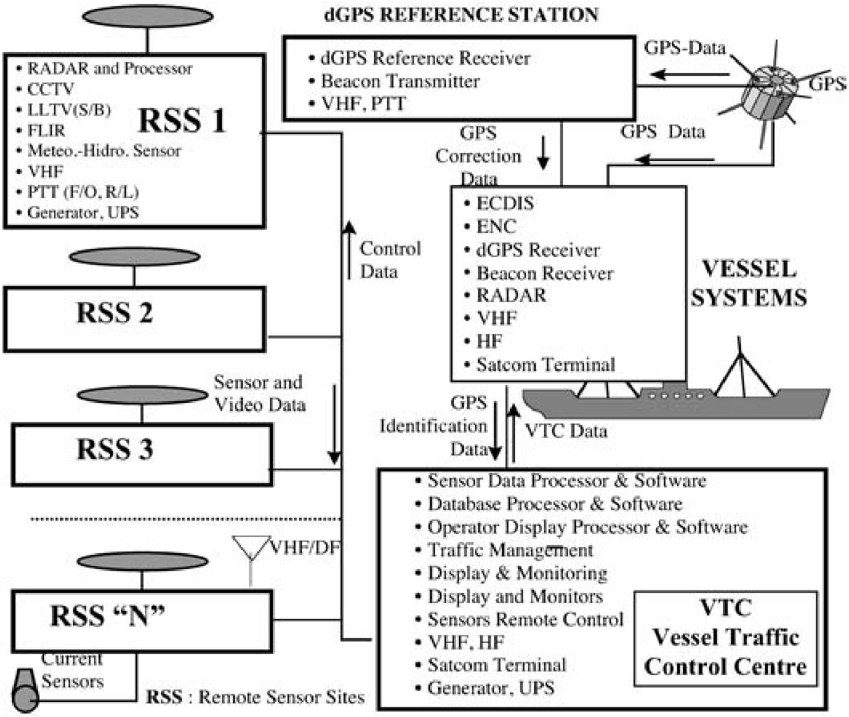

Figure 2. VTMIS configuration for the Turkish Straits.

- "Hydrodynamic Prediction Model" (HPM). Currents are a major contributor to accidents in the Strait. The HPM uses measured real time data as input to predict the Strait currents to be encountered by the vessel on its course.
- "Vessel Traffic Flow Model" (VTFM) constitutes the main building block of the ES. It is responsible for the scheduling and monitoring of vessels transiting through the Strait. VTFM also provides the man-machine interface for decision-makers, as well facilities for statistical analysis of the traffic data.

These modelling and simulation tools will be discussed in more detail in the following sections.

2. MODELLING AND SIMULATION OF VESSEL MOTIONS.

2.1. *The role of simulation programs in preventing casualties.* Marine Navigational Simulators (MNS) are found to be useful, even essential, tools for the general training of seamen in order to prepare them to cope with unusual situations during sailing and more generally with maritime activities of all kinds. Today, most of the world's maritime organizations use MNS tools of various kinds. When new ships are delivered to their owners, vessels are often accompanied by their specific, validated navigation simulation programs. Within the context of this paper the role of the MNS is to predict ship's behaviour in sea regions with critical navigation conditions, and hence, they must take into account numerous and instantly changing external conditions, which influence the ship's motion. There are several commercial MNS tools available which are delivered with libraries containing large numbers of validated ship models and with facilities that allow the control of both ship and environmental conditions. These enable us to conduct various trials, almost impossible to do in real life. These simulators provide modules for ship control, external effects and navigational aids. The elements for ship control are; options for the engine selection, change of rudder angle and selection of thrusters (if they exist). The controllable external effects are direction and speed of wind and current. A three dimensional view of the environment and radar video images are used as the navigational aids. It is therefore possible to stipulate risk-minimizing navigational rules, assess their effectiveness, and determine the measures to be taken, or to be brought to the attention of the ship's master by the simulation for the designated ship and environmental parameters, taking into account the casualties that occurred in the past and possible ones in the future.

The hydrodynamic characteristics of a vessel can be specified using analytic and empirical methods and are tabulated as parameters of a system of equations. A table prepared in this way contains all the basic information needed for the determination of the accelerated translational and the rotational movements of the vessel. The second aspect to be modelled would be the propeller or propellers. There are tables available which give the performance characteristics of the various types of propellers used (with 3, 4 or more blades and fixed or variable pitch). When selecting the rotational speed and power characteristics of the propeller it is necessary to know the characteristics of the engine used in the vessel or alternatively to model the engine separately or together with the propeller. The third important aspect to be modelled is the rudder. Modelling of the rudder is accomplished by determining the hydrodynamic forces as defined by the rudder hydrodynamical parameters as a function of the rudder profile characteristics and rudder angle.

In addition to the critical navigational conditions, engine and rudder malfunctions, fire etc. may be the cause of casualties. All of these may be conceived as "Ship Safety State Model" [2]. In this model, the state entities (risk entities), which can be an initiator or contributor to accidents, would be as follows:

- Bridge operations (commands, process, staff),
- Route (channel width, other ships, depth, heading, docks),
- Ship engine,
- Ship control (response to rudder commands),
- Environment (wind, current, visibility),
- Ship cargo (fire potential, loading),
- Ship structure.

The state entities which may change the above states by interaction may be:

- Ship data (radar, charts),
- Condition of ship (corrosion, design, equipment, maintenance),
- VTS Authority (data, inspection, navigation aids, radio, radar, SAR),
- Ship ownership (management, access to capital, experience),
- Logistics (food, fuel) and personnel (number, training, experience).

The factors listed in the first group above are also represented in our simulation trials.

2.2. *Simulation trials.* We have conducted an extensive simulation campaign using a Vessel Motions Model (VMM) built on a commercial MNS tool by modifying

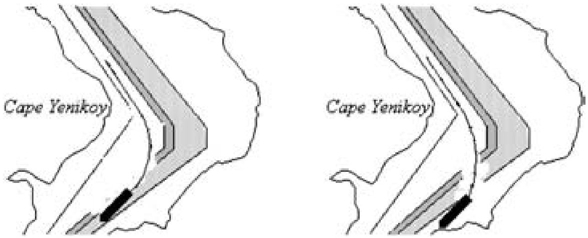

Figure 3. A 261 m tanker, a) crossing over to the other lane, b) Ramming into the opposite shore.

its environmental modelling modules in order to be able to realistically represent the variabilities of current/wind conditions encountered in the Strait. Experienced masters took part in the campaign in order to verify that the ship models used in the simulation tests react truthfully to commands of their masters under different navigational conditions. The aim of the campaign was the identification of: (a) navigational scenarios which bear high accident risk, and (b) applicable risk mitigation measures. Simulations were performed using different ship models in scenarios which, based on the historical data on accidents in the Strait or on expert opinion, were identified as possible suspects for build-up of high risk conditions for transiting vessels.

Investigation of past accidents shows that, in addition to the navigational parameters which are common to most accidents, the ship's parameters are also important. Among the numerous parameters which affect ship maneouvres the most important ones are: the ship's hydrodynamic performance, length, structure, engine power, propeller and rudder characteristics, thruster etc. Another important factor in examining the critical navigation conditions, relates to wind and current which, under the conditions necessitating sailing with low speed, may seriously hamper the ship's ability to maintain its designated route thus becoming the main reason for ship accidents. To further illustrate this point it would be helpful to discuss a typical example of the outcome of the simulation trials in more detail.

2.3. *A closer look at a simulation trial.* The site for this test is chosen as the Cape Yeniköy (Figure 3). Cape Yeniköy, one of the sharpest turning points in the Strait of Istanbul is also one of the most critical regions for navigation. There is a shallow area (less than 20 m deep) just near the Cape, and the width of the designated Traffic Separation Lane for this region seems quite "narrow". A 10 knot speed limit with respect to the ground, imposed in the Strait in order not to disturb small vessels in the area as well as the shore assets, worsens the effects of the above negative factors, particularly for vessels sailing downstream, when weather and current conditions deteriorate.

The vessel considered in this test is one of the larger tankers, the likes of which transit the Strait at a frequency of about 0·8 vessels/day. The set of investigated environmental conditions are given in Table 1, together with the main characteristics of the vessel. In the four test cases representing the different environmental conditions shown in Table 1(b), the tracks obtained for different ship speeds were different as illustrated for the two cases in Figure 3 even though the rudder was commanded hard-starboard always at the same location when approaching Cape Yeniköy. The results of the trials are summarized in Table 2, where shaded areas

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Table 1. Vessel characteristics and environmental parameters used in the tests.

(a) Vessel characteristics		(b) Environmental parameters Currents: Downstream (along the course), Winds: NW	
Type	Oil Tanker	Testcase 1	No current, No wind
Length (m)	261	Testcase 2	Current 3 kn, No wind
Displacement (t)	159 584	Testcase 3	Current 6 kn, No wind
Max. cruising speed (kt)	15	Testcase 4	Current 6 kn, Winds 30 kn
Turning radius/length (deep/shallow water)	4·5–8		
Thruster	No		

Table 2. Trial results with a 261 m tanker.

Ship speed kn	Test 1	Test 2	Test 3	Test 4
4	Successful	Crossing over to the other lane	Ramming into the opposite shore	Ramming into the opposite shore
5	Successful	Crossing over to the other lane	Crossing over to the other lane	Ramming into the opposite shore
10	Successful	Successful	Crossing over to the other lane	Crossing over to the other lane

indicate that corresponding vessel/current speed combinations violate the 10 kn speed limit with respect to the ground imposed in the Strait. The results of this test, as well as of the numerous other tests we performed using different scenarios clearly demonstrate the need for adoption of risk-minimizing operating rules and procedures for transit traffic through the Strait. The information thus provided by the simulation trials as described above, for the designated ships and environmental conditions, allows forward planning and navigation which would prevent dangerous situations from arising in the future.

3. MODELLING OF CURRENT CONDITIONS.

3.1. *Model outline.* Surface sea currents affect navigation and therefore safety and their presence and future intensities/directions should therefore be measured and predicted for safe and efficient navigation as well as for pollution control. This is achieved via the Hydrodynamic Prediction Model (HPM) to be discussed in this section. The HPM was developed by our group and will be used to predict currents up to four hours in advance anywhere in the waterway for the preparation of sail plans for vessels thus minimizing the risk of accidents. The system design includes an adequate number and type of sensors (current, water level, atmospheric pressure, wind, water salinity and temperature) to be deployed in the Strait, in order to provide input data for the model. The objectives set forth for the model were derived from the operational requirements as: (a) to be able to extend the surface current data measured in real time at nine appropriately chosen locations in the Strait to all points of a 50 m × 50 m mesh bounded by the two traffic lanes, (b) to be able

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to predict future variations of these currents for a time span of four hours, and (c) to perform both tasks within error margins of $\pm 0{\cdot}5$ kn in amplitude and $\pm 10^\circ$ in direction.

The currents in the Strait are of a quite complicated nature: under normal conditions the flow is in the North–South (N–S) direction, from the Black Sea to the Sea of Marmara and the Aegean Sea, and it is in the reverse direction (S–N) in the bottom layers. These two flows are separated by a spatially as well as temporally varying zero-velocity boundary layer. The main driver of the surface currents is the water-level difference between the two ends of the Strait which in turn depends on the water balances in the Black Sea and the Sea of Marmara and on the direction and force of the winds prevailing in the area. Currents are also affected by several other factors, such as the salinity and temperature gradients, tidal conditions, and, of course, the geography and bathymetry of the Strait. Given the above outlined complicated nature of currents and the fact that no systematically measured data was available, we had to launch an extensive, continuous measurement effort which lasted for about 18 months in order to identify the main characteristics of the currents in the Strait and their spatial and temporal variabilities. An extensive account of the results of the campaign will be reported elsewhere. Here, it suffices to say that it is the understanding gained through the processing and analysis of this measurement data, which made the development of the HPM possible. On the other hand, this data has also allowed us, albeit in a necessarily limited sense, to validate our model. The final calibration and validation tasks will be performed, once the meteorological and hydrographical sensors are deployed in the Strait and the measured sensor data is made available to the model.

The mathematical framework of the HPM is based on the Navier-Stokes equations, which, however, utilizing the understanding gained through the measurements, have been cast into a numerically manageable form suitable for calculating the current conditions encountered within the traffic lanes in the Strait. The resultant mathematical model involves depth integrated momentum and mass conservation equations for a constant density turbulent fluid flow and can be expressed as [3, 4],

$$\frac{\partial(UH)}{\partial t}+\beta\left[\frac{\partial(U^2H)}{\partial x}+\frac{\partial(UVH)}{\partial y}\right]-fVH+gH\frac{\partial\eta}{\partial x}-\frac{\rho_a C^* W_x\sqrt{W_x^2+W_y^2}}{\rho}+\frac{gn^2U\sqrt{U^2+V^2}}{\sqrt[3]{H}}-\varepsilon H\left[2\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}+\frac{\partial^2 V}{\partial x\partial y}\right]=0 \tag{1}$$

$$\frac{\partial(VH)}{\partial t}+\beta\left[\frac{\partial(UVH)}{\partial x}+\frac{\partial(V^2H)}{\partial y}\right]-fUH+gH\frac{\partial\eta}{\partial y}-\frac{\rho_a C^* W_y\sqrt{W_x^2+W_y^2}}{\rho}+\frac{gn^2V\sqrt{U^2+V^2}}{\sqrt[3]{H}}-\varepsilon H\left[\frac{\partial^2 V}{\partial x^2}+2\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 U}{\partial x\partial y}\right]=0 \tag{2}$$

$$\frac{\partial\eta}{\partial t}+\frac{\partial(UH)}{\partial x}+\frac{\partial(VH)}{\partial y}=0 \tag{3}$$

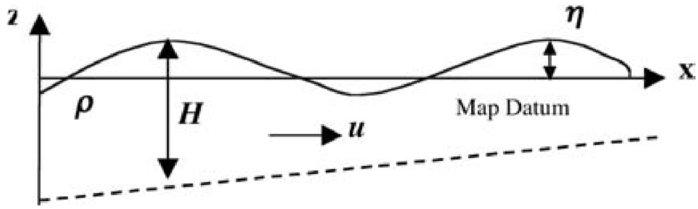

Figure 4. Model parameters.

In the above equations U, V stand for x and y components of the depth averaged velocity, respectively, and t denotes time; β, a correction factor to account for the non-uniformity of vertical velocity profile; f, Coriolis parameter; η, water surface elevation above Chart Datum; H, total depth of flow above the boundary layer; g, gravitational acceleration; ρ_a, air density; C^*, air-water interfacial resistance coefficient; ρ, fluid density; n, Manning bed roughness coefficient; and ε, depth averaged eddy viscosity. The coordinate system is shown in Figure 4. The associated boundary conditions in the horizontal plane are the vanishing of the normal velocity component on the physical boundaries of the waterway and a radiation condition on the boundaries of the computational domain.

3.2. *Model outputs.* The mathematical model described above is implemented utilizing a finite difference algorithm expressed in an alternating direction implicit form, which results in basically second order accurate iteration scheme with no stability constraints [4]. The model is configured to work on a stand-alone PC platform, to import measured sensor data from the sensor database of the VTMIS and to feed its outputs to the ES database. The model also provides a Graphical User Interface (GUI) and archiving facilities to external users, for off-line statistical analysis.

HPM was subjected to several test runs, utilizing water-level differences measured by us at both ends of the Strait in real time as the driving mechanism, and the output of a single current sensor deployed by us on a central location in the Strait as for calibration purposes. The data generated by the model were then compared with the measured current data in discrete time and space obtained from a boat-mounted sensor. Typical distributions of magnitude and angle errors between model estimates in real time and corresponding measurement data are depicted in the histograms given in Figure 5. Differences between the current data predicted at any location up to 4 hours ahead and the data measured at that location at the corresponding times exhibit a similar behaviour and, hence, are not reproduced here.

4. MODELLING AND SIMULATION OF VESSEL TRAFFIC FLOW.

The objective of the traffic flow simulation is to study the traffic system in a narrow and congested waterway, as exemplified by the Turkish Straits, formed by the transiting vessels interacting with each other, with traffic regulations and with the environmental factors (geographic, meteorological, hydrologic). Traffic Flow simulation helps to conduct experiments on the narrow passages and allow the following questions to be answered:

- What is the quality of service provided?
  - How many vessels can transit in a limited time period?
  - How many vessels have to wait in the queue and for how many hours?

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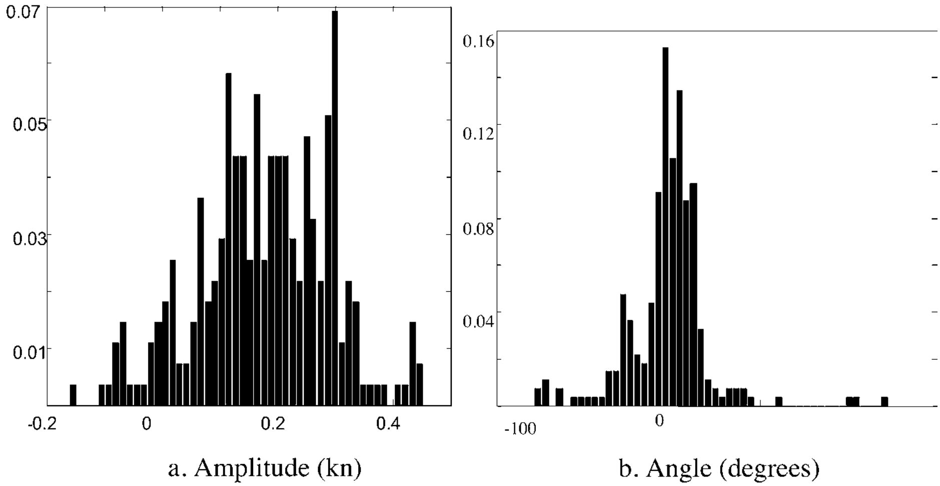

Figure 5. Distribution of (a) amplitude and (b) angle errors.

  – What is the accident risk associated with the traffic regulations in force?
- What if traffic service demand increases in future and what kind of possible system weaknesses can result?
  – What happens if the number of vessel increases?
  – What are the effects of an increase in the number of specific vessel types?

The simulator also provides a test bed environment, which allows the development of optimum navigational rules before they are formalized for the waterway, and the estimation of additional system improvements which may be brought about by technological developments. A simulation tool is often required for the design of new VTS systems and/or improving the safety and efficiency of navigation in existing VTS areas including ports, harbour approaches, straits and channels.

The following factors bear on these problems:

– geographical restrictions imposed by the waterways: width, turns and bathymetry.
– environmental factors: winds and currents, visibility, precipitation and waves.
– vessel traffic characteristics: density and variance, composition, arrival statistics.
– vessel characteristics: length, weight, speed, manoeuvring capabilities, cargo and associated risks.
– "service regime": set of national and international rules for regulating traffic.
– priority rules: used to determine the order in which the vessels waiting in the queue enter the waterway; FIFO (first in first out), smaller before large, hazardous before non-hazardous, etc.

The simulator that is needed must be designed in such a way to enable the maritime authorities to address the following specific issues:

i. Determine the inter-relationships between the above given factors in a quantitative manner.

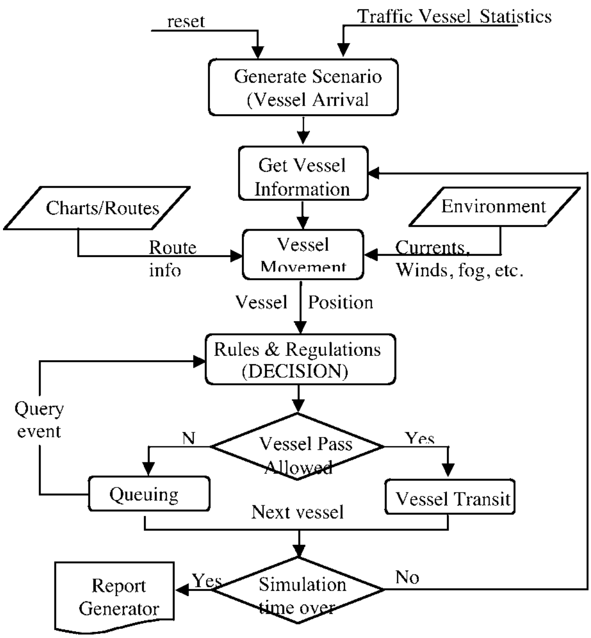

Figure 6. The logical flow of GETSIM.

ii. Determine the optimum "service regime", a balance between safety and efficiency.
iii. Generate simulated statistical data on traffic flow to be used for planning of future upgrades of the service regime, system software/hardware features and for risk assessment.

4.1. *Model outline.* "GETSIM" (Vessel Traffic Simulator) which has been developed and used for the Turkish Straits project has the logical flow diagram depicted in Figure 6. The functions performed by different blocks shown in the figure are described below:

4.1.1. *Traffic statistics.* The flow of maritime traffic, as the flow of any traffic, is determined primarily by the arrival statistics and the characteristics of the waterway. Normally, some statistical data on certain aspects of the maritime traffic in the area of interest would be available. We shall assume that the following are known:

- Statistical data on ship arrival times,
- Statistical data on ship parameters, including:
  - dimensions (length, width, height),
  - speed (maximum, cruising),
  - manoeuvring capabilities (thrusters, one or two propellers),
  - cargo (type, hazard class).

In general, some processing of the available statistical data and in some cases additional observations would be needed in order to determine and to validate the traffic statistics to be used in the model. The following conditions are assumed to apply for the specific application of GETSIM discussed in this section.

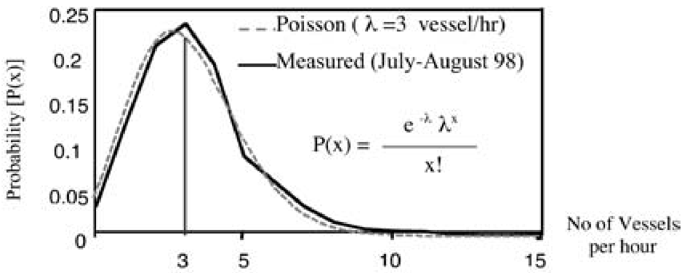

Figure 7. Validated vessel arrival statistics for the Strait of Istanbul.

- Arrivals per unit time of the transiting vessels are closely represented by Poisson distribution with given average arrival rates in each direction (see Figure 7).
- Dimensions and speeds of ships can be assumed to obey a truncated Gaussian distribution with specified average values and standard deviations.
- The probabilities related to the composition of the traffic in terms of ship types is available. This information can be used to distinguish between ships carrying hazardous cargo and those that do not.
- Information is available on the flags, and sometimes also on ship identities, which can be used to assess the manoeuvring capabilities of the various ship classes in a statistical manner.

4.1.2. *Environmental factors*. The model uses the geography of the area, and the statistics on the temporal and spatial variation of the currents, winds, and visibility conditions in the area. Currents and winds are used to modify ship speeds on the various legs along its planned course and are assumed to be constant during a simulation run. Seasonal visibility statistics are used to generate random time intervals within which different rules may apply to transiting vessels. Geographical data relate to the map data. The model is designed to operate on Electronic Navigational Chart (ENC) data but can also accept raster map data. Facilities are provided to define water column depths, man-made and natural obstructions and hence the limits of navigable waters for different ship types. Traffic planning and monitoring aids can also be obtained including Traffic Separation Schemes (TSS) and high risk zones, i.e. areas such as sharp bends, narrow stretches and areas with high currents where overtaking and encounters may be very hazardous.

4.1.3. *Rules and regulations*. The model accepts various rules of navigation and enforces them to all vessels, thereby simulating a traffic situation wherein all vessels comply with all the rules applicable to them. These rules and regulations which constitute the "service regime" may include [2]:

- Service discipline. This is related to the priorities given to arriving vessels when ordering them in the queue of vessels waiting their turn to enter the waterways and may include such rules as FIFO (first in first out, or first come first served), LIFO (last in first out), large before small, etc.
- Distance between ships between ships sailing in the same direction.
- Maximum sailing speeds in various parts of the area, and corresponding minimum sailing speeds.
- Rules for overtaking.

- Rules for ship encounters as a function of ship length, cargo (hazardous, non-hazardous), geographical area of the encounter and the prevailing environmental conditions in the area, etc.
- TSS limits.
- Types of limitations on the flow of traffic and the conditions under which they apply. These limitations may include:
  - Closing one or both directions (total closure) to traffic,
  - Modifying the rules which apply under normal conditions, such as setting different criteria for distances between ships, ship speeds, and for overtaking and encounters, depending on the environmental conditions (visibility, fog, strong unpredictable currents) and on the characteristics of the vessels (large vessels carrying dangerous cargo, etc.).

The model performs all the necessary logical controls in order to assure that the motions of each vessel in the traffic comply with the appropriate subset of these rules.

4.1.4. *Input queue*. The construction of the input queue is described below assuming that the arrival statistics conform to a Poisson distribution and the distribution of the vessels among various ship types as well as their lengths and speeds approximates to a truncated Gaussian distribution as noted above. The model takes the simulation time (T) and the number of ships (N) to be generated in a specific simulation run as inputs, together with the probabilities of ship types and averages, standard deviations, and the truncation criteria of ship speeds and lengths, which are all derived from existing statistical data and performs the following operations:

- A ship is scheduled to arrive at simulation time zero. Subsequently the inter-arrival time differences between the arrival times of, say n-th and $(n+1)$th vessels is obtained from an exponential distribution

$$\Delta t_n = \frac{-1}{\lambda} \log_e U; \quad n = 1, 2, \ldots, N \tag{4}$$

  where U stands for an uniformly distributed random number in the interval 0, 1, and λ represents the average arrival rate of the Poisson distribution i.e., $\lambda = N/T$. These inter-arrival times are then normalized so that their sum complies with the total simulation time T. The time of arrival of the n-th vessel, (t_n), can then be expressed as,

$$t_n = T \sum_1^n \Delta t_n \Big/ \sum_1^N \Delta t_n \tag{5}$$

- For all vessel arrival times t_n, as determined above, the model assigns a vessel with an average ship length obtained by utilizing the frequencies of occurrence of that average length as determined from existing statistical data, and randomises this length using a truncated normal distribution. The following algorithm is used for this purpose:

  Generate two random numbers R_1, R_2, from a uniform distribution in $(-1, 1)$ and calculate:

$$\Delta L = \sigma R_1 \sqrt{\frac{-2 \log_e(s)}{s}}; \quad s = R_1^2 + R_2^2 \tag{6}$$

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where, σ is the standard deviation of the distribution. If ΔL is not less than a user specified truncation limit (default value used is 2σ) repeat the above steps as necessary until this condition is met. Calculate the randomized value of ship length as, $L = \bar{L} + \Delta L$. The model then assigns a type (tanker, container ship, cruiser, etc.) for each ship, using the frequencies provided for these ship types as derived from the existing statistical data. The arrival times, lengths, and types of vessels are written in a file for further processing.

4.1.5. *Ship routes.* Ships are assumed to move along prescribed routes, defined as a sequence of waypoints. The model provides facilities to define the waypoints and assign different random components to its average speed at different waypoints which are determined as a function of the prevailing local current and wind conditions. These random components are updated at user defined intervals.

4.1.6. *Service regime.* Together with the ship arrival statistics, the service regime, which is the totality of rules and regulations imposed selectively on all transiting vessels, is the main factor in determining the traffic delays and the throughput of the waterways. Arriving vessels, in both directions of the waterways either pass freely through the waterways, or they queue up (on both sides) and wait for their turn to enter, as determined by the service regime imposed. The waiting times of vessels in the queue will be referred to as "delay", since they add up to the normal transiting time of each vessel. Clearly, delay is a random variable which is a function of the vessel's arrival time, type, speed, and of the service regime. On the other hand, the aim in introducing a service regime is to reduce the risk of accidents, while at the same time increase the efficiency of traffic flow. The efficiency of traffic flow can best be described by the "throughput" which is the average of the vessel-transiting rate. Since there is limit to the traffic handling capacity of all waterways the throughput has an upper bound which is a function of the service regime as well as the permissible average delay. It is well known from queuing theory [5] that throughput of a channel can, in general, be increased by increasing the average delay which in turn will result in longer queues. The determination of a balance between delay and optimal throughput is one of the main problems of traffic engineering and is one of the main issues which GETSIM is designed to address.

In the simulation, the service regime is modelled through a sequence of logical operations, which perform various controls, in order to ensure that the specified rules and regulations are properly exercised. The logical operations performed by the model can be outlined as follows:

- At the start of the simulation, a sail plan for the first vessel is generated and its transit scheduled, and then its position on the assigned ship route is updated until it exits from the area of interest. When this ship leaves the area of interest the ship statistics (type, length, time of exit, time spent in the queue, i.e., delay) are recorded for the purposes of generating reports and the ship is dropped from the simulation.
- At subsequent simulation times, when the simulation time reaches the arrival time of the next vessel, and the input queue is empty, i.e., no ships are waiting for service, all applicable rules and regulations (service regime) are imposed and considering all other vessels presently in transit, a decision is made as to whether or not the arriving vessel can be allowed to enter the waterways. If yes, the vessel proceeds as explained above, if no, the ship is put into the input queue.

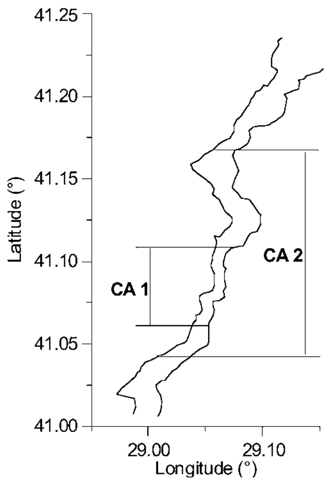

Figure 8. The Strait of Istanbul and critical areas.

- If the input queue is not empty at the time of arrival of the ship, then using the specified "service priorities" the entrance order of the waiting ships is updated.
- When the service regime allows the entrance of a vessel to the waterways from either direction, then the pending ship from the respective queue is scheduled for entrance and the order of the waiting ships in the queue is updated accordingly.

4.2. *Sample outputs.* Some examples of the outputs that can be generated using GETSIM assuming the specific geography, traffic parameters and service regime which are descriptive of the Strait. The environmental parameters will, however, be grossly simplified for the sake of brevity. The input data used in these simulation exercises can then be listed as follows:

4.2.1. *The area: The Strait of Istanbul.* The geography of the Strait is illustrated in Figure 8 together with the two sub-areas referred to as Critical Area 1 (CA1), and Critical Area 2 (CA2), since different rules may apply to ships when sailing in these areas.

4.2.2. *Traffic.* Average transit traffic density is 4200 vessels/month (both ways). The relative normalized frequencies (probabilities) of the various ship types/lengths, for which different rules may apply, together with the abbreviations to be used to represent these different cases in describing the service regime are as shown in Table 3.

4.2.3. *Ship routes – Transiting speeds.* Ship movements will be accounted for in a simplified manner in these simulation exercises, namely the ships will be assumed to move at constant speed along predetermined routes at constant (maximum 10 knots) speed with respect to ground.

4.2.4. *Environmental effects.* As noted above, for brevity the environmental factors, especially those related to the representation of the very complicated nature of the currents in the strait are introduced in a greatly simplified manner. The average effects of the prevailing currents are accounted for, in a grossly approximated manner, by making allowance for different ship speeds when sailing in opposite directions, i.e., north-to-south (N→S) and south-to-north (S→N), in order to represent an

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Table 3. Probabilities of ship types/lengths.

Ship type	Ship length (m)	Probability	Abbreviation
Any	$L \geqslant 300$	0,05	LS
Tanker	$300 \geqslant L > 250$	0,55	LT
Tanker	$250 \geqslant L > 150$	3,60	MT
Tanker	$150 \geqslant L$	5,80	ST
Non-Tanker	$300 \geqslant L > 150$	25,8	MS
Non-Tanker	$150 \geqslant L$	64,2	SS

Table 4. Probabilities and durations of various visibility conditions.

Visibility (nm)	Probability (%)	Duration (hr)	σ (hr)
<1,0	0,066	6	2
<0,5	0,045	6	2

average effect. The probability for occurrence and duration of the three visibility conditions for which different transiting rules may apply are listed in Table 4. Durations are assumed to obey Gaussian distribution with the indicated standard deviation σ, truncated at the $\pm 2\sigma$ limits.

4.2.5. *Service regime*. The service regime described here derives from the actual service regime in force in the Istanbul Strait. However, certain omissions (e.g., rules depending on current strength), modifications and simplifications are introduced for convenience. In particular, only the following six rules of navigation are outlined below which are a small subset of the whole of the applicable rules:

- Rule 1: Large ships "LS" (Ship length >300 m). No other ships can use the Strait before the LS completes its transit, i.e. Strait is closed to all other traffic in both directions. LS can transit day and night. If, however, the LS carries dangerous cargo (a tanker) then it can transit only in daylight.
- Rule 2: Large Tankers "LT" (300 m $\geqslant$ vessel-length $\geqslant$ 250 m). Vessel completes its transit in daytime, and the Strait is closed in the opposite direction.
- Rule 3: Medium–large Tanker "MT" (250 m $\geqslant$ vessel-length $\geqslant$ 150 m). The vessel is not allowed to encounter any vessel in both critical areas (CA1 and CA2, in Figure 8), additionally, tankers longer than 150 m are not allowed to enter to the Strait from either direction until MT completes its transit.
- Rule 4: Medium–large Ships "MS" (Ships carrying non-hazardous cargo, with length greater than 150 m). Encounters are not permitted within CA1 with similar ships (and with ships specified in Rules 1 through 3).
- Rule 5: Limited visibility (visibility <1·0 nm). If visibility drops below 1 nm, the Strait will be open for vessel traffic only in one direction, until visibility conditions improve.
- Rule 6: Bad visibility (visibility <0·5 nm). If visibility drops below 0·5 nm, the Strait will be closed for all vessel traffic until visibility conditions improve.

Some examples of the outputs that can be generated by the report generator are given in Table 5 and Figure 9. Vessel transit speeds are taken as 10 knots in North–South (N–S) and 7 knots in S–N directions in all calculations except for the

Table 5. Increase of waiting and strait closure times with increasing number of hazardous cargo carrying vessels.

Tanker ratio (%)	No of vessels passed (%)	Average waiting (hr)	Closure (hr) One dir	Closure (hr) Two dir	Encounter prevented (%)
10 (today)	100	2	12	83	48
15	85	60	15	132	48
20	70	146	22	158	48
25	54	283	31	205	48
30	47	404	45	240	48

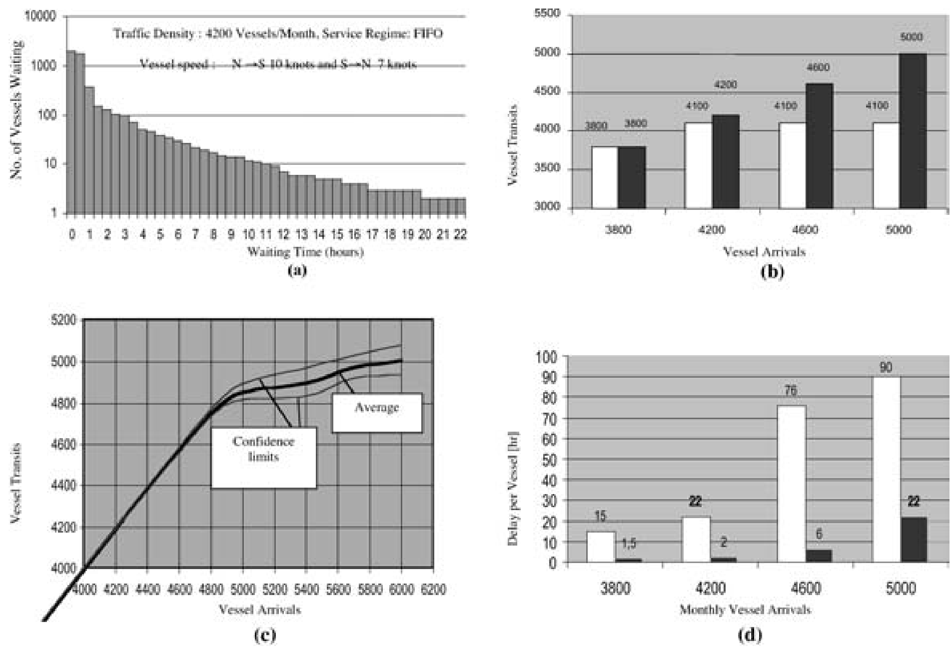

Figure 9. (a). Monthly vessel delay distribution; (b). Monthly vessel transit statistics for two sets of speeds; (c). Monthly average throughput with 95% confidence limits; (d). Variation of average delay as a function of vessel arrival rate and speed.

results shown with white bars in Figure 9b and 9d which correspond to the assumption that the transit speeds are 10 knots and 5 knots in the N–S and S–N directions, respectively.

5. CONCLUSIONS. The following important conclusions may be drawn from the above simulation studies for the Strait of Istanbul.

– As for all channels, the capacity of the Strait of Istanbul is limited and there is a trade off between the number of vessels which can transit and the queueing delay. Regardless of how many vessels arrive for passage through the Strait the

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number that can actually pass without incurring unacceptable delays does not exceed 5000 vessels per month.

– The casualties in Istanbul are expected to be reduced to levels below one fifth of the present level. This is made possible by the traffic regulations which will be enforceable by a modern VTMIS which is at present being implemented.
– The traffic regulations are expected to reduce the probability of encounters (i.e. risk of collision) of vessels carrying hazardous cargo in critical areas from zero to 50% depending on the extent of these areas.

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