A Real-Time Ship Manoeuvring Simulation Study for the Strait of Istanbul (Bosporus)

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During the past thirty years, there has been a steady growth in the size and number of ships that use the Strait of Istanbul (Bosporus), which is one of the most difficult, crowded, and potentially dangerous waterways in the world. There have been over two hundred accidents over the past decade resulting in loss of life and serious damage to the environment. Many of the proposed export routes for forthcoming production from the Caspian sea region pass westwards through the Black Sea and the Bosporus en-route to the Mediterranean Sea and world markets. The risks and dangers associated with tanker navigation, maritime accidents and environmental catastrophe are aggravated with the increase in the density of traffic, tanker size and cargo capacity, as well as the nature of the cargo. In order to ease the problem, a Traffic Separation Scheme (TSS) was established and approved by IMO in 1994. This scheme has drastically reduced the number of collisions. However, one-way or two-way suspension of traffic in the Bosporus is inevitable for ships that cannot comply with the TSS because of their type, size or poor manoeuvring characteristics. The selection of size criteria to comply with the TSS has been a matter of discussion. This paper presents the results of a real-time simulation study investigating the manoeuvring performance of large tankers in the Bosporus. The study was conducted with a simulator capable of subjecting a given hull form to any combination of environmental conditions, i.e. wind, current and wave drift forces. The results indicate that, when realistic environmental conditions are taken into account, the size of ships that can navigate safely in compliance with the traffic separation lanes is limited.

1. INTRODUCTION. The Turkish Straits, comprised of the Bosporus, the Dardanelles, and the Sea of Marmara, form a vital link between the Black Sea and the Mediterranean. The Strait of Istanbul (Bosporus) lies between the Black Sea to the North, and the sea of Marmara to the South, which is connected to the Mediterranean via the Dardanelles, as shown in Figure 1. A satellite view of the Bosporus is shown in Figure 2. The Bosporus is approximately 16·74 nautical miles long, with an average width of 0·81 nautical miles. It is only 700 metres wide at its narrowest. This narrow, and difficult-to-navigate, channel is one of the busiest seaways in the world. An average of 50 000 ships pass through the Bosporus annually, along with about 2000 ferries and smaller passenger boats. They, and countless fishing, cruising and leisure craft, contribute to make the Bosporus one of the most crowded waterways in the world. The Bosporus is roughly four times busier than the Panama canal, and three times busier than the Suez canal.

Over the past twenty years, there has been a steady growth in the number and size

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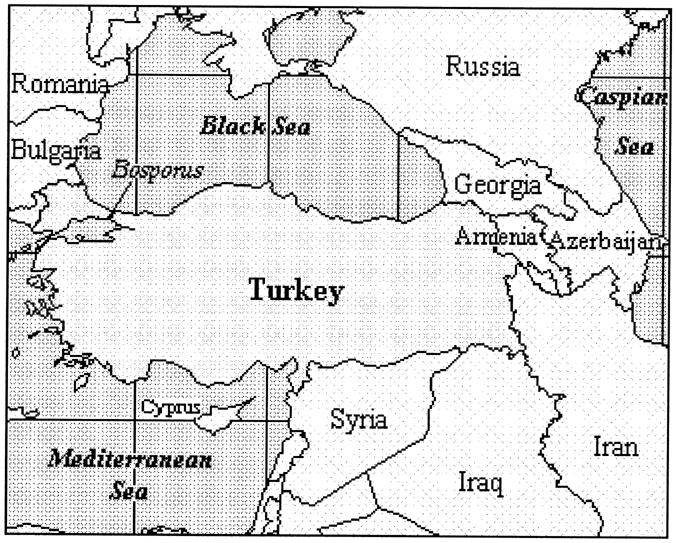

Figure 1. Geographical location of the Bosporus.

Figure 2. Satellite view of the Bosporus.

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of the ships using the Bosporus as a transit highway between the Black Sea and the Mediterranean. The following are the main contributing factors:

(a) Opening the Main-Danube Canal has linked the Rhine and Danube rivers, thereby creating a direct route between Rotterdam and Constanza. The North Sea and Black Sea have thus been integrated.
(b) An increase has recently been observed in the traffic originating from the Volga-Baltic and Volga-Don Canals bound for Mediterranean and Turkish ports.
(c) The ports of the Black Sea are the largest outlets for Russian oil exports. Exports through the Bosporus have grown since the break-up of the Soviet Union in 1991.

The already congested maritime traffic in the strait is expected to increase further, as many of the proposed export routes for forthcoming production from the Caspian Sea region pass westwards through the Black Sea and the Bosporus en-route to the Mediterranean Sea and world markets. During the next ten years, it is predicted there will be a substantial increase in the quantity of crude oil and liquefied gas exported by states bordering the Black Sea. Some estimates indicate an increase of as much as 100 million tonnes of crude oil per annum; a large percentage of this crude oil will probably be shipped out of the Black Sea through the Bosporus.[1] There is growing concern that projected Caspian Sea export volumes will exceed the ability of the Bosporus to accommodate the required tanker traffic.

The high volume of traffic in the Bosporus has increased the number of collisions and the probability of major environmental disasters. There have been over 200 collisions over the past decade. Statistics show that half of the casualties that occurred were caused by failures in ship handling such as groundings and collisions. The major causes of accidents are found to be:

(a) Rules of the road misunderstood or misconstrued,
(b) Traffic congestion leaving insufficient manoeuvring or stopping room,
(c) Adverse environmental conditions such as fog and cross currents.

Safe transportation is only possible if it is done strictly according to regulations and in a safe marine environment.[2] Control of traffic in navigational channels is considered and implemented to provide for safe, convenient and economic means of ship navigation. Today, traffic control is widely recognised as an essential element in ensuring that sea transport operate safely and efficiently. On 1 July 1994, an IMO approved Traffic Separation Scheme (TSS) was implemented to help regulate shipping through the Bosporus waterway.[3] The TSS comprises designated traffic lanes and associated separation zones. Within these lanes and zones, regulations require compliance with the TSS, but this is not possible for some ships because of their type, size or manoeuvring characteristics. Therefore, one-way or two-way suspension of traffic in the Bosporus is inevitable for ships larger than the specified size limits. The selection of these limits is mainly based on the experience of the pilots and has been a matter of discussion between the ship operators and the regulatory bodies.

The safety of navigation in channels requires precise knowledge of the manoeuvring behaviour of a ship under the effects of water depth, channel bank, hydrodynamic interactions between ships meeting and passing, and environmental conditions such as wind, wave or current. Clearly, analytical techniques need to be developed to evaluate qualitatively the navigational safety of large ships in the Bosporus. A well established and proven manoeuvring simulation study is considered to be the most reliable method for such a purpose.

In this paper, a computer-aided ship manoeuvring simulation procedure[4] is used to assess the adequacy of channel size against ship size and ship manoeuvring response. The program calculates the external environmental and thrust forces, and solves the non-linear equations of motion in the time domain so yielding the required movement and speed of the vessel. The goal of the methodology is to determine how consistently, given the ship and environmental characteristics, a pilot can navigate a specific vessel through the traffic lane in a safe manner. The study was specifically designed to address the following critical questions:

(a) Are present operations of large tankers safe?
(b) What is the margin of safety for navigating large tankers?
(c) What is the effect of environmental conditions on the manoeuvring performance of large tankers?
(d) What manoeuvring characteristics are required to navigate large ships safely?

2. CHANNEL LIMITATIONS AND NAVIGATION DIFFICULTIES.

The Bosporus is unique in many respects. The very narrow and winding shape of the strait is more akin to that of a river. All the dangers and obstacles characteristic of narrow waterways are present and acute in this critical sea lane. The Bosporus runs right across Istanbul, the largest city in Turkey with a population of 10 million. The Bosporus strait forms part of the port of Istanbul and is included within the port limits. One of the legs of the two bridges is grounded in the waters of the strait.

The Strait of Istanbul has several sharp turns. Because of abrupt bends in the route, a ship travelling through must change course at least twelve times to avoid running aground. At the narrowest point, Kandilli (700 m), a 45° course alteration is required. The current can reach 7–8 knots at this point. At Yeniköy, the required course alteration is 80°. At these turns, the rear and forward views are totally blocked prior to and during the course alteration. Ships approaching from the opposite direction cannot be seen around these bends.

The Bosporus has unique physical, hydrological and oceanographic characteristics, and complicated navigational conditions prevail in the area. Fog is most likely from September through April and can reduce visibility to below 1000 metres on 2–5 days per month during this period. It is worse in the late night and early morning. Winds are variable, particularly in autumn and winter, and are also strongest during this period. The dominant wind directions are north-northeast and south-southwest.

There are two-level currents flowing in the Bosporus, which may vary depending on the difference in the water levels of the Black Sea and the Marmara, the amount of water carried by the rivers flowing to the Black Sea, the amount of rain, the difference of density and temperature of the Black Sea, and the Marmara, and the morphological structure of the strait. Rapid changes in the speed of currents and turbulence may occur depending on the change in these factors. In general, the surface current flows from the Black Sea to the Mediterranean through the Straits of Istanbul and Canakkale and the Marmara Sea. The deep current flows in the reverse direction. The surface current flows southbound in the mid-channel and changes direction when blocked by points or entered into bays; reverse currents cause

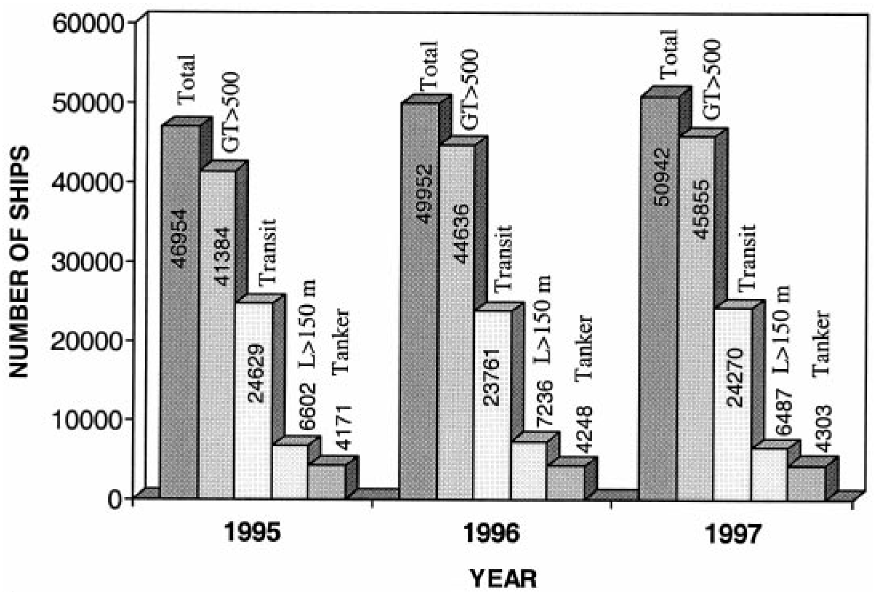

Figure 3. Number and types of ships.

turbulence and running circles in these areas. Vessels may have difficulty with steerage at the points where running circles meet the surface current. However, when a strong southern wind is blowing, the strength of the surface current weakens and even reverses; this causes a very dangerous environment for the navigation of a vessel, due to its imbalanced and non-predictable character. The average speed of the surface current is 4 knots; however, with a strong prevailing wind, rates of 7–8 knots are not uncommon.

3. VESSEL TRAFFIC AND MARITIME INCIDENTS. Approximately 50000 vessels transit the Bosporus each year; total vessel movements per day are approximately 1350. This figure does not include the movement of transiting ships (vessels in transit southbound and/or northbound through the Bosporus), leisure craft and fishing vessels. In 1997, 24270 foreign flag vessels transited through this narrow waterway, with a total regular tonnage of 91575535 tons. Figure 3 shows the number and types of ships that used the Bosporus in 1995, 1996 and 1997.

This dense traffic includes the transport of noxious, dangerous and hazardous cargoes (oil, LNG, LPG, chemicals, other explosive and environmentally hazardous substances). There is also very heavy ferry traffic, which crosses between the European and Asiatic sides. The number of local crossings by intra-city ferries, and other shuttle boats, is approximately 2000 a day. One-and-a-half million people are daily on the move at sea, crossing from one side of Istanbul to the other.[5] The ferries cross the strait on both straight and diagonal routes.

Serious maritime accidents are common in the Bosporus. For the period 1990–1997, there were 189 major incidents and many near-casualties reported. Forty-three sailors died from a single collision in 1979, which resulted in one of the worst oil spills in maritime history. In March 1994, the Cypriot tanker Nassia, which was carrying 30000 tons of crude oil, was involved in a collision which resulted in the loss of 28 lives and a serious oil spill. Figure 4 illustrates the variation of the number of

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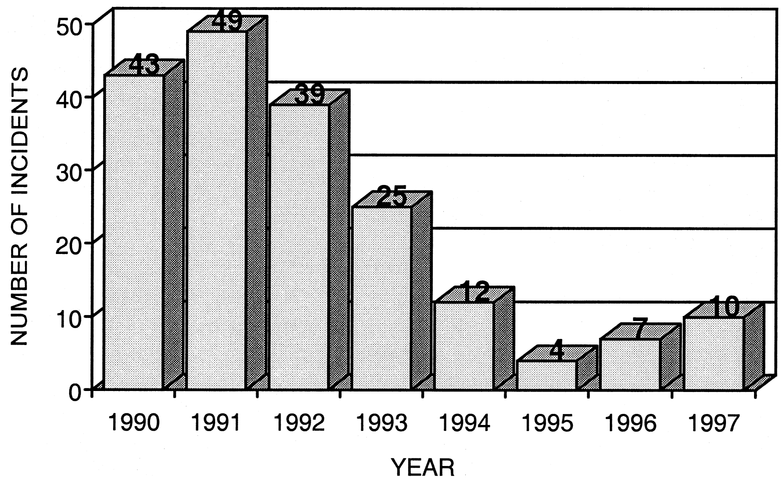

Figure 4. Number of major incidents.

incidents. It may be noted that the traffic separation scheme introduced in 1994 has drastically reduced the number of accidents.

4. THE SIMULATION STUDY.

The simulation study was conducted using PC-based, ship manoeuvring simulation software.[4] The program can be used for two basic purposes:

(a) Evaluation of basic ship manoeuvring characteristics over the range of loading and environmental conditions (fast-time simulation), and

(b) Validation or verification of passage plans through specified channels under a range of environmental conditions (real-time simulation).

In the fast-time simulation mode, the equations are integrated as fast as possible by the computer, and the rudder/propulsion system commands are controlled by some predetermined logic. This mode is used to simulate standard definitive manoeuvres including turns, zig-zags, and spirals, and can also be used for simulation of manoeuvres controlled by an autopilot.

In the real-time mode, the program integrates equations at a rate that corresponds to real time, and a visual scene is provided on the computer screen. The visual scene is updated as the ship motion model computes a new ship's position and heading resulting from manual control input based on the pilot's commands (rudder, engine throttle, and tug commands), ship hydrodynamics, and external forces. The external force capability of the simulator includes the effects of wind, waves, currents, banks, shallow water, ship/ship interaction, and tugboats. In addition to the visual scene, the user is provided with navigation information such as speed and heading of the vessel, wind speed and direction, magnitude and direction of current, etc.

The effectiveness of the simulation procedure requires a robust and physically oriented hydrodynamic model which explicitly accounts for the hydrodynamic contributions of the hull/engine/propeller/rudder complex and their interaction with the environmental inputs (wind, wave, current). It is beyond the scope of this paper to describe in detail the ship simulator; however, a brief explanation will be made.

4.1. *Mathematical Modelling of the Behaviour of a Large Tanker.* The basic mathematical model to represent a manoeuvring large ship in the presence of wind and current consists of a set of coupled non-linear differential equations in six degrees of freedom; the three components of the velocity U (u,v,w), and the three components of the angular velocity Ω (r,p,q). The Earth-fixed and ship (moving) coordinate systems are shown in Figure 5. The ship's centre of gravity is located at $(x_G, y_G, 0)$ in

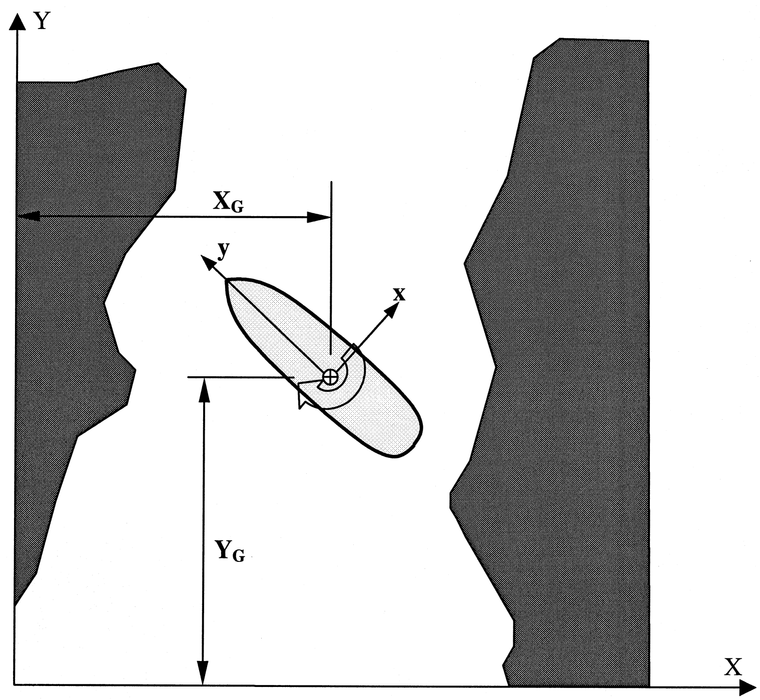

Figure 5. Global and ship coordinate systems.

the system of coordinates. In order to simplify the problem, it can be assumed that the principal axes of inertia of the ship are parallel to the chosen axis system, the ship is symmetric about its centreplane, and that roll angles are small. These assumptions will reduce the number of degrees of freedom to four, and the equations of the motion can be written as:

$$\begin{aligned}
&\text{Surge} \quad m[\dot{u} - rv - x_G r^2] = X_H + X_R + X_P + X_{EXT} \\
&\text{Sway} \quad m[\dot{v} + ru + x_G \dot{r}] = Y_H + Y_R + Y_P + Y_{EXT} \\
&\text{Yaw} \quad I_z \dot{r} + m x_G (\dot{v} - ur) = N_H + N_R + N_P + N_{EXT} \\
&\text{Roll} \quad I_x \dot{p} = K_H + K_R + K_P + K_{EXT}
\end{aligned}$$

where:

m = mass of the ship,
u, v = ship velocities in *x* and *y* axes, respectively,
r, p = yaw and roll rates, respectively,
I_x, I_z = hull moments of inertia about axes Ox and Oz, respectively,

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X, Y = hydrodynamic and external forces about Ox and Oy axes, respectively,

K, N = moments acting on the manoeuvring ship about Ox and Oz axes, respectively,

H, R, P, EXT = subscripts indicating hull, rudder, propeller and external forces.

An additional equation is needed to describe the response of the propulsion system to external forces:

$$2\pi I_P \dot{n} = Q_E + Q_P,$$

where Q_E and Q_P represent the propeller torque and the main engine torque, respectively, n is the propeller speed, and I_P is the propeller moment of inertia.

This yields a model of the ship that includes surge, sway, yaw and roll, and which is sufficient to account for the planar manoeuvring model of the ship and the sea surface. Solution of the equations of motion yields ship velocities and trajectories. It should be noted that the present equations use a square absolute representation for higher order terms. This, compared with a *third order Taylor expansion* method, provides better representation of hydrodynamic forces at large drift angles and is valid for low and zero speed conditions.[6]

The manoeuvring simulator is based on the concept of modularity.[7] This is achieved by isolating the forces exerted on each of the separate components of the ship by using detailed models for these, and by accounting for the interaction between these various components in selecting the hull coefficients. Each module, whether it relates to hydrodynamic or control forces or external effects, is self-contained. The modules are designed by reference to the detailed physical analysis of the process being modelled. The system as a whole is then modelled by combining the individual elements and expressing their interaction by other physical expressions.

4.1.1. *Hull Module*. The hull module contains all the hydrodynamic data specific to the underwater part of the hull. The hydrodynamic forces acting on the hull can be broken down into inertial hydrodynamic forces or added masses, viscous dissipative forces or hull lifting and cross flow effects, and hydrostatic forces. The only hydrostatic contribution is due to the roll motion, which can be calculated easily.

The acceleration inertia forces are, basically, a function of the underwater hull geometry and expressed in terms of added mass values. It can be safely assumed that the interaction between inertia and viscous forces is negligible, and hence the acceleration forces can be obtained using potential flow theory. These forces are essentially independent of forward speed and can be calculated as a function of underwater hull geometry and frequency of oscillations. A strip method is employed in the simulation program in which the total added masses are calculated by integrating the sectional added mass values along the ship length, and a semi-empirical 3-D correction technique is applied.

Calculation of the viscous force components is the most critical part of the modelling. Viscosity affects the flow around the ship in two basic ways. First, in the boundary layer close to the hull, the fluid velocity is significantly affected by viscosity. At small drift angles, the ship hull can be regarded as a lifting surface with the drift angle taking the role of the conventional angle of attack. At large drift angles, the ship hull and the appendage damping forces are generated by pressure loss and contribute to the losses in oblique flow, with drift and yaw angle velocities, by cross-flow pressure. Both the circulatory and cross-flow forces are present and equally important in typical ship manoeuvres. A multiple regression procedure was adopted for the simulation procedure based on the results of 36 PMM tests, including a wide range of ship types from naval ships to super tankers.

4.1.2. *Propeller Module*. The ships are assumed to have one or two propellers that may be fixed or have controllable pitch. Realistic modelling of the propeller force is important for manoeuvres involving thrust, torque and speed reversal, and indirectly for rudder force modelling. The propeller force is represented by a quadratic equation in terms of ship's resistance, length, relative speed, propeller diameter, propeller advance coefficient and efficiency. The total resistance of the ship is considered to be a sum of the viscous, wave-making, appendage, bulbous bow, transom stern and correlation components. The regression expressions are based on the model test results of a large number of experiments.[8,9] The propulsion coefficients (i.e. the wake and thrust deduction coefficients, and the relative rotative efficiency) are predicted by using similar regression techniques. The thrust and torque coefficients are estimated by using standard techniques based on open-water characteristics corrected for the behind-hull conditions.

4.1.3. *Rudder Module*. The ships can have one or two rudders. The rudders are assumed to be a low-aspect ratio wing submerged in a flow, shadowed by the hull and augmented by a propeller. The interaction of the rudder with the propeller slipstream is fully taken into account and, for large turning angles, some empirical corrections are provided.

4.1.4. *Engine Module*. The engine of the ship is modelled using standard models for Diesel engines and steam power plants. Characteristics of the engines need to be specified by the user; however, some default inputs based on standard power plants are provided.

4.1.5. *External Force Models*. The external models include current effects, wind forces, bank effects, ship-ship interaction, mooring lines, fender forces, anchor forces, and wave forces. The current forces are not treated as external forces, but they are taken into account to determine the relative speed of the vessel.

4.1.5.1. *Current Effects*. The equations of motion are in terms of relative velocities and yaw rate to allow the introduction of a current velocity that can vary along the ship length. Relative velocities and relative yaw rate are calculated by vector addition of ship inertial velocities (u,v), yaw rate (r), the current velocities (u_C, v_C) and apparent current yaw rate (r_C) as follows:

$$u_R = u - u_C \quad v_R = v - v_C \quad r_R = r - r_C.$$

For numerical calculations, a matrix of current velocities (v_{cij}) and directions (Ψ_{cij}) at specific locations x_{ij} and y_{ij} are defined. The location of ship bow (x_B,y_B), midships (x_M,y_M) and stern (x_S,y_S) are used, together with the current speed and direction matrices to determine, by interpolation, the actual current speed and direction at the bow (u_{CB},Ψ_{CB}), midships (u_{CM},Ψ_{CM}), and stern (u_{CS},Ψ_{CS}).

4.1.5.2. *Wind Model*. There are two aerodynamic models available in the simulation. The relatively simple standard model employs empirical aerodynamic force coefficients, while the specific model will require the ship-specific aerodynamic force and moment coefficients as a function of relative wind angle.

4.1.5.3. *Bank Effects and Ship-Channel Interaction*. The basic effect of a channel bank on a ship is the existence of an asymmetrical lateral force and moment acting on the ship even when it is laterally symmetric with no sideslip, yaw or rudder deflection. Generally, the lateral force on the ship is directed toward the bank, and the lateral moment tends to turn the bow away from the bank.

The effect of bank suction on a ship, which moves in a steady state parallel to a long, straight bank, is a force that pulls (suctions) the ship toward the bank, and a moment that tends to push the bow away from the bank. To balance the suction force and bow-out moment, it is necessary to find an equilibrium position with the ship in a bow-out direction and rudder deflected toward the bank.

In order to simulate the bank effects, the force and moment on the sides of the ship are calculated independently, and the resulting forces and moments are summed to provide the total bank effect. The bank forces and moments are calculated for the vertical bank case and then corrected for effects of bank slope and partial depth banks. The effects of banks that are discontinuous, or that change characteristics along the length of the ship, are approximated by calculating the nominal incremental bank force and moments using the bank distance and parameters local to the bow, midships and stern.

4.1.5.4. *Ship–Ship Interaction*. The interaction between two ships, when they are meeting or overtaking, involves a complex hydrodynamic phenomenon that is difficult to predict in a form useful in real-time simulations. The problem is further complicated by the presence of channel boundaries and depth effects. The ship–ship interaction model, employed in the simulation software, is based on a theoretical approach with empirical corrections based on model test results.

4.1.5.5. *Mooring Lines*. The effect of mooring lines is introduced into the simulation as external forces in the equations of motion. Up to six mooring lines may be active at one time. The load on each mooring line is resolved into X, Y and N components, and calculated on the basis of a non-linear spring with damping.

4.1.5.6. *Fenders*. Fenders on piers are treated as external forces in the equations of motion. The fender forces are zero as long as a predefined fender point on the ship is more than a specified distance from the pier. When the fender point is close to a pier, a force is calculated using specified non-linear spring characteristics. This force acts in a direction perpendicular to the pier and toward the ship.

4.1.5.7. *Anchors*. The simulator has the capability to handle two anchors at any location on the ship. The anchor model includes simulation of releasing, winching in/out, and locking the anchor chain. The force model is based on a catenary equation in the form of a look-up table that compares the cord with the actual length of chain. The anchor holding force is linearly increased to maximum holding force as a function of chain length to water depth.

4.1.5.8. *Wave Forces*. Waves affect a manoeuvring ship in two distinct ways:

(a) first-order oscillatory forces centred on the dominant wave frequency encountered, and
(b) second-order drift forces which consist of a steady component and a low frequency component.

The first-order forces are much larger in magnitude than the second-order forces. A strip-theory based approach is used to compute the first-order hydrodynamic coefficients. The type and properties of the wave spectrum are specified by the user. The program calculates the six motion components for every time step.

4.2. *Graphical User Interface*. The Graphical User Interface (GUI) provides a bird's-eye-view of the ship and the different environmental features such as depths, wind, waves and current indicated by coloured regions/contours. The view has a large zoom in/zoom out capability. Data input to the ship model can be via text files, or via menus through the GUI. The track of the ship is recorded on the screen and in files, which include information about the speed and forces on the ship. The display includes simulated bridge instruments, including engine telegraph and rudder controls.

Waterway configurations taken from nautical charts were fed into the simulation software in digital form together with environmental data such as current speed and direction. Figure 6 shows the whole region and the most critical part of the Bosporus

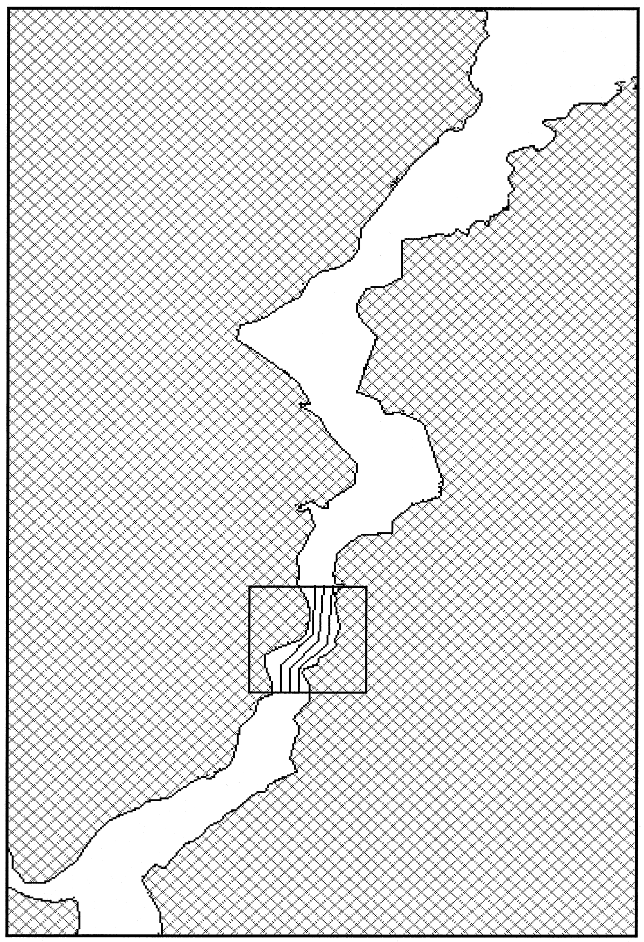

Figure 6. Overview of the Bosporus and the simulation area.

in which the simulation tests were carried out. The restriction of the study to a smaller critical part instead of the whole region is due to the time restrictions in a real-time simulation and the number of scenarios requiring representation of realistic ship and environment conditions.

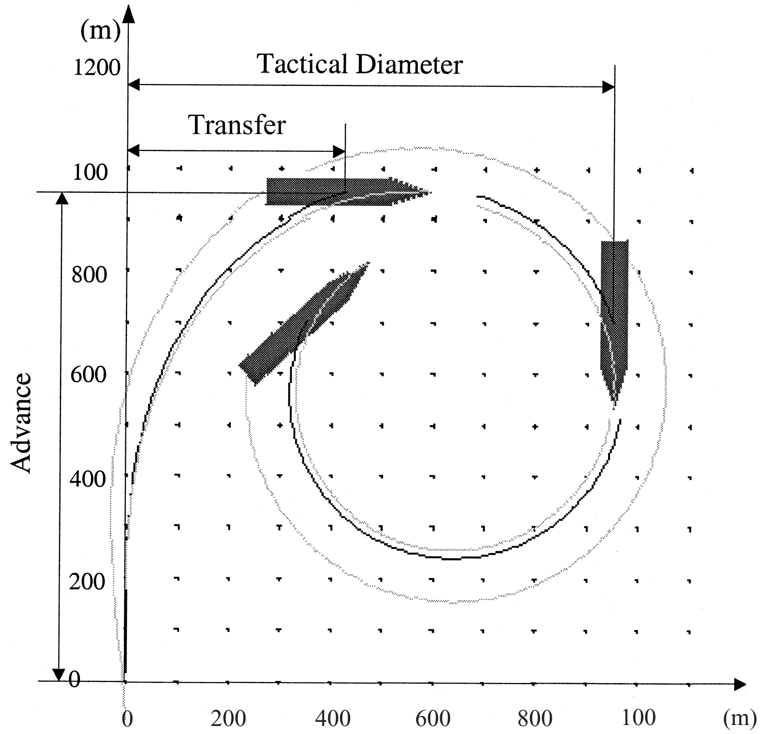

Figure 7. Turning circle comparison for Esso Osaka.

Table 1. Esso *Osaka* turning circle parameters.

Depth/Draft Ratio H/T	Rudder 35° starboard, Approach speed = 7·7 knot					
	Advance (m)		Transfer (m)		Tactical diameter (m)	
	Trial	Simulation	Trial	Simulation	Trial	Simulation
∞	1015	960	360	415	925	946

4.3. *Validation of the Simulation Model.* To validate the simulation software, turning and zig-zag manoeuvre tests were carried out for a number of ships for which full-scale trial and model test results are available. A typical result is shown in Figure 7, where the predicted and measured turning circles are compared for an approach speed of 7·7 knots. The advance, transfer and tactical diameter comparisons are given in Table 1. It is clear from these figures that the simulation results are in good agreement with the model test and full-scale trial results.

In order to assess the simulated manoeuvring performance of large ships, some objective performance measures need to be defined. The obvious measure of performance is the consistency with which the position of the ship can be maintained in the proper location relative to the waterway and traffic lane boundaries. This may raise the question that, since the simulation is controlled by a user, the results will depend on the experience of the user. However, the results indicate that, when large

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ships manoeuvre in narrow channels, there is little scope for the user to influence the outcome because of the large inertia forces, and similar tracks will be obtained regardless of the experience of the user.

4.4. *Test Vessels.* The analysis of manoeuvring simulation requires that the size and main characteristics of the tankers that use the Bosporus regularly need to be identified. The current regulations assume that ships larger than 200 metres in overall length cannot navigate safely or without violating the traffic separation zone, hence traffic has to be suspended temporarily. Therefore, two distinct tanker sizes, one smaller and the other larger than the current size limit, were chosen as representative designs, and two individual test vessels were identified. The principal dimensions of the chosen vessels are presented in Table 2.

Table 2. Test ship characteristics.

Type	Ship A Tanker	Ship B Tanker
DWT (t)	25000	165000
Length over all (m)	168	288
Breadth (m)	23	50·6
Draught (m)	9.75	17

Two different loading conditions for each vessel, i.e. loaded and ballast, were considered. For most tests, the North-to-South vessel was the loaded tanker and the South-to-North vessel was the tanker in ballast. This reflects actual traffic entering and leaving the Bosporus, with oil imported from Black Sea ports to Mediterranean ports.

4.5. *Scenarios.* A matrix of simulation cases was defined so that the influence of the different factors that affect the safety of navigation can be investigated independently. Three different environmental conditions representing ideal (no current, no wind, no wave), normal (current 3 knots, wind 20 knots, wave 1 metre) and the worst-case (current 5 knots, wind 40 knots, wave 2 metres) were selected. The matrix analysis methodology can result in a significant number of scenarios. These scenarios are as follows:

Two tanker sizes	25,000 DWT and 165,000 DWT
Two loading conditions	loaded and ballast
Three current speeds	0, 3, and 5 knots
Three wind speeds	0, 20 and 40 knots
Two dominant wind directions	NE and SW

5. ANALYSIS OF SIMULATION RESULTS. The simulation studies were carried out to assess the effectiveness of the TSS under various environmental conditions for the different characteristics of the two test vessels. In particular, the aim was to determine the size of the largest tanker that can navigate safely within the TSS and to determine the effect of different environmental conditions. Each subject (user) of the simulation tests faced four situations, namely:

(a) a northbound tanker A in ballast condition under ideal, normal and worst-case environmental conditions,

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(b) a northbound tanker B in ballast condition under ideal, normal and worst-case environmental conditions,
(c) southbound tanker A in loaded condition under ideal, normal and worst-case environmental conditions,
(d) southbound tanker B in loaded condition under ideal, normal and worst-case environmental conditions.

These situations, combined with the environmental scenarios, resulted in over 600 realistic cases. In each case, the ship's course was kept as close as possible to the centre line of the traffic lane. The tests were repeated several times with similar results. Ship trajectories and swept tracks were obtained and examined, whether the traffic separation lanes were violated or not. In some cases, grounding was inevitable. To simplify the problem, passing and meeting ships were not included.

Typical examples of the computer-plotted ship trajectories are shown in Figures 8 through 13 for the case of the 25000 DWT (Ship A) and 165000 DWT (Ship B) tankers under various environmental conditions. The simulation results of the course-keeping operation, in the most critical part of the Bosporus under typical environmental conditions, are shown in Figures 8, 9 and 10 for Ship A. Figures 11,

Figure 8. Ship A (25,000 DWT tanker), 10 knot transit speed, loaded, ideal conditions. (no wind, no current, no wave)

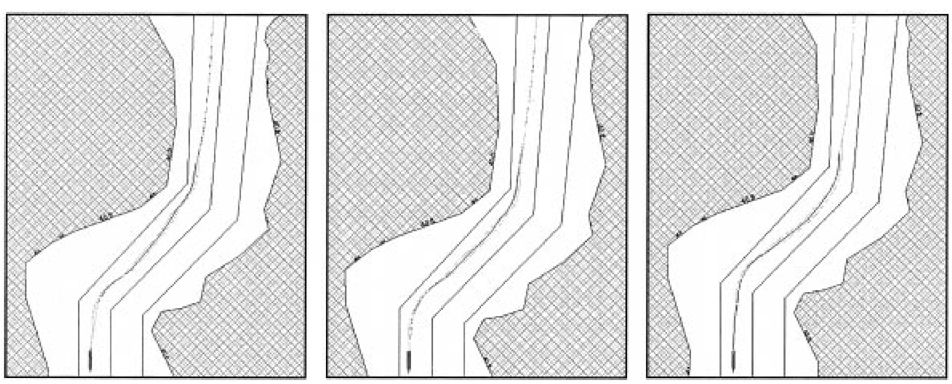

Figure 9. Ship A (25,000 DWT tanker), 10 knot transit speed, loaded, normal conditions. (20 knot NE wind, 3 knot current)

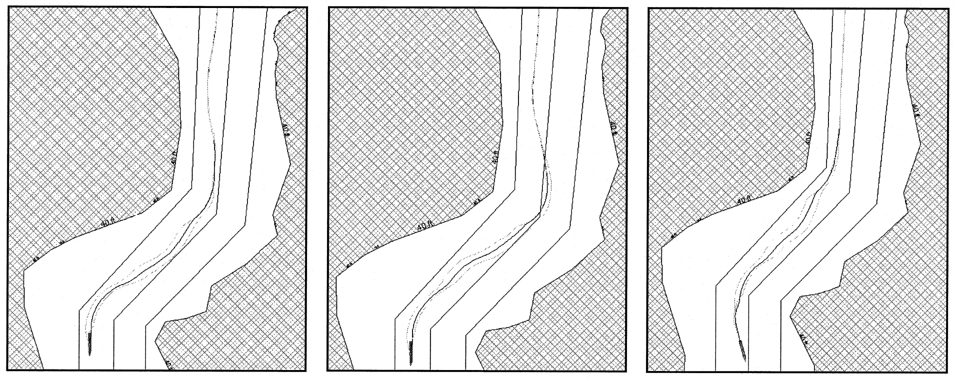

Figure 10. Ship A (25,000 DWT tanker), 10 knot transit speed, loaded, worst case scenario.
(40 knot NE wind, 5 knot current)

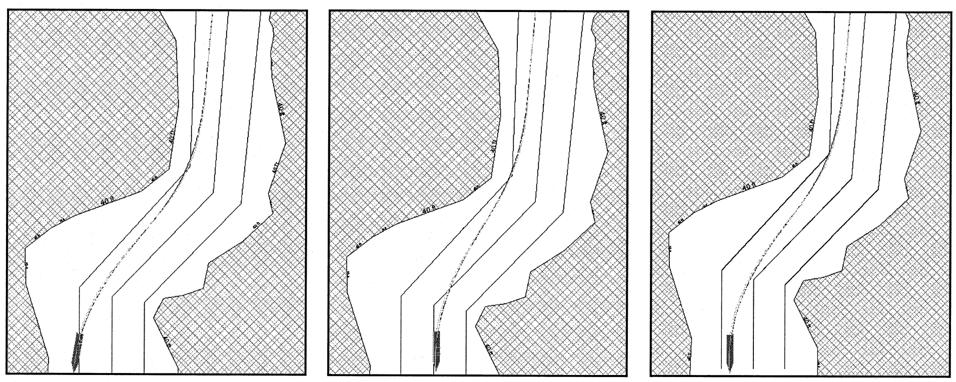

Figure 11. Ship B (165,000 DWT tanker), 10 knot transit speed, loaded, ideal conditions.
(no wind, no current, no wave)

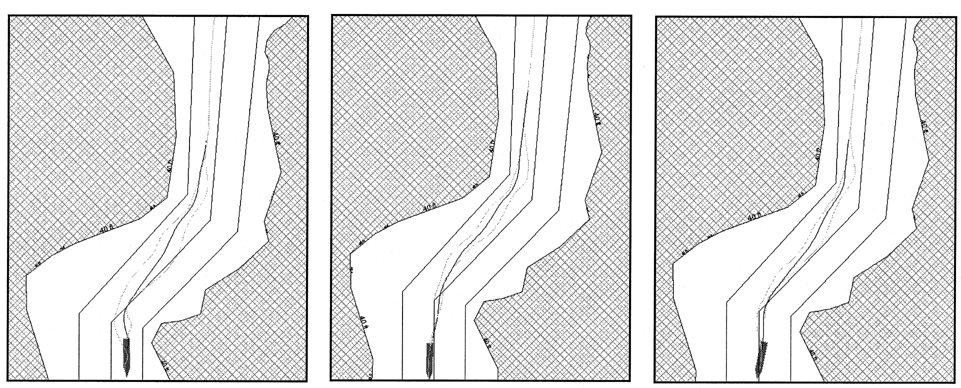

Figure 12. Ship B (165,000 DWT tanker), 10 knot transit speed, loaded, normal conditions.
(20 knot NE wind, 5 knot current)

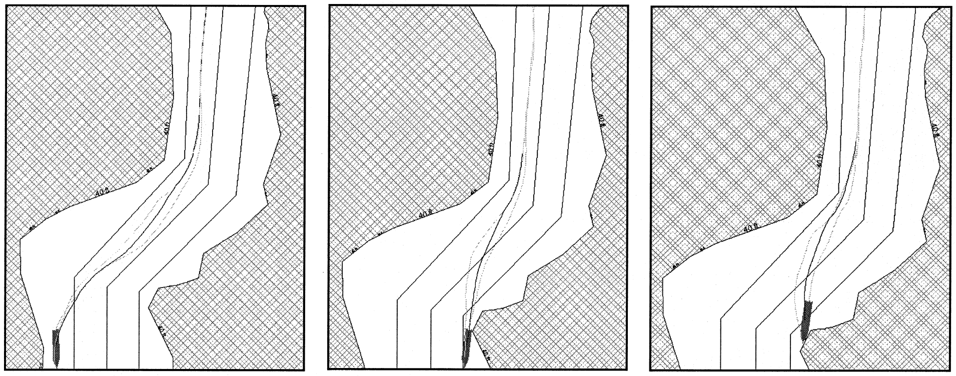

Figure 13. Ship B (165,000 DWT tanker), 10 knot transit speed, loaded, worst case scenario. (40 knot NE wind, 5 knot current)

12 and 13 illustrate the equivalent results for Ship B in similar conditions. Each simulation, for each scenario, was repeated by three different users in order to minimise the influence of any subjective human performance factor. The simulations of the ideal, normal and worst case scenarios demonstrated the effects of current and wind conditions on the manoeuvring performance of large ships.

6. CONCLUDING REMARKS. The transport of oil through narrow channels, such as the Bosporus, involves serious risks that need to be carefully assessed and analysed. One of the most promising methods to assess and analyse the risks is computer-aided manoeuvring simulation. The main purpose of this paper was to review results obtained in computer simulation studies. Emphasis was placed on the application of simulation to actual ships under realistic operating conditions. The major findings of the study are summarised as follows:

(a) Computer-generated manoeuvring simulations, based on reliable model test data, appear to be a practical and reliable method to investigate the full-scale manoeuvring of large tankers in critical waterways. The advantages of the manoeuvring simulation procedure are repeatability and the ability to isolate and study unique environmental conditions.

(b) The effectiveness of the present methodology is demonstrated by the ability to sense changes in all critical parameters, i.e., the ship size and main environmental conditions (wind, current and waves).

(c) Even under ideal conditions (no wind, no current, no wave), there is a size limit for ships that can manoeuvre safely without violating the traffic separation lanes in the Bosporus. Under strong winds and current conditions, maintaining position (within the specified TSS lanes) is not possible for ships larger than certain limits. The current size limits are considered to be appropriate for conventional ship types with no additional manoeuvring equipment or an escort tug.

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KEY WORDS

1. Marine. 2. Simulation. 3. Safety.