Application of Ship-Handling Simulations in the Evaluation of Channels for Two-Way Traffic

BENT K. JAKOBSEN, EUGENE R. MILLER JR., AND LARRY DAGGETT

The application of ship maneuvering simulations in the evaluation of restricted channels that are required to accommodate two-way traffic is described in this paper. The application is illustrated by results from actual studies of the Baltimore channels carried out to validate channel reductions from 800 to 700 ft and from 1,000 to 800 ft, respectively, and an increase of the water depth from 42 to 50 ft to allow ships with deeper draft and larger tonnage to call at Baltimore. Initial studies were conducted using two coupled ship-handling simulators, each conned by a separate pilot and crew in communication and visual contact with the other ship. This initial study covered meeting situations for two-way traffic in the Craighill Angle channels. The data from these simulations provided the meeting situation strategies used by the pilots. Based on these strategies, a traffic ship control system was developed for use in later phases of the program. In all meeting situations, both ships are described with full hydrodynamic models. The later phases of the program involved simulation studies of the Brewerton channels, Rappahannock Channel, and York Spit channels. These studies consisted of fast-time simulations in which both own ship and traffic ship were computer controlled, and real-time simulations in which the own ship was controlled by a pilot and the traffic ship was computer controlled. A rule-based traffic ship control system was developed to control both ships in fast-time simulations and the traffic ship in real-time simulations.

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B. K. Jakobsen and E. R. Miller, Jr., Traycor Hydronautics, Inc., 7210 Pindell School Road, Laurel, Md. 20723. L. Daggett, U.S. Army Corps of Engineers, P.O. Box 631, Vicksburg, Miss. 39180-0631.

INTRODUCTION

Restricted waterways and channels that are required to accommodate two-way traffic are a feature of many port and waterway development programs. The design and evaluation of these channels have a major impact on the safety and efficiency of navigation, and the capital and operating costs associated with port development. The designer must balance the conflicting demands placed on channel dimensions by the ship operators and economic constraints. Until recently, the designer was forced to rely on general published design criteria, the subjective judgment of pilots, and personnel experience. In general these approaches have worked but have limitations when unusual geographic and environmental conditions exist.

In the past 5 years, ship-handling simulation has been increasingly used as a tool to support the designer with quantitative evaluations of channel design alternatives. These simulator studies have been particularly effective when applied to channel design for one-way traffic (*1*). However, until recently simulator studies for channels with two-way traffic have been limited by the capabilities of available ship-handling simulators. These limitations have included

- Inability to model the complete hydrodynamic response of the traffic ship;
- Inability to introduce the interaction between the two pilots on the meeting ships or the inability to model the response of the pilot on the traffic ship; and
- Deficiencies in the modeling of ship-ship interactions particularly in shallow water and in the presence of channel banks.

These limitations have now been largely overcome by advances in the capabilities available in some ship-handling simulators.

Recently the Corps of Engineers had the requirement to evaluate the design of the new 50-ft depth channel system serving the Port of Baltimore. The new channel, which must allow two-way traffic over its entire length of more than 100 mi, follows the existing 42-ft channel. However, because of cost considerations, it appeared necessary to reduce the existing width of most of the deepened channel by between 100 and 200 ft. Simulator studies were used to evaluate the safety of the planned deepened channel. Tracor Hydronautics was assigned the task of conducting the simulator studies under the overall direction of the Corps of Engineers, Waterways Experiment Station (WES).

In the conduct of these simulation studies, Tracor Hydronautics and WES decided to use recent advances in simulation capabilities to overcome the limitations of previous simulator studies of two-way traffic situations. Described in this paper are the technical approach and some of the results that were developed for the evaluation of the deepened Baltimore channels.

TECHNICAL APPROACH

Ship-handling simulators have been improved with more realistic modeling, including ship-ship and ship-waterway interaction. This development also has been supported by significant advances in the quality and realism of computer- generated images of the out-of-window view from the ship's bridge. In 1988, a new ship-maneuvering simulation facility, owned and operated by MarineSafety International (MSI) and located at Newport, Rhode Island, became available for use in the Baltimore study. This facility is unique in that it contains four simulators that can be operated together in a completely interactive simulation. This facility was used to model two interacting ships using two coupled simulators, each conned by a separate pilot and crew in communication and visual contact with the other ship. The use of such a simulation facility allows testing and measurement of passing maneuvers at specific locations in proposed channel designs.

Based on the availability of ship-handling simulators with these improved capabilities, the following technical approach was applied:

- Identify critical simulator requirements for evaluation of two-way traffic channels,
- Conduct initial simulations using two coupled ship simulators to evaluate a critical section of the channel system,
- Use the results of the coupled two-ship simulations to determine the piloting strategies used in meeting situations in straight reaches and bends,
- Develop a traffic ship control system based on these piloting strategies for use in later phases of the study that were conducted on a single-ship simulator,
- Implement a traffic ship simulation with full hydrodynamic modeling and response,
- Conduct coupled fast-time simulations using the traffic ship control system for both ships to identify critical locations for real-time piloted simulations,
- Evaluate other channel sections using a single real-time piloted simulator interacting with a traffic ship conned by the traffic ship control system, and
- Evaluate the new channel design based on comparisons with simulations conducted in the existing channel.

In the Baltimore study, there are a large number of channels and bends. Each of these has unique dimensions, bank configuration, current, and wind conditions. For each channel and bend, there are a large number of meeting locations and traffic conditions (e.g., inbound containership meeting outbound bulkcarrier under ebb conditions) that need to be tested. It is prohibitively expensive and time consuming to evaluate all of these conditions with real-time simulations. Therefore, fast-time simulations using the traffic ship control system to control both ships is used to rapidly and efficiently determine the location and traffic condition that will be most critical in establishing channel dimensions. Real-time simulations are then conducted for the critical cases to evaluate the final channel dimensions. The real-time simulations are carried out using local licensed pilots. This approach has been used in the studies of the Brewerton channels, Rappahannock Channel, and York Spit channels. Data have been collected from simulations of 240 meeting situations using 18 different pilots familiar with the channels (*2–4*). All meeting situations were carried out in daylight clear weather conditions with maximum current and wind conditions (wind 20 knots from the northwest).

The performance of the pilots in the existing and planned channels was assessed quantitatively by calculating the following parameters:

- Clearance maintained between the ships;
- Clearance to the adjacent bank; and
- Ship controllability factors such as time histories of heading, rate of turn, rudder activity and propeller rpm.

The differences between piloting in the existing and planned channels were assessed qualitatively by interviewing the pilots and having them complete a questionnaire following the real-time simulations.

SIMULATION FACILITIES

MarineSafety International Shiphandling Simulator Facility

The MSI ship-handling simulator center is located at Newport, Rhode Island. This facility has four ship-handling simulators that are unique in that they are the only ones in the world that can be linked together so that each simulator conned by a separate pilot can be in communication with all the other ships. This study made use of two of the simulators linked together and operating in the same channel to produce representative meeting situations. This provided a realistic simulation of meeting situations in a channel that was not restricted by any artificial constraints on the motions on either ship. The two visual ship-handling trainers include the following major elements:

- Pilot house with typical bridge equipment
- Pelorus
- Four channel visual display system with 180-degree horizontal x 30-degree vertical field of view
- Raytheon RACAS V RADAR display with ARPA
- Simulated VHF communication system
- Video Situation Display (VSD) with touch-screen control
- Chart table with PMP and light

The VSD provides a birds-eye view of the ship tracks in the simulated channel. The simulator operator's area includes a terminal to control the simulator, monitors to display the visual scene and VSD, a printer, and a video hard copy device (Figure 1). The simulators are described in a paper presented at MARSIM 88 (*5*).

Tracor Hydronautics Ship-Handling Simulator Facility

The second simulator facility used in this study is located at Tracor Hydronautics Inc., Laurel, Maryland. This simulator has been used for numerous simulation studies over several years. The simulator system has been developed so that two ship simulations can be carried out with one ship conned by a pilot and the other ship controlled by a traffic ship control system. Both ships are modeled with complete hydrodynamic models. The simulation facility, as shown in Figure 2, includes the following major elements:

- Pilot house with mock-up of bridge equipment;
- One channel high resolution visual display system, 45-degree horizontal field of view that can be switched to view in different directions (e.g., rear view, and also to bridge wing view, port and starboard); and
- VSD (birds-eye view).

Two-Ship Simulation

The two-ship simulation programs are set up in such a way that the own ship and the traffic ship use exactly the same hydrodynamic calculations. Therefore, the full hydrodynamic model, including environmental effects, bank effects, and ship-ship interactions, is fully implemented for both ships. The own ship is controlled from the bridge mock-up, and the traffic ship is controlled from either the other simulator's bridge mock-up or from a rule-based system that controls an autopilot. The two simulation programs are controlled by a master program that lets the calculations alternate between the simulation programs for the own ship and the traffic ship. The master program also transfers the ship position and velocity to the other program.

DATA BASE AND INPUT DESCRIPTION

The input data include channel geometry, bottom topography, currents, tides, wind, waves, aids to navigation, the visual scene for the existing and planned channels, and ship parameters. These data are put into the following data bases for use during the simulations.

Current and Tides Data Base

The current data base is the simulator's source of information concerning current speed, current direction, and water depth. This information is assigned to a flexible grid that covers the simulated area. To obtain the current values, a finite element model of the channels has been developed by WES. Tidal and velocity measurements obtained from field measurements or a verified physical model are usually used to ensure that the model reproduces tidal velocity conditions in a reasonable manner. The current data was developed by WES and was provided for use in the simulation studies.

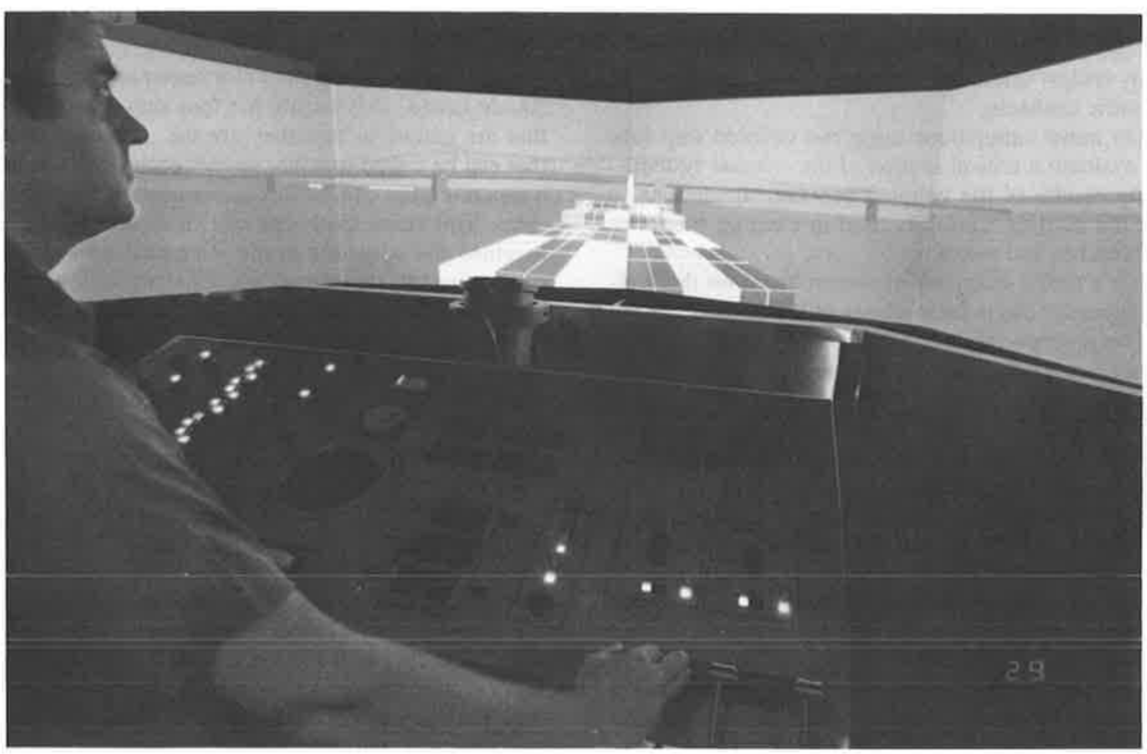

FIGURE 1 Visual ship-handling trainer, MarineSafety International, Newport, Rhode Island.

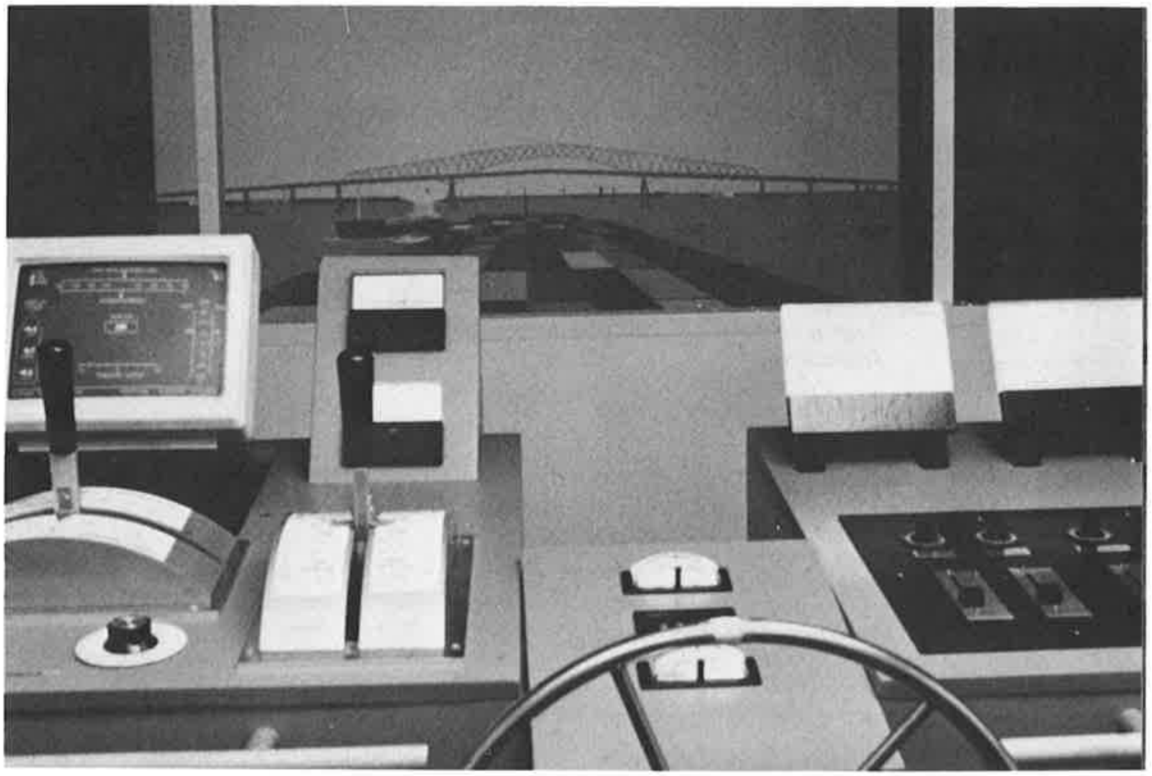

FIGURE 2 Tracor Hydronautics ship simulator.

Visual Scene Data Base

The visual scene data base contains a description of the significant objects in the visual scene, including aids to navigation such as buoys and ranges, land, and cultural contents. These scenes are generated by separate computer systems and high resolution projectors.

Radar Data Base

This data base contains the list of coordinates defining the border between land and water and the pertinent objects (e.g., traffic ships and aids to navigation). These data are generated by a radar signal generation computer and are displayed on an actual radar repeater for use by the pilots.

Hydrodynamic and Mathematical Ship Models

Valid ship models are one of the most critical items in harbor and restricted waterway studies. Significant efforts by WES and Tracor Hydronautics have been undertaken in recent years to ensure that the simulated ships perform realistically. This means that the simulated ship realistically responds to control and environmental forces and interacts with banks, channel bottom, and meeting or passing ships in a way similar to that in the real environment. The validity of ship models is directly tied to the availability of reliable information about ship performance.

Ship-ship interactions involve significant hydrodynamic forces and moments when two ships are moving in close proximity. These forces and moments are increased considerably when the meeting situation takes place in a channel that typically involves shallow water effects and bank effects. The interaction forces change with the square of the ship velocity, so ship speed is an important factor. Before the simulations, WES and Tracor Hydronautics devoted significant effort to the modeling and validation of the ship-ship interaction hydrodynamic forces. Some minor corrections were made based on the initial pilot evaluations (*6,7*).

SHIP CHARACTERISTICS

The two ships used in the Baltimore Channel simulations were a Panmax containership and a 150,000 DWT bulkcarrier. These ships were chosen to represent typical maximum size ships coming to Baltimore now and in the future. The ships have been used and validated in other simulation studies. The principal characteristics of the test ships are shown in Table 1.

TEST PROGRAM

Validation Tests

The ship-handling simulator provides realistic ship maneuvering performance of an actual ship in a given environment. Validation is the process used to evaluate whether the behav-

TABLE 1 PRINCIPAL CHARACTERISTICS OF TEST SHIPS

	Containership	Bulkcarrier
Length, overall, ft	949.79	950.00
Length, b.P., ft	915.00	915.00
Breadth, mld. ft	106.00	145.00
Propulsion system	direct diesel	direct diesel
Test conditions		
Existing channel		
Draft, ft	36.00	37.00
Displacement		
S.W. L. tons	79346	106554
Maximum speed (deep water)		
Knots	22.15	16.81
RPM	120	100
Test conditions		
Planned channel		
Draft, ft	36.00	45.00
Displacement		
S.W. L. tons	79346	129593
Maximum speed (deep water)		
Knots	22.15	15.99
RPM	120	100

ior of a simulation model agrees with that of the real system under study. Typically, validation methods cover both objective and subjective approaches. In the objective category, the ship responses are examined by fast-time computer predictions, which were compared with reliable data typically consisting of the generalization of the validated results from full-scale trials, model tests, and analytical predictions. Fast-time simulations are then carried out to validate the meeting situations to check all input data. Final validation tests (which are subjective) are carried out, using real-time computer simulations with experienced pilots, to determine the realism in the modeled ship dynamics, environment, instrumentation, and the visual scene, and to ensure maximum simulator performance validity.

Pilots and Quartermasters

All of the participating pilots were selected from the Association of Maryland Pilots and had extensive experience in piloting all types of ships through the Baltimore channels. All pilots were briefed on the purpose of the study, channel modifications, the ships and their characteristics, environment, bridge equipment, and data collection requirements (i.e., filling out of briefing and debriefing forms). Before the start of the simulation, each pilot was given the opportunity to become familiar with the ship models, channel configuration, bridge equipment, and the simulator in general.

The pilots were instructed to use normal piloting practice in positioning their own ship relative to the other ship in the meeting situation. The speeds for transit of the test ships were selected on the basis of normal piloting practice in each particular area of interest, so the meeting situation could take place at predetermined meeting locations based on these speeds. The pilots were, however, free to adjust propeller revolutions per minute (rpm), and thus the ship speed.

The ship simulations at MSI also included a quartermaster to make the simulations as realistic as possible. In the later phase, the simulation runs were carried out without a quartermaster. This has a tendency to affect the simulations to some degree, but it is not considered important for the conclusions of the study. The majority of pilots give rudder commands in multiples of 5 degrees. This form of maneuvering is similar to a "bang-bang" servo. When a pilot steers the ship himself, typically the rudder inputs are made in many smaller increments. The autopilot gives rudder commands even more smoothly, but the characteristics are similar to the pilot-controlled simulation. This may be seen in a comparison of rudder angles in Figures 3 and 4.

PILOTING STRATEGIES FOR MEETING

From the Craighill Angle simulation study with two coupled ship-handling simulators, each conned by a separate pilot, the following general observations were made:

1. The pilots started the meeting procedure when the ships were about 18 ship lengths apart. The pilot then steered in the direction the ship should be at the time of meeting. About two ship lengths before the meeting location, the ship was put on a course parallel to the channel. When the stern of each ship left the other, the ships were maneuvered back to the center of the channel. An example is shown in Figure 5.
2. The majority of pilots kept the propeller rpm constant during the entire meeting situation.
3. There was no clear pattern of which ship goes closest to the bank to give more room to the other ship (e.g., the containership would go closer to the bank than the bulkcarrier, which has the greater draft and displacement).
4. The rudder activity in the meeting situation is typically given as 10 or 15 degrees to starboard for a short period of

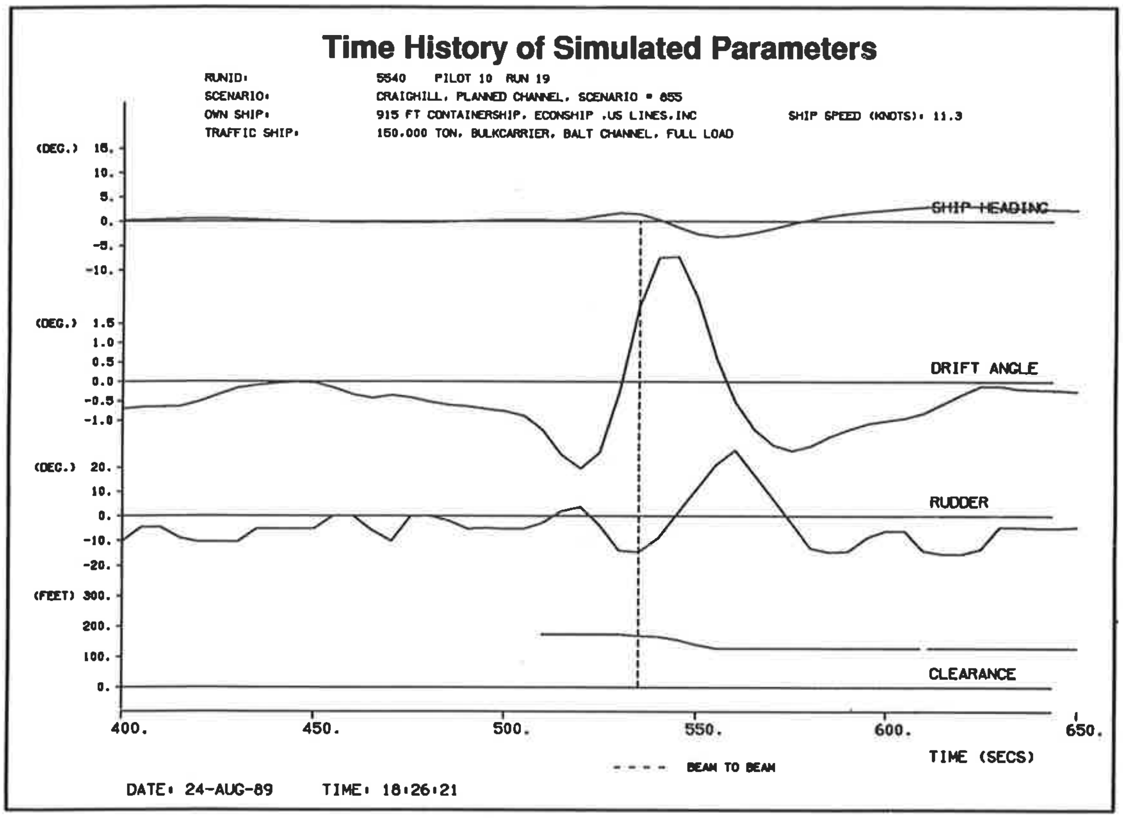

FIGURE 3 Time history of simulated parameters, pilot-conned ship.

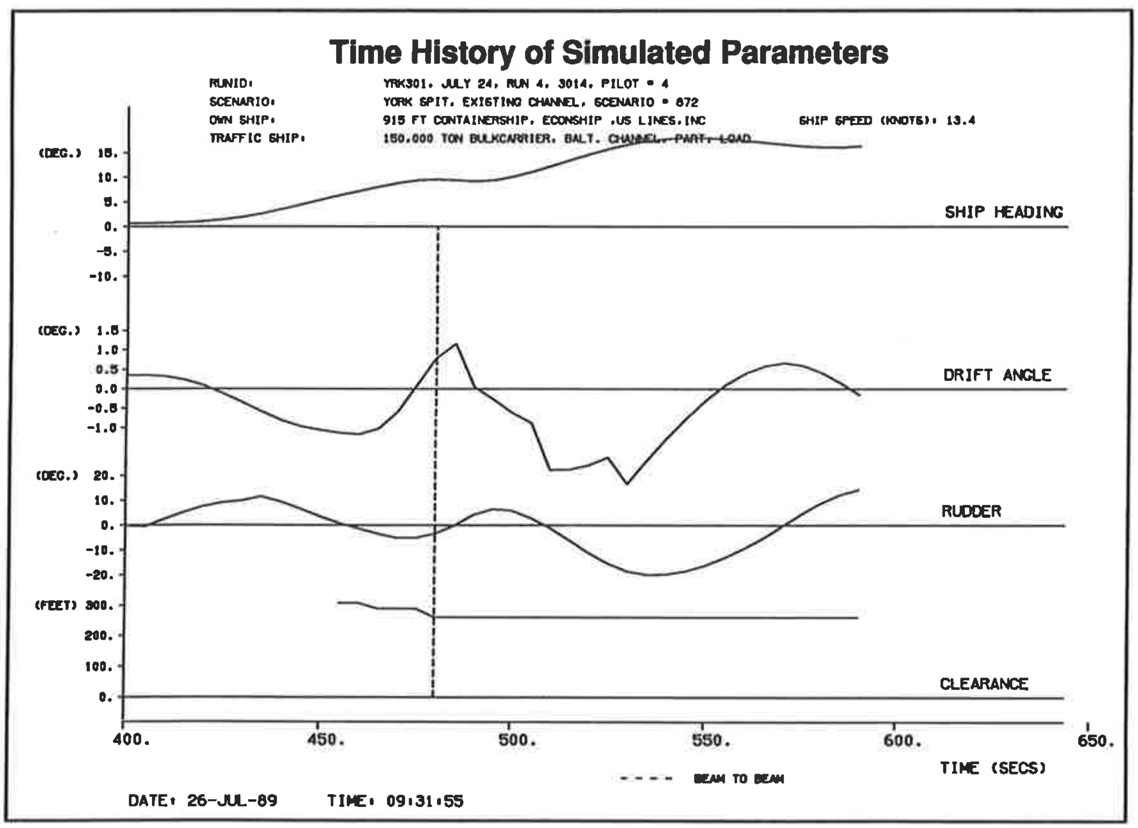

FIGURE 4 Time history of simulated parameters, autopilot controlled.

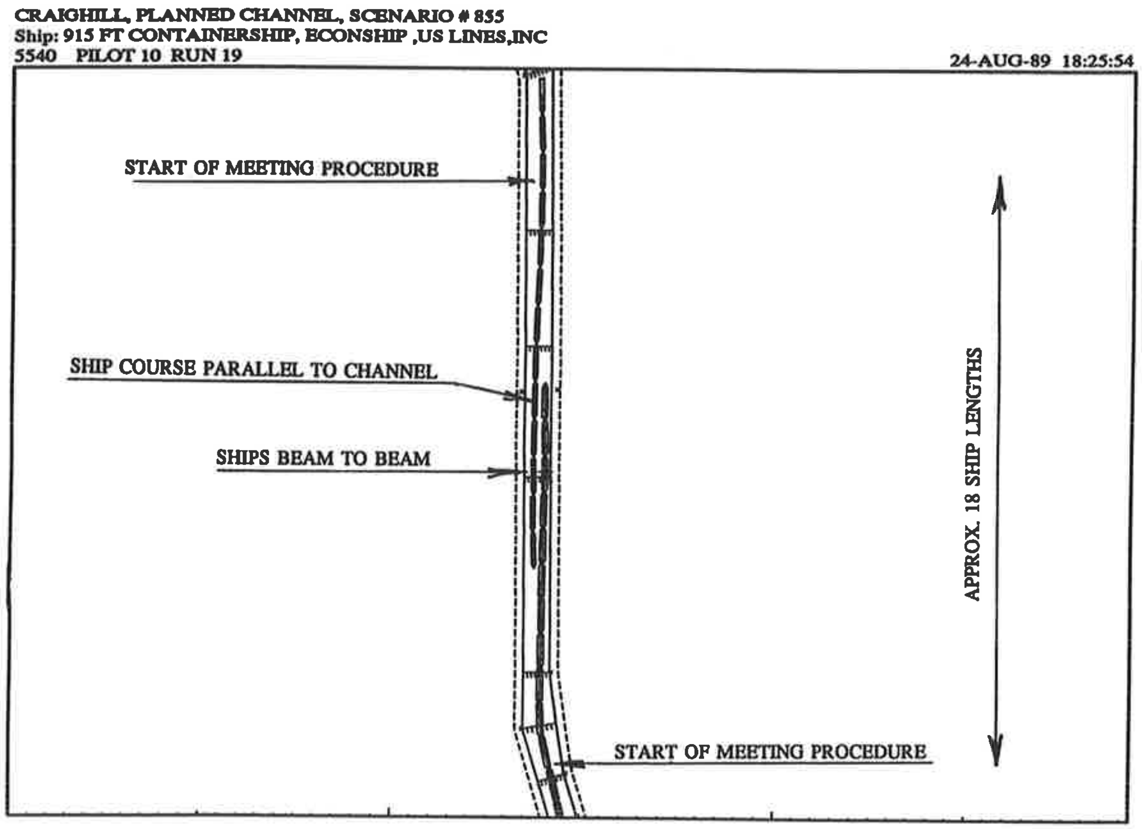

FIGURE 5 Track pilot of meeting situation.

time, where the pilot is watching the response of the bow. Then the rudder is activated again if the turning of the bow is not as expected.

DEVELOPMENT OF AUTOPILOT AND RULE-BASED SYSTEM

Based on 64 real-time simulation runs with eight pilots running coupled simulations of the Craighill Angle, a rule-based system was developed for the control of the traffic ship. The autopilot that was used in the simulations was a track-keeping autopilot controlled by six gain coefficients, which included control of the following:

1. Ship distance from predefined track,
2. Integrated distance from the predefined track,
3. Difference between current ship heading and command heading,
4. Turn rate of the ship,
5. Drift angle of the ship, and
6. Current rudder angle.

TRACKS

The basic track that a ship should follow when it transits the channel without meeting another ship is input to the simulation program. This track is defined by a location in the center of the channel and the heading the ship should follow to transit the channel. A plot of a track is shown in Figures 6 and 7. The tracks consist of a number of straight legs (lines) and circles that link the legs together into a track. The simulation program calculates a circle, defined by its radius, so that the two legs are tangents to the circle. The tangent points are indicated on the plots by crosses. The cross in the middle of the straight leg is the initial condition or start position.

Rule-Based System

A meeting situation is set up when two ships are heading toward each other and are 20 ship lengths apart. The track for the controlled traffic ship is then redefined to follow a path that will position the ship as desired in the channel when the ships are beam to beam. The autopilot is then commanded to follow the new track. This procedure is repeated every two ship lengths as the ships come closer to each other. The predicted position of the ship at meeting is also compared with the distance to the bank. Current and wind effects are also considered in the redefining of the track. When the two ship bows are one ship length apart, the command track for the autopiloted ship is made parallel to the channel centerline. When the two ships have passed each other, the track is again redefined so that the computer-controlled ship will be conned back to the original track in the center of the channel. The relative position of the ships at which the commands are made to return each ship to the centerline of the channel has been

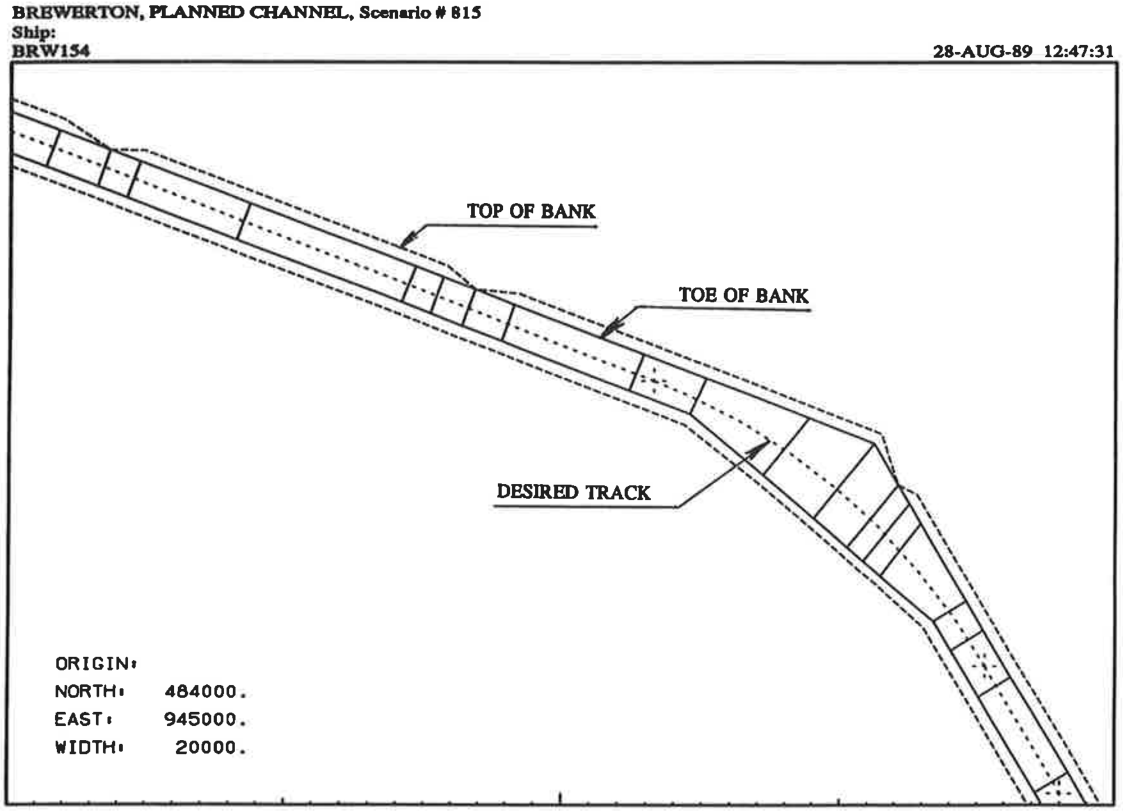

FIGURE 6 Track definition, Brewerton Channel.

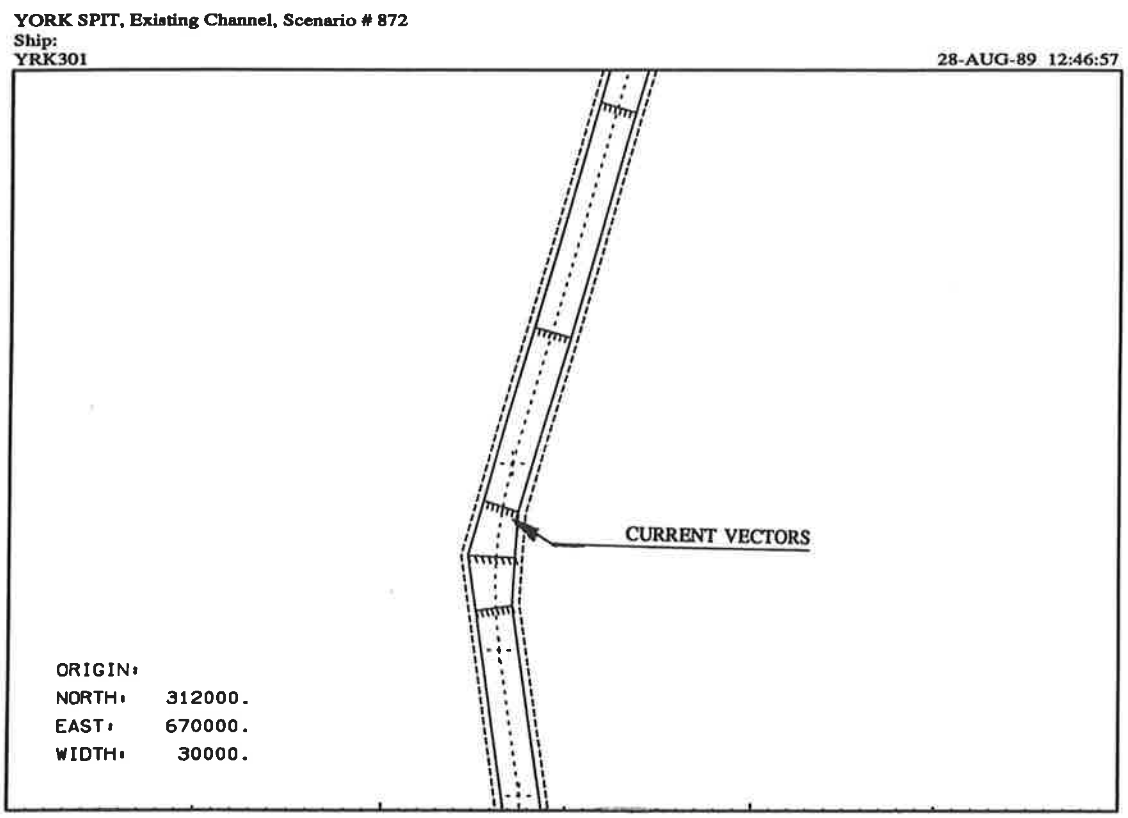

FIGURE 7 Track definition, York Spit Channel.

found to be important for the amount of rudder required to complete the maneuver.

When the meeting takes place in an "angle" where the ships also are making a turn, the meeting procedure becomes more complicated. Special logic in the program takes care of redefining the track circle to make room for the oncoming pilot-conned ship.

DATA EVALUATION

Track plots and parameter time histories were generated for all simulation runs. For each simulation run the following plots were generated:

1. Plots of the whole simulation run. A typical plot is shown in Figure 5.
2. Plots of a selected simulation period covering the close proximity of the ships to highlight the meeting situation. When the two ships were beam to beam, a cross was plotted on each ship to indicate where the meeting took place. Typical plots are shown in Figure 8.
3. Time history plots cover the same period as the enlarged plots mentioned above. The following parameters were plotted:

- Ship heading in degrees,
- Drift angle in degrees,
- Rudder activity, and
- Minimum ship clearance.

The meeting location, where the two ships are beam to beam, is indicated by a dotted line. Typical plots are shown in Figures 3 and 4.

Numerical Analysis

During each simulation run, approximately 30 physical parameters were automatically recorded every 5 sec. These data form the basis for all numerical analyses and plots. A number of other parameters such as ship clearance and bank clearance are derived from these data. Among these parameters, the following were selected for statistical analyses:

- Ship speed,
- Propeller rpm,
- Ship heading,
- Turning rate,
- Drift angle,
- Maneuvering factor,
- Clearance to traffic ship,
- Clearance to "west" bank,
- Clearance to "east" bank, and
- Rudder angle.

In addition to the parameters mentioned, statistics were calculated on minimum and maximum values for rudder activity, minimum ship-ship clearances, and minimum bank clearance.

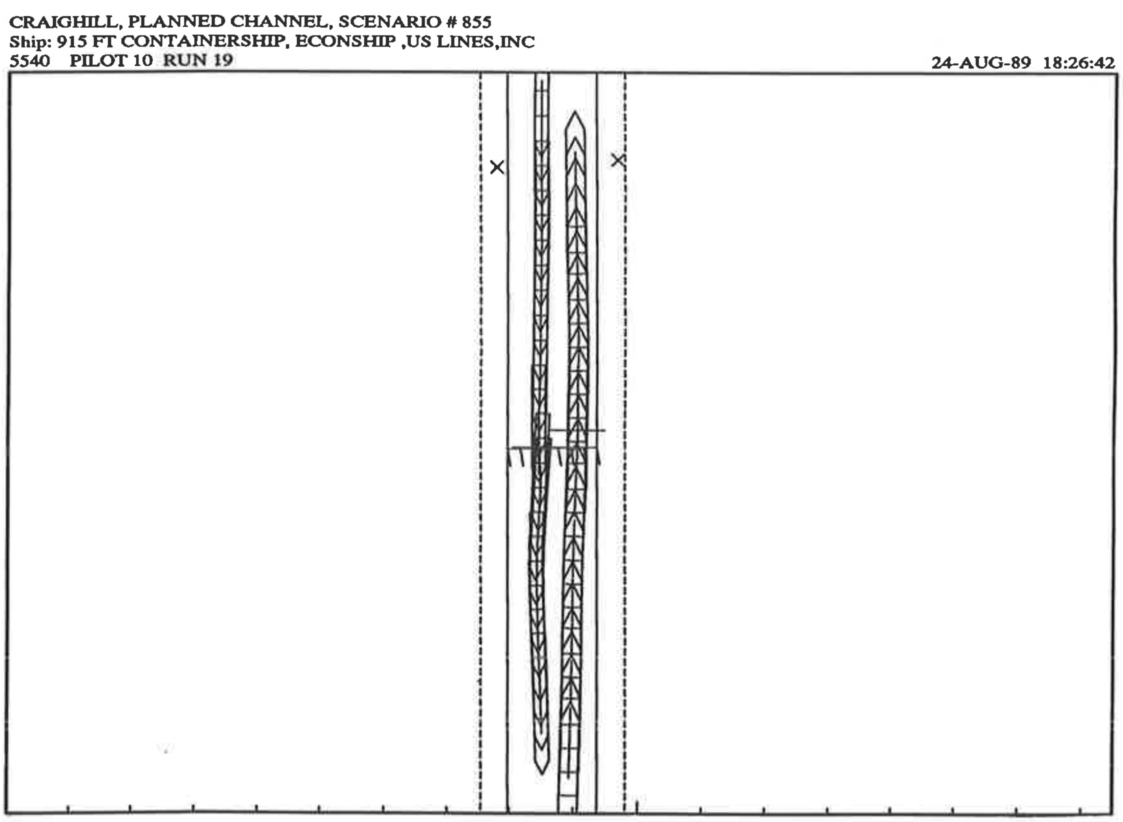

FIGURE 8 Close-up track plot of meeting situation.

Ship Controllability Measures

Results from the numerical analyses were tabulated as shown in Table 2. Further, these data are used to compare ship controllability measures from different channel sections to determine significant differences.

Ship Speed: The changes of speed for the traffic ship were all caused by hydrodynamic effects from shallow water, use of the rudder, bank effects, meeting situations, and so on. The pilots used changes in rpm now and then to keep up with a certain speed. A few pilots used a kick of rpm just before the meeting situation to increase the rudder effect.

Ship Heading: The ship heading data were included.

Turning Rate: The turning rate is a measure of the rotational speed about the ship's center of gravity. Because large masses are involved, the rate of turn should be carefully controlled to maintain good ship-handling. The simulation showed little difference between ship performance in the two channel designs.

Rudder Angle: The rudder activity (see Table 4) varies for different channel tests. High cross current generally requires more rudder activity. It is also found that the bulkcarrier needs more rudder activity than the containership. The largest rudder activity takes place when the ships are in close proximity. In meeting situations with ship clearances of about 100 ft beam to beam, full rudder deflection (35 degrees) is used to compensate for the heading change caused by ship-ship interaction, especially when the ship speeds are high. All the minimum and maximum rudder deflections found by statistical analyses of the individual pilots are collected, and then statistical analyses of these values are carried out.

Drift Angle: The drift angle, normally termed "set" by pilots, is the angular difference between the ship heading and the path of the center of gravity. These angles depend on the ship's heading relative to current, wind direction, bank effect, and ship-ship interaction effect. The drift angles are generally of the same magnitude for the pilot-conned ship and the autopiloted ship.

Maneuvering Factor: The maneuvering factor is defined as the absolute value of the product of rudder angle and rpm and is used as a comparative measure of the amount of maneu-

TABLE 2 ANALYSIS OF CONTROLLABILITY MEASURES, PILOT CONNED

	Containership Meeting Situation # 1		Bulkcarrier Meeting Situation # 2	
	Existing Ch.	Planned Ch.	Existing Ch.	Planned Ch.
SHIP SPEED [knots] over ground				
Minimum	11.11	10.69	10.05	8.22
Maximum	15.37	14.36	14.21	10.17
Average	13.64	12.73	11.11	9.22
Standard Dev.	1.04	1.16	1.28	0.43
SHIP HEADING [deg.]				
Minimum	124.50	129.95	314.14	312.95
Maximum	139.59	144.78	326.43	326.02
Average	136.02	138.05	320.29	320.35
Standard Dev.	3.09	3.36	2.90	3.16
TURN RATE [deg./sec]				
Minimum	-0.215	-0.364	-0.385	-0.286
Maximum	0.213	0.261	0.219	0.222
Average	-0.021	-0.013	-0.014	-0.016
Standard Dev.	0.054	0.091	0.080	0.077
RUDDER ANGLE [deg.]				
Minimum	-17.3	-29.2	-35.0	-29.5
Maximum	12.1	30.8	25.7	35.0
Average	-1.7	0.2	-1.9	-1.8
Standard Dev.	5.0	8.7	7.8	9.2
MANEUVERING FACTOR [rpm*rudder angle]				
Minimum	0	3	0	3
Maximum	1220	2734	3499	2631
Average	247	392	433	541
Standard Dev.	255	440	516	506
MINIMUM SHIP CLEARANCE [feet]				
Minimum	259.2	162.3	69.9	99.3
Maximum	385.4	294.4	206.1	186.6
Average	309.4	240.6	152.5	136.4
Standard Dev.	50.0	56.1	47.0	31.3
MINIMUM BANK CLEARANCE [feet]				
Minimum	-40.8	-11.4	107.6	59.8
Maximum	92.5	109.2	211.3	189.5
Average	33.2	22.3	144.6	141.9
Standard Dev.	58.1	58.1	36.0	44.6
Participating Pilots	6	4	6	6
Number of Samples	311	230	333	335

vering activity occurring in a specified maneuvering situation. Under these test conditions, low numbers are assumed to indicate fewer maneuvers than high numbers. Low numbers are an indication that a small percentage of the ship's maneuvering capability is used.

Minimum Ship Clearance and Bank Clearance: Statistical analyses of minimum ship clearance and bank distances were carried out for each meeting situation, as shown in Table 3. When the performance in channels with different widths was compared, these analyses revealed that the pilots preferred to go closer to the banks than to reduce the ship-ship clearance.

Composite Plots

Track plots for each run give useful information about ship clearances, bank distances, and the particular meeting situation. The general pilot performance in a meeting situation is well illustrated by making composite plots of all the individual track plots superimposed on each other, as shown in Figure 9. These plots give good information on where the meetings take place and how the pilots use the available space in the channel.

Pilot Evaluation Ratings

The pilot evaluation questionnaires were designed to evaluate the different meeting situations on clearance to the traffic ship and clearance to the bank. The pilots were also asked about their awareness of ship-ship interaction effects, bank effects, the amount of rudder activity, and if the traffic ship provided adequate sea room for the meeting situation. This is of particular interest if the traffic ship is computer controlled. Other questions addressed the experience level of the pilots and skill level required to carry out the meeting situation.

TABLE 3 ANALYSIS OF SHIP AND BANK CLEARANCE BASED ON MINIMUM VALUES FOR MEETING SITUATION NO. 4

Pilot	Containership				Bulkcarrier			
	Existing		Planned		Existing			
	Bank Feet	Ship Feet	Bank Feet	Ship Feet	Bank Feet	Feet	Feet	Feet
	260.	144.	240.	83.	141.	39.	328.	-11.
	339.	57.	337.	9.	254.	70.	243.	44.
	207.	168.	292.	100.	338.	51.	334.	26.
	139.	216.	328.	73.	209.	95.	287.	21.
	134.	162.	196.	115.	107.	135.	128.	67.
	203.	156.	82.	185.	127.	170.	199.	44.
	273.	54.	135.	126.	195.	88.	88.	41.
	113.	215.	129.	169.	271.	124.	129.	82.
Minimum	113.	54.	82.	9.	107.	39.	88.	-11.
Maximum	339.	216.	332.	185.	338.	170.	334.	82.
Average	209.	146.	217.	108.	205.	97.	217.	39.
Std. dev.	79.	62.	96.	56.	80.	44.	96.	29.

TABLE 4 ANALYSIS OF RUDDER ACTIVITY BASED ON MINIMUM AND MAXIMUM VALUES FOR MEETING SITUATION NO. 4

Pilot	Containership				Bulkcarrier			
	Existing		Planned		Existing		Planned	
	Min Deg.	Max Deg.	Min Deg.	Max Deg.	Min Deg.	Max Deg.	Min Deg.	Max Deg.
	-20.	20.	-15.	10.	-36.	19.	-23.	0.
	-20.	15.	-15.	15.	-18.	17.	-31.	28.
	-13.	9.	-15.	0.	17.	8.	-12.	0.
	-25.	20.	-10.	0.	-10.	2.	-22.	22.
	-11.	19.	-19.	19.	-19.	19.	-22.	11.
	-20.	20.	-20.	20.	-15.	16.	-22.	21.
	-20.	9.	-17.	19.	-22.	18.	-21.	9.
	-20.	18.	-15.	27.	-22.	20.	-22.	14.
Minimum	-25.	9.	-20.	0.	-36.	2.	-31.	0.
Maximum	-11.	20.	-10.	27.	-10.	20.	-12.	28.
Average	-19.	16.	-15.	14.	-20.	15.	-22.	13.
Std. dev.	4.	5.	3.	10.	8.	6.	5.	10.

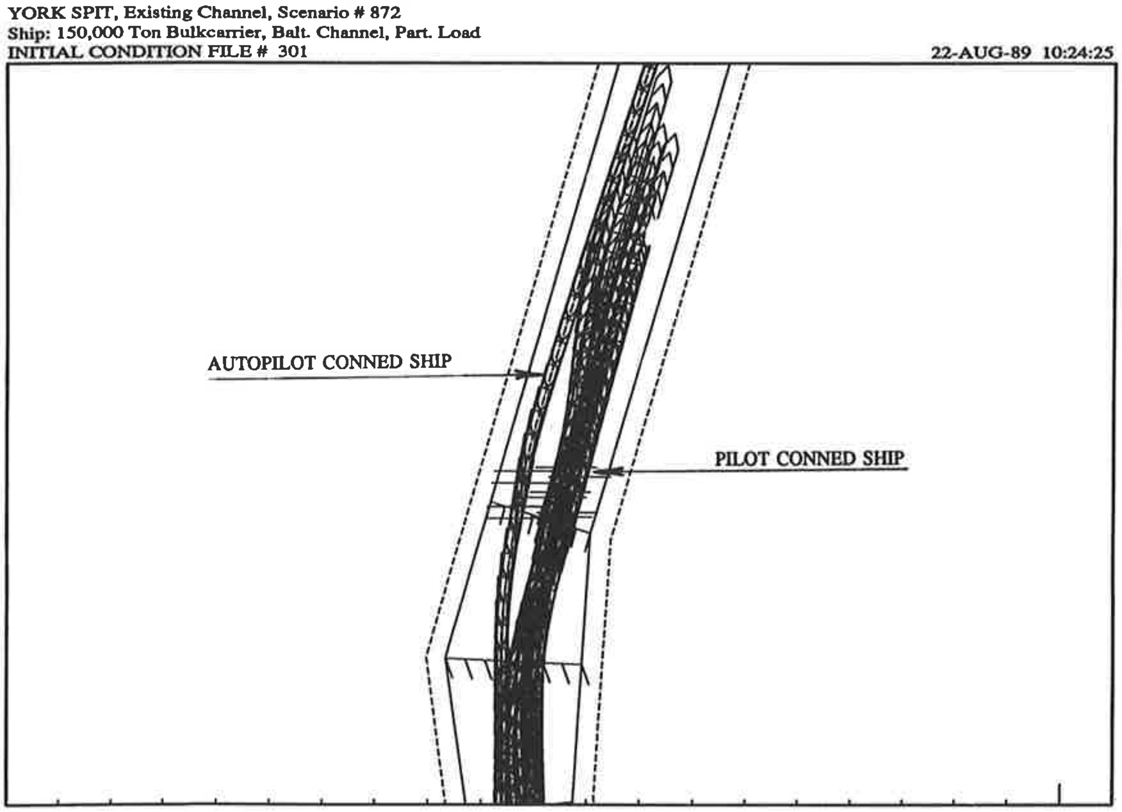

FIGURE 9 Composite plot, York Spit Channel.

CONCLUSIONS

In recent years, the process of harbor and waterway design and evaluation has increasingly made use of ship-handling simulations. These simulations have provided, in an organized way, both quantitative data and direct input of the valuable experience of pilots to the design and evaluation process. Advances in simulation technology, which are briefly described in this paper, have enhanced the applicability of ship-handling simulations to the design and evaluation of restricted channels for two-way traffic. The most significant of these advances include:

- The availability of coupled interactive simulators that allow the pilots on the meeting vessels to interact in an unconstrained and realistic way,
- The availability of interactive simulations that allow both ships to have complete hydrodynamic models that interact with each other,
- Improved models for ship-ship interaction forces and the influence of shallow water and channel banks on ship behavior, and
- The development of a traffic ship control system that makes use of data from piloted meeting situations to control ships in meeting situations for use in fast-time simulations and real-time simulations in single ship simulators.

The application of ship-handling simulations to the evaluation of a channel system with two-way traffic has been illustrated with results from studies carried out for the Baltimore 50-ft depth channel project. This study used coupled interactive simulators with full pilot interaction, as well as fast-time and real-time simulations with one or both ships conned by a traffic ship control system. In addition, improvements were made in the modeling of ship-ship and ship-waterway interactions for use in the simulation studies. In the case of the Baltimore channels, it was concluded that the planned deeper channel can be reduced in width and still allow safe piloting.

For future simulation studies of restricted channels with two-way traffic, it is recommended that

- Coupled interactive ship-handling simulators be used to properly include the effects of the pilots on navigation in unusual channel configurations,
- Simulations of two-way traffic situations use complete mathematical models for both ships and complete hydrodynamic interactions between the ships and the channel boundaries,
- Fast-time and single real-time simulations of two-way traffic meeting situations use a realistic traffic ship control system, and
- The development of traffic ship control systems that reproduce pilot behavior in meeting situations be continued and extended to more general cases.

REFERENCES

1. V. K. Ankudinov, L. Daggett, C. Hewlett, B. K. Jakobsen, and E. R. Miller. *Use of Simulators in Harbor and Waterway Development.* Paper presented at PORTS 89, Boston, Mass., May 1989.
2. V. K. Ankudinov and B. K. Jakobsen. *Craighill Angle Simulation Study*. Tracor Hydronautics Technical Report 87005.0460–3, April 1989.
3. B. K. Jakobsen. *Brewerton Section, Angle and Cutoff Angle, Real-Time Simulation Study*. Tracor Hydronautics Technical Report 87005.0414–1, May 1989.
4. B. K. Jakobsen. *Rappahannock Channel Real-Time Simulation Study*. Tracor Hydronautics Technical Report 87005.0480–1, Sept. 1989.
5. E. F. Guest and E. R. Miller, Jr. *MarineSafety International Shiphandling Learning Center at Newport, Rhode Island*. Paper presented at MARSIM 88, Trondheim, Norway, June 1988.
6. V. K. Ankudinov and B. K. Jakobsen. *Mathematical and Computer Models for Predicting Ship-Ship Interaction Forces for Use in WES/Tracor Hydronautics Ship Maneuvering Simulator*. Tracor Hydronautics Technical Report 87018.0124, Jan. 1988.
7. V. K. Ankudinov and B. K. Jakobsen. *Mathematical and Computer Models of the Ship Propeller and Slipstream Effects on Ship-Ship Interaction Forces and Their Implementation for Use in Ship Maneuvering Simulators*. Tracor Hydronautics Technical Report 87005.07, March 1989.

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