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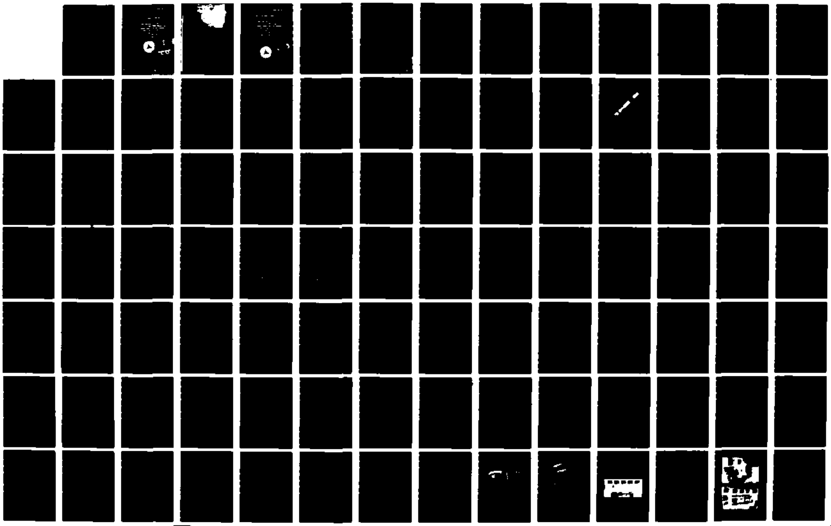

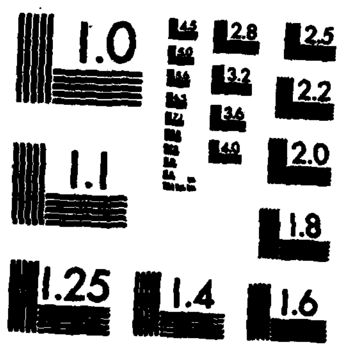

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CAORF 50-8011-02

CAORF TECHNICAL REPORT

SIMULATION EXPERIMENT

COMPARISON OF THE IMPACT ON PILOTING PERFORMANCES OF EXTREME WIND FORCES UNDER VARIABLE CONDITIONS OF SHIP CLASS AND STABILITY, CHANNEL WIDTH AND CHANNEL BANK FORCES

U. S. DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT

NATIONAL MARITIME RESEARCH CENTER
KINGS POINT, NEW YORK 11204
NOVEMBER 1982

CAORF 50-8011-02

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November 1982

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16. Abstracts
The experiment examined the ship handling performance of pilots transiting a narrow waterway under severe wind conditions and attempted to discern the variability in that performance which could be attributed to wind level and direction, ship class and stability, channel width, channel banks, as well as pilot background.

Three classes of vessels were used (two tankers and an LNG) and three levels of wind were employed, including conditions between 40 and 65 knots.

It was found that the pilots on the LNGs had significantly more difficulty than when the tankers were being conned. When transiting through a channel with vertical banks, less difficulties were encountered than with the same channel without banks. Differences in channel width affected the pilots on the LNG to a greater degree than those pilots who conned the tankers. Overall, the pilots were shown to be capable of overcoming the wind-based instabilities and, therefore, differences in performance that were noted were due to other causes, such as ship characteristics. The LNG vessel was shown to have an exceptionally high level of directional stability at high wind levels.

17. Key Words and Document Analysis. 17a. Descriptors

CAORF	Restricted Waterways
Channel Banks	Ship Stability
Channel Width	Track Keeping
Maneuverability	Wind
Pilot Performance	

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EXECUTIVE SUMMARY

COMPARISON OF THE IMPACT ON PILOTING PERFORMANCES OF EXTREME WIND FORCES UNDER VARIABLE CONDITIONS OF SHIP CLASS AND STABILITY, CHANNEL WIDTH, AND CHANNEL BANK FORCES

1.0 BACKGROUND

A portion of the Maritime Research Program conducted at CAORF since 1977 has been concerned with vessel transiting of harbors and narrow waterways. The work has been accomplished using the full capabilities of the CAORF Ship Maneuvering Simulator. It is within this area that the questions of "how" a pilot or ship handler perceives and accomplishes his tasks in restricted waterways and "what" aids assist in the assessment and accomplishment of the tasks have been addressed.

Numerous papers in recent ship hydrodynamics literature have discussed problems regarding ship stability and transiting under heavy wind conditions. Off-line fast-time computer studies at CAORF have shown that different ships are subject to varying levels of instability which are dependent on both the magnitude of wind velocity (compared with ship's speed) and the direction of the wind (relative to ship's bow). The effects of this basic ship instability due to wind have been shown to lessen when an autopilot is used to steer the vessel. How well, though, does the human compensate for this ship characteristic? Is pilot control performance related to the varying levels of stability or are other ship or channel characteristics more pertinent to ship-handling performance? Also, what is the quantification of the variability of piloted controllability across the wide background and experience of pilots? It is this series of questions which formed the basis for the investigation reported herein, a part of the CAORF Ship Maneuverability Research Area studies.

The study examined the ship handling performance of pilots transiting a narrow waterway under severe wind conditions. The specific objectives of the experiment were to:

- Determine the changes in ship handling performance for a representative group of experienced pilots under several extreme wind conditions.
- Determine if this performance is dependent upon inherent wind-induced ship instabilities.
- Determine if this performance is dependent upon the class of vessels involved.
- Determine if the performance is dependent upon the channel width.
- Determine if performance is affected by the inclusion of realistic bank effects.
- Determine if performance is affected by the background/experience of the pilots.

2.0 EXPERIMENT DESCRIPTION

The experiment compared ship-handling performance in a narrow channel using three ships (30K DWT tanker, 80K DWT tanker, and 125K m^3 LNG carrier), three wind magnitudes (40, 50, and 6[illegible] knots), and two wind directions (port and starboard). Paragraph 3.1 contains a description of the channel that was used.

Eighteen experienced pilots drawn from piloting organizations throughout the country were used for the basic experiment. Each mariner piloted a single ship similar to the class of vessel that he had previously experienced in his "real-world" background. Experimental data were obtained and examined for a total of six runs for each pilot.

A channel width variable was also designed into the experiment. An 800-foot channel was selected for the major portion of the test run scenario, but a 600-foot segment was included as the last segment of each run for comparison with the first segment. The conditions of segment 1 (first major segment) were identical with those of segment 5 (last segment) except for channel width. Therefore, the effects of channel width on demonstrated performance were also investigated.

Another variable designed into the experiment concerned bank effects. The main portion of the experiment was conducted in a passage through a channel with vertical banks. The effects of these banks were then assessed by means of an additional grouping of six pilots who used a single vessel class (80,000 DWT tanker) and a similar channel. The channel used with this second grouping of six pilots was identical to that used in the main experiment except that the channel's bank effects were removed. This second assessment is referred to as the bank/no bank comparison in this report.

2.1 EXPERIMENT DESIGN

The experiment design was structured around three principle independent variables:

A) Ship Type
   1. 125,000 m^3 LNG carrier
   2. 80,000 DWT tanker
   3. 30,000 DWT tanker

B) Wind-Ship Speed Ratio
   1. 8:1
   2. 10:1
   3. 13:1

C) Wind Side
   1. Port
   2. Starboard

These variables were combined in a completely factorial, mixed design arrangement. In the mixed design model each of the 18 subjects was observed under only one of the three levels of the between-groups variable A (Ship Type) and under each of the six conditions of variables B (Wind Ratio) and C (Wind Side).

A total of 108 runs comprised the main experiment. The sequence for testing Ship Type was an alternating one within each level of Ship Type; the order for testing Wind Ratio was counterbalanced with Wind Side alternating on each successive run.

Two supplemental sub-experiments were conducted as part of the overall investigation. In the first, Ship Type was constant, utilizing only the 80,000 DWT tanker, while Bank Effects (Variable F), Wind Ratio (Variable B) and Wind Side (Variable C) were experimental variables. The experimental design for this study was a three-factor mixed design with Bank Effects as the between-groups variable and with Wind Ratio and Wind Side as within-subjects variables. Seventy-two runs comprised this sub-experiment with half in each bank effect condition. No attempt was made to counterbalance the bank effects factor since the six subjects participating in the no banks condition were run in an unstructured random manner.

In the second sub-experiment, Pilot Experience Group (Variable E), Wind Ratio (Variable B) and Wind Side (Variable C) were experimental variables while Ship Type was equally represented for both Experience Groups and, therefore, not treated as an experimental variable. The experiment design for this study was also a three-factor mixed design with the Pilot Experience Group as the between-groups factor and with Wind Ratio and Wind Side as within-subjects variables. Since this sub-experiment used data from the main experiment no additional counterbalancing of run sequence was necessary.

Data analyses of the performance measures that are discussed in this report utilized the analyses of variance (ANOVA) technique.

Five different ANOVA models were used for data analyses purposes in this investigation:

- o The first ANOVA model enabled significance determinations for effects of Ship Type (Variable A), Wind Ratio (Variable B), Wind Side (Variable C) and all possible interactions of these factors. These are the primary variables examined in the study and therefore this can be considered the "Main Analyses."

- o The second ANOVA model enabled significance determinations for Bank Effects (Variable F), Wind Ratio (Variable B), Wind Side (Variable C), and all possible interactions of these factors. There was redundancy in this ANOVA model and the "Main Analysis" for the Wind Ratio and Wind Side factors. The Bank Effects factor and its interactions were the primary concern of the analysis, referred to as the "Bank-No Bank Analyses."

- o A comparison of ship control performance in two sections of the test channel, Sections 1 and 5, form the basis of a "Channel Width Analyses." The ANOVA model used in these analyses enabled significance determinations for Channel Width (Variable D) and all possible interactions of this factor with Ship Type (Variable A), Wind Ratio (Variable B) and Wind Side (Variable C).

- o A set of comparisons were conducted to evaluate "Pilot Experience Group" (Variable E) and its interactive effects with Wind Ratio (Variable B) and Wind Side (Variable C).

- o The final ANOVA model used in this investigation enabled a direct comparison to be drawn between ship control performance in two test channel sections constituting a set of "Rudder Effect Analyses," as well as tests of the interactive effects of this factor with Ship Type (Variable A), Wind Ratio (Variable B) and Wind Side (Variable C).

2.2 PERFORMANCE MEASURES

Seven performance measures were assessed via the Analysis of Variance in this Experiment:

1) Absolute Magnitude Off-Track deviation
2) "Factored" Off-Track deviation
3) Consistency
4) Boundary Penetrations
5) Ship Speed
6) Rudder Angle
7) Zero Rudder Crossings

In all cases the measures were computed across either five sections of the test channel (Legs 1-5) excluding the turn and transition areas or across the five legs including the turn area.

3.0 SCENARIO AND VESSEL DESCRIPTIONS

3.1 Scenario

The scenario used in this experiment is shown in Figure ES-1 and consists of two straight channel legs, the first running at 000° and the second on a course line of 045°. The scenario has been broken into segments L_1, 1, 2, 3, 4, L_2, and 5 for identification purposes.

L_1 starts at entrance buoys 1 and 2 and runs for 1/4 nm. Leg 1 runs for 3/4 nm followed by segment 2, which starts 1/4 nm beyond buoys 3 and 4 and includes the 45° turn up to buoys 9 and 10. Segment 2 is further subdivided into segments 2a, 2b, 2c and 2d as shown. Segment 2a is 1 nm long. The start and end of segments 3, 4, L_2 and 5 are coincident with the appropriate buoys, as shown. The channel is 800 feet wide except for part of transition segment L_2 and segment 5. The perception of the change of channel width was accomplished by a 200 foot shoal, which effectively changes usable width to 600 feet. The primary analyses were accomplished over five legs, which did not include the turn or transition areas. Each Leg relates to a segment (Seg) as follows:

Leg 1 - Seg 1
Leg 2 - Seg 2a
Leg 3 - Seg 3
Leg 4 - Seg 4
Leg 5 - Seg 5

The depth of water to ship draft ratio throughout the usable portion of the channel is approximately 1.25 so that channel depth was 50 feet for the 80,000 DWT tanker (40 foot draft) and 45 feet for the LNG and 30,000 DWT tanker (35 foot and 36 foot drafts respectively). The 15 foot high shoal could cause a simulated grounding for all three vessels because of a 5 foot or 6 foot "interference." Bank effects were present for the appropriate runs and forces acted on the ships based on a bank height to water depth ratio of 0.8.

The channel described above was used for all experiment runs. Runs were inbound with clear visibility and no traffic. Differences between the runs were only related to differences in wind magnitude and direction and the presence or absence of banks. Currents were always zero.

There were a total of 13 wind conditions for this experiment:

- A light wind condition of 10 knots (135° true), used as a channel familiarization run for all vessels.
- Six wind conditions (three wind magnitudes - 40, 50 and 65 knots, and two sides - port and starboard), used for LNG vessels.
- Six wind conditions (three wind magnitudes - 40, 50 and 65

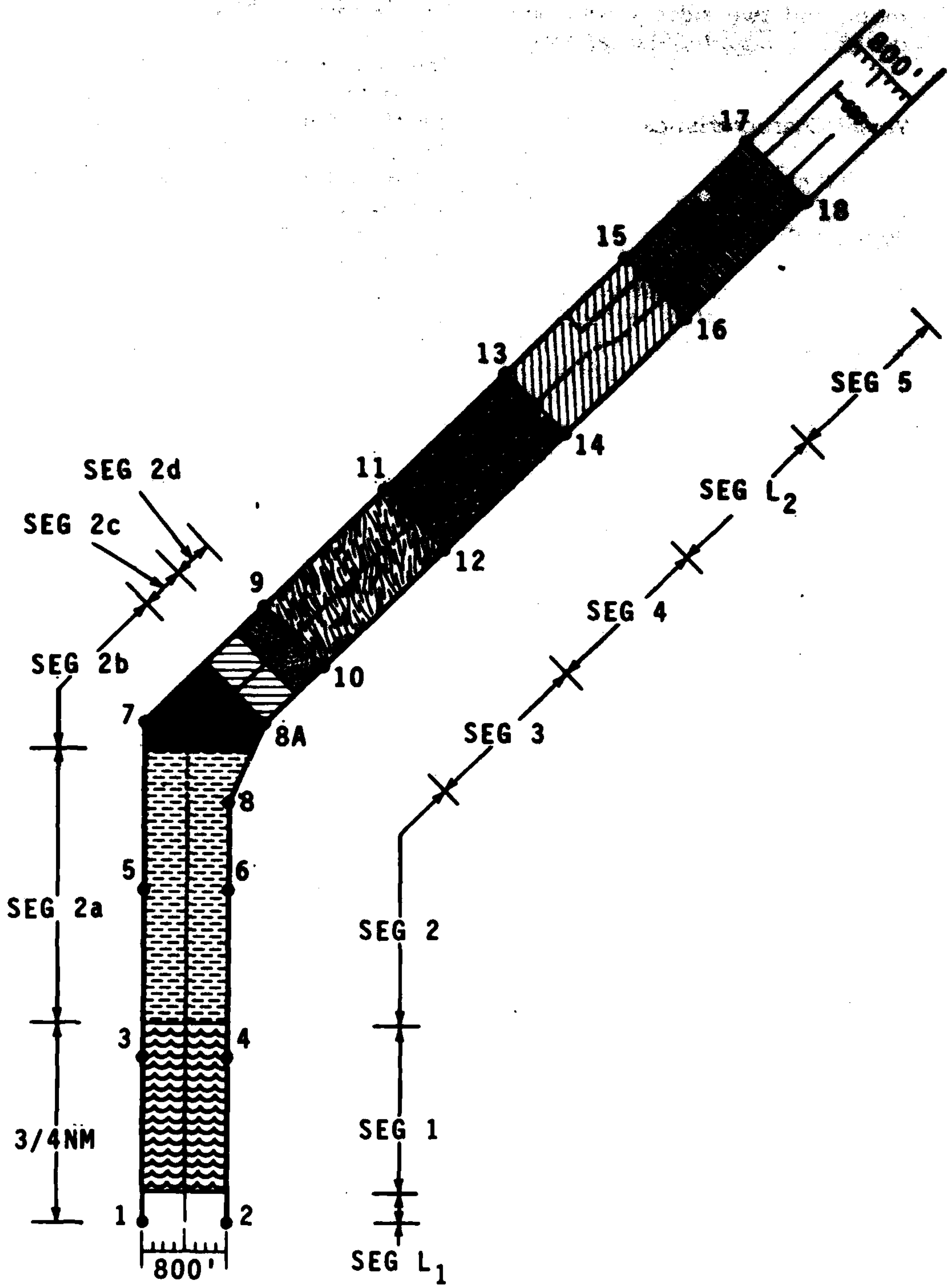


Figure ES-1 Basic Scenario

knots, and two sides - port and starboard), used for the tankers.

3.2 Vessel Characteristics

- 125,000 m^3 LNG
- 80,000 DWT Tanker
- 30,000 DWT Tanker

One of the variables established for the Ship Characteristics experiment was the class of ship used. The hydrodynamic characteristics of three ships (an Aquarius Class 897 foot long LNG, an 80,000 DWT 763 foot long tanker, and a 30,000 DWT 595 foot long tanker) were incorporated into the CAORF simulator for this purpose.

4.0 TEST SUBJECTS

This experiment required a total of 24 full branch harbor pilots experienced with the type of vessel that they were to handle at CAORF. Eighteen of these subjects (six for 30,000 DWT tankers, six for 80,000 DWT tankers, and six for LNGs) were used with the bank effects scenario while six of them (for the 80,000 DWT tanker) were used with a scenario which did not contain vertical banks. Since the LNG grouping consisted of pilots inexperienced with the CAORF simulator, it was highly desirable that the other 18 test subjects also have little or no experience with the simulator.

Each test subject transited through the channel scenario seven times. The first experiment run was designated a baseline run (under low wind conditions), while the following six runs occurred at three different wind magnitudes from the port side and the same three magnitudes from the starboard side.

5.0 RESULTS AND CONCLUSIONS

The experiment was structured so that the data was capable of being efficiently analyzed from a variety of viewpoints. The purpose of the statistical analyses was to determine if differences existed in the performance exhibited by sample groups of experienced pilots under various controlled conditions. Performance was evaluated by means of a set of seven measures, three of which were concerned with the pilot actions (pilot performance measures) and four with the results of the actions (system performance measures). Five sets of comparisons were performed on the data:

- Main
- Bank/No Bank
- Channel Width
- Rudder Effects
- Special Experience

The primary performance comparisons (i.e., main comparisons) were made between pilotage exhibited on different classes of ships under different wind conditions during passages through a narrow, shallow, vertically banked waterway. The comparisons were based on the total performance during the straight legs of the channel.

The remaining four sets of analyses were refinements of secondary issues concerned with the basic comparisons. A bank/no bank comparison investigated the question of the effects and/or usage of bank forces during the total passage through the channel. This was done with only one ship type, the 80K tanker. A channel width comparison analyzed the difference in performance on the three classes of ships within an 800 foot wide channel leg and a 600 foot wide channel leg.

One of the vessels, the LNG carrier exhibited an unusual rudder characteristic under conditions of heavy wind forward of the ship's beam. An examination of the effects of this phenomenon was also conducted. The last comparison was based on an experience factor; one group was selected for actual experience with a particularly long and narrow waterway, while its comparitive group did not necessarily have this type of background.

The multiple analyses of the data which were performed on the various measures resulted in a myriad of findings; i.e., differences in ship handling control were shown to exist at many levels of significance for both main effects of the variables that were investigated as well as interactions between these variables. A non-statistical overview based on these findings is presented in the following subparagraphs:

5.1

The experiment clearly showed a marked difference in narrow channel ship-handling performance by pilots conning the LNG carriers as compared with those conning the tankers. Under some conditions of winds, banks, channel widths, etc., differences between the performances by pilots on the 80K tankers and 30K tankers were also in evidence. Overall, the pilots assigned to the LNG carriers exhibited the largest degree of control difficulties under the extreme wind conditions used in the experiment. When differences existed between performance on tankers, the mariners on the 80K tankers exhibited better controllability.

5.2

The experimental design as well as the scenario itself were structured to impose high levels of stress on the men and the ships used in the experiment so as to discern more clearly differences in performance which might exist. As a consequence, numerous penetrations of the shoal area and channel boundaries occurred, and these became a sensitive measure of control difficulties encountered. The pilots on the LNG had a larger number of such incidents than did the tanker pilots, and there were more of these incidents occurring at higher winds then at the 40 knot condition. The 30K tanker pilots also had a greater number of incidents at the highest wind level, but still far fewer than the pilots conning the LNG carrier.

5.3

Ship control difficulties did not correlate in a positive manner with inherent wind-based ship instabilities. The inference that the more unstable vessel would be more difficult to control was not borne out and, in fact, the reverse was found to be true. The LNG vessel was shown to have a lower level of wind induced instabilities, yet the pilots that conned that ship had the most difficulty with the channel passage. Tanker pilots were able to overcome their vessels' instabilities and transited the channel with less problems. It was apparent, therefore, that ship characteristics other than instability caused by high wind levels were more dominant in the determination of controllability.

5.4

The LNG pilots found that their rudder was not effective under the wind conditions that they encountered. They were forced to increase engine rpm to counter the control problems that they were experiencing and, in an attempt to maintain control, increased the speed of their vessel through the water by more than 100% over the desired speed.

5.5

Based on the sampling techniques and analyses that were used in this experiment, estimations of probable LNG ship-handling performance by any experienced pilot indicate that it would be highly injudicious to make an actual passage in a 600 to 800 foot waterway without tug assistance under any of the wind conditions that were studied. This would especially be true if the vessels, for any reason, were unable to have their speed through the water increased to more than 10 knots.

5.6

The 80K tanker pilots made use of the channel banks as an aid during the passages through the narrow waterway. Transits through a channel with banks was safer (fewer boundary penetrations) than those passages which occurred in a channel that had no banks. The pilots also progressed through the banked channels at a slightly higher speed then when no banks were present.

5.7

The 600 foot channel width affected the LNG pilots to a greater degree than it did those who conned the tankers. The trend of decreased safety with increased wind levels that was observed for the 800 foot wide channel segment did not occur when the channel was only 600 feet wide. The LNG pilots perceived that the narrower channel would be more difficult/dangerous and substantially increased their ship's speed during that portion of the passage to acquire a greater degree of control over their vessel.

5.8

Prior experience with a very narrow channel did not surface as a significant factor in the performance exhibited in 800 and 600 foot wide channel segments. This finding was most probably caused by the structuring of the samples used in the mini-analysis of this particular issue since the "experience factor" was investigated as an afterthought, i.e., after the experiment had commenced. The question of specific types of experiences affecting performance in a narrow channel would benefit from a more thorough, detailed investigation.

5.9

On most ships, including an LNG vessel, a positive rudder causes a turn to port. For certain particular wind directions and magnitudes, an anomoly occurs in the ship-handling characteristics of the LNG, resulting in a positive rudder causing a turn to starboard. The effects on performance of this "rudder reversal phenomenon" were studied during the experiment but the findings were inconclusive. The general difficulties that the LNG pilots faced with ship controllability overshadowed any "special effects" differences in ship handling that might exist. By increasing their speed in the "reverse rudder" portion of the channel the pilots attained much better control, thereby masking any difficulties that existed because of a lack of familiarity with this phenomenon. This question, related to "reverse rudder effects," would also benefit from more detailed future research.

5.10

Pilots were shown to be capable of overcoming the wind-based instabilities of their vessels, and therefore differences in performance in heavy winds were caused by other ship characteristics. An example of one such ship characteristic is the development of a turn rate. Analyses have shown that the LNG vessel exhibits an extremely limited capability for the development of a turn rate into the wind, caused by exceptional levels of directional stability. Further research could address issues of which characteristics dominate the controllability problems for the LNG in winds and how ship-handling performance can be better managed in narrow waterways.

CHAPTER 1

INTRODUCTION

1.1 PURPOSE

This report presents the results of the "Comparison of the Impact on Piloting Performances of Extreme Wind Forces Under Variable Conditions of Ship Class and Stability, Channel Width, and Channel Bank Forces" experiment* conducted at the Computer Aided Operations Research Facility (CAORF), Kings Point, NY. The study examined the ship handling performance of pilots transiting a narrow waterway under severe wind conditions. The specific objectives of the experiment were to:

- o Determine the changes in ship handling performance for a representative group of experienced pilots under several extreme wind conditions.
- o Determine if this performance is dependent upon inherent wind-induced ship instabilities.
- o Determine if this performance is dependent upon the class of vessels involved.
- o Determine if the performance is dependent upon the channel width.
- o Determine if performance is affected by the inclusion of realistic bank effects.

1.2 BACKGROUND

A portion of the Maritime Research Program conducted at CAORF since 1977 has been concerned with vessel transiting of harbors and narrow waterways. The work has been accomplished using the full capabilities of the CAORF Ship Maneuvering Simulator, including the fully instrumented ship's bridge and the computer generated visual imagery described in Appendix A.

The studies have tended to be divided into two research areas: one, a series of experiments related to the channel or waterway design itself, and two, investigations in which Pilot/Master behavior and related ship characteristics and controllability factors are studied. It is within the latter area that the questions of "how" a pilot or ship handler perceives and accomplishes his tasks in restricted waterways and "what" aids assist in the assessment and accomplishment of the tasks have been addressed. For example, an associated research experiment assessed the potential assistance (or lack of assistance) that specific shallow water maneuvering data cards yield as a ship-handling aid.

All of these investigations were aimed at the Maritime Administration goals of improved safety and productivity. These goals were also addressed by the Society of Naval Architects and Engineer (SNAME) report "High Priority Research for the U.S. Maritime Industry," which states "As the traffic on waterways and ports increases in density and in vessel size, the risks of collisions, rammings or groundings increase, as do their potential consequences. To reduce risk, this interaction of the operator, the vessel, and the waterways must be understood. The reduction in collisions, rammings, and groundings provides a saving in

* Informally, for brevity, referred to as the Ship Characteristics experiment.

property damage and lives. The development of system requirements and the definition of ship controllability define the operating envelope for the vessel, making clear the limits of one element of the system."

The recent September 1979 IMCO subcommittee on Ship Design and Equipment working group report entitled "Maneuverability of Ships" also indicated that "in the area of maneuvering characteristics, information, reports, studies, etc. related to trackkeeping during harbor entry in cross currents and beam winds conditions... would be helpful to adequately address the area."

Numerous papers in recent ship hydrodynamics literature have discussed problems regarding ship stability and transiting under heavy wind conditions. O. Khattab in "Steering Control of a Ship in a Canal" (1979), Koyama et. al. in "A Study of the Instability Criteria of the Manual Steering of Ships" (1977), and papers by H. Eda in 1971 and 1965, to mention just a few, have discussed these problems. It is most unfortunate that the recent tragic occurrence in Tampa Bay, Florida also underscores the timeliness of obtaining a better understanding of the limitations associated with various ship classes in restricted harbor areas under heavy wind conditions.

1.3 OVERVIEW

Off-line fast-time computer studies at CAORF have shown that different ships are subject to varying levels of instability which are dependent on both the magnitude of wind velocity (compared with ship's speed) and the direction of the wind (relative to ship's bow). A technical memorandum on this subject is included in Appendix B. The effects of this basic ship instability due to wind have been shown to lessen when an autopilot is used to steer the vessel (Eda, 1968). How well, though, does the human compensate for this ship characteristic? Is pilot control performance related to the varying levels of stability or are other ship chacteristics more pertinent to ship-handling performance? Also, what is the quantification of the variability of piloted controllability across the wide background and experience of pilots? When, i.e. at what magnitude, does the level of wind become "excessive" for this range of qualified mariner? How is this affected by the class of ship that is involved with these extremes of environmental condition? Is there a limiting consideration due to channel width that affects the problem and is it aided or hindered by the type of channel banks (vertical or mildly sloping) that are involved? It is this series of questions which formed the basis for the present investigation, a part of the CAORF Ship Maneuverability Research Area studies.

One of the purposes of the experiment was to assess the effects on shiphandling performance of wind-induced ship instabilities which are caused by inherent ship design and geometry. The inherent instability of ships has been studied in the past by techniques which make use of mathematical models of the ships (see Appendix B). These models have been subjected to analyses through the use of off-line computer simulations which mathematically investigate the areas of instability. These analyses have been further augmented through the use of autopilot equations in conjunction with the ship model to mathematically explore the nature of the combined autopilot-ship instabilities (Eda, 1968). However, the human controller (i.e., the pilot) has not as yet been sufficiently defined in a mathematical sense to allow the use of these techniques to accurately and directly explore the instability that can exist in pilot/ship combinations. Therefore, to study the effects of the pilot/ship interaction, an indirect approach was used to examine the presumed effects of instability, i.e., variability in levels of piloted performance, with poorer performance associated with lower stability.

Piloted performances can be compared by means of a ship maneuvering simulator under varying controlled conditions of ship, wind direction, and wind magnitude which are known (mathematically) to cause varying levels of ship/wind stabilty and instability. The differences in performance can then be compared with the differences in stability levels which are associated with the controlled conditions. If a positive association is determined (i.e., the more unstable conditions correlate with the poorer performances) then the "instability-controllability difficulty" inference has been borne out. The differences in performance are then linked to differences in stability. The stability differences would therefore be indicative of the variability of the ship/pilot performance to be found in real world situations under the same conditions as those studied and the consequences of the effects of these ship characteristics would be highlighted for future ship design considerations during retrofit or new construction programs. If the inference is not borne out (i.e., more unstable conditions do not correlate directly with poorer performance) then the accumulated data and comparisons are useful in their representation of the variability of ship controllability in real life under the conditions studied.

1.4 EXPERIMENT DESCRIPTION

The experiment was designed to address several issues related to the effect of wind on piloted performance in restricted waterways. Under conditions of extreme winds, off-line analyses have shown that many vessels are inherently unstable and that for particular wind directions, wind speeds greater than a given amount (dependent upon the ship) result in instabilities. Examples of this for CAORF vessels are shown in Appendix B, Figures B-3, B-5, and B-8. These figures plot the roots of the system equations (eigenvalues) versus absolute wind angle (ship track is assumed to be north) for different values of wind magnitude and ship speed. A positive eigenvalue represents an unstable condition. For each ship the steady state static rudder angle vs. wind direction for several wind speed/ship speed ratios is also presented. Previous computer-based simulation research has been conducted along these lines by Dr. Eda and others, and it has been shown that automatic steering based on autopilot algorithims reduces this area of instability. The relevant relationships extracted from a paper for the Mariner Class vessel (Eda, 1968) are shown as Figure B-1 and indicate the manner in which instabilities have been reduced by an autopilot. The upper portion of this figure is for an unsteered vessel, comparable to Figures B-3, B-5, and B-8, while the lower portion presents the same ship with the inclusion of an autopilot.

One major issue investigated in the current experiment was the determination of the level of control which can be exercised by representative groupings of experienced pilots under conditions of wind magnitude and wind direction which have been shown to cause basic ship instabilities. It is quite obvious that one could encounter wind magnitudes of a sufficiently high level so that ships are simply "blown away," i.e., insufficient rudder is available to counteract the wind effects. The question of interest here though was that with sufficient available remaining rudder would the pilots be able to overcome instabilities that existed because of ship design and, if not, at what level of wind do their performances markedly degrade?

The experiment compared ship-handling performance in a narrow channel using three ships (30K DWT tanker, 80K DWT tanker, and 125K m^3 LNG carrier), three wind magnitudes (40, 50, and 65 knots), and two wind directions (port and starboard), as depicted in Table 1-1. The reason for port and starboard wind as a variable of interest in spite of the fact that the ship characteristics curve (instability vs. wind angle) is essentially symmetrical about the longitudinal axis of the vessel is that in the major portion of the experiment the channel that was used contained bank effects. It was thought that banks might affect performance, tending to help (or hinder) the pilot as he attempted to control the ship.

A channel width variable was also designed into the experiment. An 800 foot channel was selected for the major portion of the test run scenario, but a 600 foot segment was included as the last segment of each run for comparison with the first segment. The conditions of segment 1 (first major segment) were identical with those of segment 5 (last segment) except for channel width. Therefore, the effects of channel width on demonstrated performance were also investigated.

Another variable designed into the experiment concerned bank effects. The main portion of the experiment was conducted in a passage through a channel with vertical banks. The effects of these banks were then

TABLE 1-1. BASIC EXPERIMENT DESIGN

	Wind Speed/Ship Speed* Ratio					
	8:1 (40 kn. Wind)		10:1 (50 kn. Wind)		13:1 (65 kn. Wind)	
	Side		Side		Side	
Ship	Port	Stb.	Port	Stb.	Port	Stb.
LNG						
30K						
80K						

* Ship Speed is five knots.

assessed by means of an additional grouping of six pilots that used a single vessel class (80,000 DWT tanker) and a similar channel. The channel used with this second grouping of six pilots was identical to that used in the main experiment except that the channel's bank effects were removed. This second assessment is referred to as the bank/no bank comparison in this report.

Eighteen experienced pilots drawn from piloting organizations throughout the country were used for the basic experiment. Each mariner piloted a single ship similar to the class of vessel that he had previously experienced in his "real-world" background. Experimental data were obtained and examined for a total of six runs for each pilot.

CHAPTER 2

METHODOLOGY

2.1 EXPERIMENT VARIABLES

This CAORF experiment was designed to investigate variables that were likely to effect vessel behavior under extreme environmental conditions. The major variable, ship type, allowed comparison of ship/pilot performance while piloting a 30,000 DWT tanker, an 80,000 DWT tanker, and an LNG ("Acquavius Class"). Three levels of a second variable, wind, were used (40 knots, 50 knots, and 65 knots) resulting in ratios when compared to a five knot ship's speed of 8:1, 10:1, and 13:1. These winds were encountered from both the starboard and port sides, and wind side was therefore a third variable.

All runs were made in restricted waters, i.e. a channel containing a shoal area which allowed for a 2-level (600 vs. 800 foot) channel width variable. A final comparison was accomplished via a bank effects variable of two levels, i.e., bank effects and no bank effects.

2.2 EXPERIMENT DESIGN

2.2.1 Experiment Model and Statistical Analyses

A mixed factorial design treating ship type (30K, 80K, LNG) as the between-subjects factor and both wind ratio (8:1, 10:1, 13:1) and wind side (starboard, port) as within-subject factors was used for the experiment. In this mixed design model each of the 18 subjects was observed under only one of the three levels of the between-subjects variable (ship type). In contrast, each of the 18 subjects was observed under each of six combinations of the within-subjects variables of wind ratio and wind side, as shown in Table 2-1.

A total of 108 runs comprised the basic experiment. The run order matrix is also shown in Table 2-1, wherein the sequence for testing ship type changes with each run and is indicated under the "subject run order" column. Within each level of ship type, the order for testing wind speed/ship speed ratio is counterbalanced. Wind side alternates on each successive run.

Eighteen licensed pilots were selected for participation based on their availability and experience. Because ship type was treated as a between-subjects factor and because few pilots have extensive experience on LNG carriers, it was necessary to select subjects from different pilot organizations. This situation required careful matching of relevant experience on the ships used for testing each pilot. Hence, subject assignment to ship type conditions was not totally random, i.e., LNG subjects were randomly selected from organizations with appropriate experience but tanker subjects were selected on a totally random basis.

Wind angle was identical in legs 1 and 5 for comparisons based on channel width. In leg 1, channel width was 800 feet. Performance in this area was compared with performance in leg 5 where the channel width was reduced by a shoal area to 600 feet. The relative wind direction was identical in these two areas to allow for comparisons based on the other experimental variables. The data for this

TABLE 2-1. RUN ORDER MATRIX FOR MIXED DESIGN MAIN COMPARISON

Ship	Subject Run Order	Experimental Condition Run Order: Wind Speed/Ship Speed 8:1 Ratio Stb.	Wind Speed/Ship Speed 8:1 Ratio Port	Wind Speed/Ship Speed 10:1 Ratio Stb.	Wind Speed/Ship Speed 10:1 Ratio Port	Wind Speed/Ship Speed 13:1 Ratio Stb.	Wind Speed/Ship Speed 13:1 Ratio Port	Number of Runs
LNG	1	2	5	6	3	4	1	36
	4	1	4	5	2	3	6	
	7	6	3	4	1	2	5	
	10	5	2	3	6	1	4	
	13	4	1	2	5	6	3	
	16	3	6	1	4	5	2	
80K	2	2	5	6	3	4	1	36
	5	1	4	5	2	3	6	
	8	6	3	4	1	2	5	
	11	5	2	3	6	1	4	
	14	4	1	2	5	6	3	
	17	3	6	1	4	5	2	
30K	3	2	5	6	3	4	1	36
	6	1	4	5	2	3	6	
	9	6	3	4	1	2	5	
	12	5	2	3	6	1	4	
	15	4	1	2	5	6	3	
	18	3	6	1	4	5	2	
Run Totals		18	18	18	18	18	18	108

analysis was assessed with an analysis of variance (ANOVA) procedure appropriate to its mixed design and is found in Appendix C.

The appropriate ANOVAS were used for all comparisons and were supplemented by Neuman-Keuls Multiple Comparison Procedures and t-tests using the appropriate error term for the ANOVA. The source tables for each of the models used, as well as the complete analytical findings for all comparisons, are contained in Appendix C.

The main experiment has been described based on passage through a channel with realistic vertical banks. To detect the effects of these banks (that is, the effects of the wind alone on the ships), a separate investigation would normally be required. Therefore, in an additional supplementary sub-experiment, the influence of banks in the channel was also assessed. Using data from one ship type condition in the main experiment (80,000 DWT tanker), additional data were generated using a new group of subjects under conditions of no banks. Thus, ship type was a constant while bank effects, wind ratio, and wind side were experimental variables. The experimental design for this study is shown in Table 2-2 as a three-factor mixed design with bank effects as the between-subjects variable and wind ratio and wind side as within-subjects variables. Pilots experienced banks or no banks throughout all six of their runs with each combination of wind ratio and wind side presented. Seventy-two runs comprised this sub-experiment with half in each bank effect condition. As shown, no attempt was made to counterbalance the bank effects factor since the six subjects participating in the no banks condition were run in an unstructured random manner. ANOVAS appropriate to the model were applied to the data as shown in Appendix C.

2.2.2 Performance Measures

Comparative evaluations of track-keeping accuracy were accomplished using both system performance and pilot performance measures. Whereas system performance measures provide indices of ship state relative to ideal reference values, pilot performance measures reveal the pilots' procedures in accomplishing the passage. All analyses were conducted both within individual legs and across the entire passage. However, the turn section per se was not analyzed since track-keeping accuracy is the focus of attention from the performance assessment standpoint and the variability in pilot perception of proper ship-handling procedures in turns is quite wide.

2.2.2.1 System Performance Measures

2.2.2.1.1 Absolute Value of Off-Track Deviation

The primary index of system performance in this application was ship's track deviation. This value was determined by measuring along a perpendicular line drawn between ship location and track line in the track-keeping areas of the passage. The track line was defined as the channel centerline in both the 800 foot width channel and the 600 foot channel. Track deviation values therefore yielded an index of pilot ability to control the ship's location. Means of absolute values were calculated as indicants of average track-keeping accuracy. Since a measure which allowed track deviation to one side of the track line to cancel the effects of deviation to the other side would be unsatisfactory, the absolute value of

TABLE 2-2. RUN ORDER MATRIX FOR MIXED DESIGN - BANK EFFECTS

Bank Condition	Subject Run	Experimental Condition Run Order: Wind Speed Ship Speed 8:1 Ratio Stb.	Wind Speed Ship Speed 8:1 Ratio Port	Wind Speed/ Ship Speed 10:1 Ratio Stb.	Wind Speed/ Ship Speed 10:1 Ratio Port	Wind Speed/ Ship Speed 13:1 Ratio Stb.	Wind Speed/ Ship Speed 13:1 Ratio Port	Number of Runs
Banks	2	2	5	6	3	4	1	36
	5	1	4	5	2	3	6	
	8	6	3	4	1	2	5	
	11	5	2	3	6	1	4	
	14	4	1	2	5	6	3	
	17	3	6	1	4	5	2	
No Banks	19	2	5	6	3	4	1	36
	20	1	4	5	2	3	6	
	21	6	3	4	1	2	5	
	22	5	2	3	6	1	4	
	23	4	1	2	5	6	3	
	24	3	6	1	4	5	2	
Run Totals		12	12	12	12	12	12	72

deviation ($\overline{|X|}$) was used. This measure, however, encompasses several additional difficulties which were overcome by appropriately "factoring" the off-track deviation average values.

2.2.2.1.2 Consistency

A second index of system performance is the pilot's ability to control his vessel about his desired, or track-made-good, line. A small variation around his actual mean off-track deviation line indicates tight, consistent control while a large value indicates a condition of control difficulty. The standard deviation of the ship's off-track deviation is the measure of consistency (C) used in this experiment.

2.2.2.1.3 Factored Absolute Value of Off-Track Deviation

The track line that the subject wished to follow might not be the centerline of the channel, and might vary from subject to subject. The measurement from centerline therefore doesn't totally reflect the subject's ability to control the vessel to a desired reference.

One approach which would overcome this problem would be to require the subject to maintain center track. This approach was rejected since it could have an impact on the techniques normally used by the pilot, resulting in a large deleterious effect on his exhibited control capability.

A second method that could be used would be to have each subject indicate his desired track before his runs. This was in fact attempted but difficulties arose because of the variability of subject response. Some thought it through quite seriously before indicating a track line. Some responded very quickly, without much thought. Others wouldn't answer, saying "it depends."

A third approach, which incidently gives an indirect indication of the pilots' desires, is to adjust the magnitude of off-track deviation as a function of his consistency (C) derived from his standard deviation of off-track deviation. As previously noted, if the standard deviation is small then it obviously reflects good ship position control (that is, a high degree of consistency) even if the associated off-track deviation is not small. For example, if the deviation was 200 feet on average, but the standard deviation was only 50 feet, then the test subject with this performance was trying to stay closer to the 200 foot mark off-track and doing it more successfully than another test subject with a 200 foot average off-track deviation but a larger standard deviation, say 150 feet. The former test subject showed more consistent performance than did the latter and his off-track deviation score should be reduced to reflect it. This could be accomplished by multiplying the mean off-track deviation by a factor of consistency (in feet) divided by one hundred feet. When this C/100 ratio becomes one or more, the reduction function is eliminated. When it is smaller than one, the function reduces the "factored" off-track deviation.

Another distortion exists when using the unfactored off-track deviation measure for comparison of performance. Individual runs were labeled according to wind ratio. With a given wind speed it is more difficult to control a slowly moving vessel than one that is moving more quickly. Therefore, the attempt was made to standardize the ship speed at five knots and vary the wind speed to effect a variation of the wind ratio variable. The wind speed was controllable by system program control but ship speed was under test subject control.

While all subjects were told to maintain five knots, not all of them did. Therefore a factor to account for the higher ship speed used was needed to penalize (or enlarge) the off-track deviation obtained by means of excessive ship speed. This factor was a function of $\frac{\text{ship speed}}{5}$.

Therefore, a factored performance measure for off-track deviation was generated with

$$\overline{|X|}_{\text{Factored}} = \overline{|X|}\left(\frac{C}{100}\right)^m \left(\frac{S}{5}\right)^n$$

where $\overline{|X|}$ is average absolute value of off-track deviation and m and n are constants larger than or equal to one.

2.2.2.1.4 Boundary Penetrations

Of practical significance is the number of times the ship exceeded the channel boundaries. Each such incident is referred to as a boundary penetration. The run continued to completion despite such occurrences. Although the off-track deviation (|X|) and consistency (C) measures were based on the track of the center of gravity of each vessel in each run, the ship's length, width, and crab angle were taken into account in determining when a portion of the ship's hull penetrated the channel boundary.

2.2.2.2 Pilot Performance Measures

2.2.2.2.1 Ship Speed

The ship speed (S) was measured instantaneously and compared against the desired level in each experimental run. It was suspected that pilots manipulated their ship speed to enhance controllability. Since pilots were initially instructed to maintain a five knot ship speed, variations about this value resulted in redefinition of the wind ratio experimental variable. Pilot ability to maintain the assigned speed provided an index of the degree of difficulty encountered while attempting to follow instructions and remain within the experimental framework. Mean and standard deviation values were obtained by leg, by subject, and by all experimental conditions.

2.2.2.2.2 Rudder Angle

Rudder angle was measured to determine the relative amount of rudder needed across experimental conditions. Differences in the amount of rudder that is used by different ships under identical external environmental conditions are highly dependent on the individual ship designs and therefore equal values of rudder do not necessarily reflect equal levels of control requirements for the vessels. On the other hand, differences in rudder used on the same vessel for different conditions do measure the variability in control needs caused by the variation in external conditions.

2.2.2.2.3 Zero Angle Rudder Crossings

A smooth passage with little control difficulty would normally require some changes in rudder angle for minor course-keeping needs. However, major changes in the rudder angle, and especially changes that cross the mid-rudder position as the ship controller reacts and over-reacts to the conditions of the passage, are all evidence of large control problems. The number of rudder zero angle (midship) crossings therefore was used to indicate the degree of heading rate control required across experimental conditions, as well as the degree of difficulty encountered maintaining track during the run.

2.2.2.2.4 Kick Turns

It was anticipated prior to the experiment runs that the number of kick turns that were used would be an effective measure of both pilot control and difficulties encountered. Unfortunately, changes in propeller speed to establish or decrease a turn rate and changes in ship speed to attain a higher degree of control (in general through higher average speed) became indistinguishable from one another in many instances, thereby nullifying the effectiveness of this measure.

2.3 SCENARIO AND VESSEL DESCRIPTIONS

2.3.1 Scenario

The scenario used in this experiment is shown in Figure 2-1 and consists of two straight channel legs, the first running at 000° and the second on a course line of 045°. The scenario has been broken into segments L_1, 1, 2, 3, 4, L_2, and 5 for identification purposes.

L_1 starts at entrance buoys 1 and 2 and runs for 1/4 nm. Leg 1 runs for 3/4 nm followed by segment 2, which starts 1/4 nm beyond buoys 3 and 4 and includes the 45° turn up to buoys 9 and 10. Segment 2 is further subdivided into segments 2a, 2b, 2c and 2d as shown in Figure 2-1. Segment 2a is 1 nm long. The start and end of segments 3, 4, L_2 and 5 are coincident with the appropriate buoys, as shown. The channel is 800 feet wide except for part of transition segment L_2 and segment 5. The perception of the change of channel width was accomplished by a 200 foot shoal, which effectively changes usable width to 600 feet. The primary analyses were accomplished over five legs, which did not include the turn or transition areas. Each Leg relates to a segment (Seg) as follows:

Leg 1 - Seg 1
Leg 2 - Seg 2a
Leg 3 - Seg 3
Leg 4 - Seg 4
Leg 5 - Seg 5

The depth of water to ship draft ratio throughout the usable portion of the channel is approximately 1.25 so that channel depth was 50 feet for the 80,000 DWT tanker (40 foot draft) and 45 feet for the LNG and 30,000 DWT tanker (35 foot and 36 foot drafts respectively). The 15 foot high shoal could cause a simulated grounding for all three vessels because of a 5 foot or 6 foot "interference." Bank effects were present for the appropriate runs and forces acted on the ships based on a bank height to water depth ratio of 0.8.

The channel described above was used for all experiment runs. Runs were inbound with clear visibility and no traffic. Differences between the runs were only related to differences in wind magnitude and direction and the presence or absence of banks. Currents were always zero.

There were a total of 13 wind conditions for this experiment:

- o A light wind condition of 10 knots (135° true), used as a channel familiarization run for all vessels.
- o Six wind conditions (three wind magnitudes and two sides), used for LNG vessels.
- o Six wind conditions (three wind magnitudes and two sides), used for the tankers.

The actual wind magnitudes and wind directions for each leg of the scenario are shown in Table 2-3 for the tankers and Table 2-4 for the LNG carriers. A 3% random perturbation in magnitude was used at all levels of wind.

2.3.2 Vessel Characteristics

- o 125,000 m^3 LNG
- o 80,000 DWT Tanker
- o 30,000 DWT Tanker

One of the variables established for the experiment was the class of ship used. The hydrodynamic characteristics of three ships (an Aquarius Class

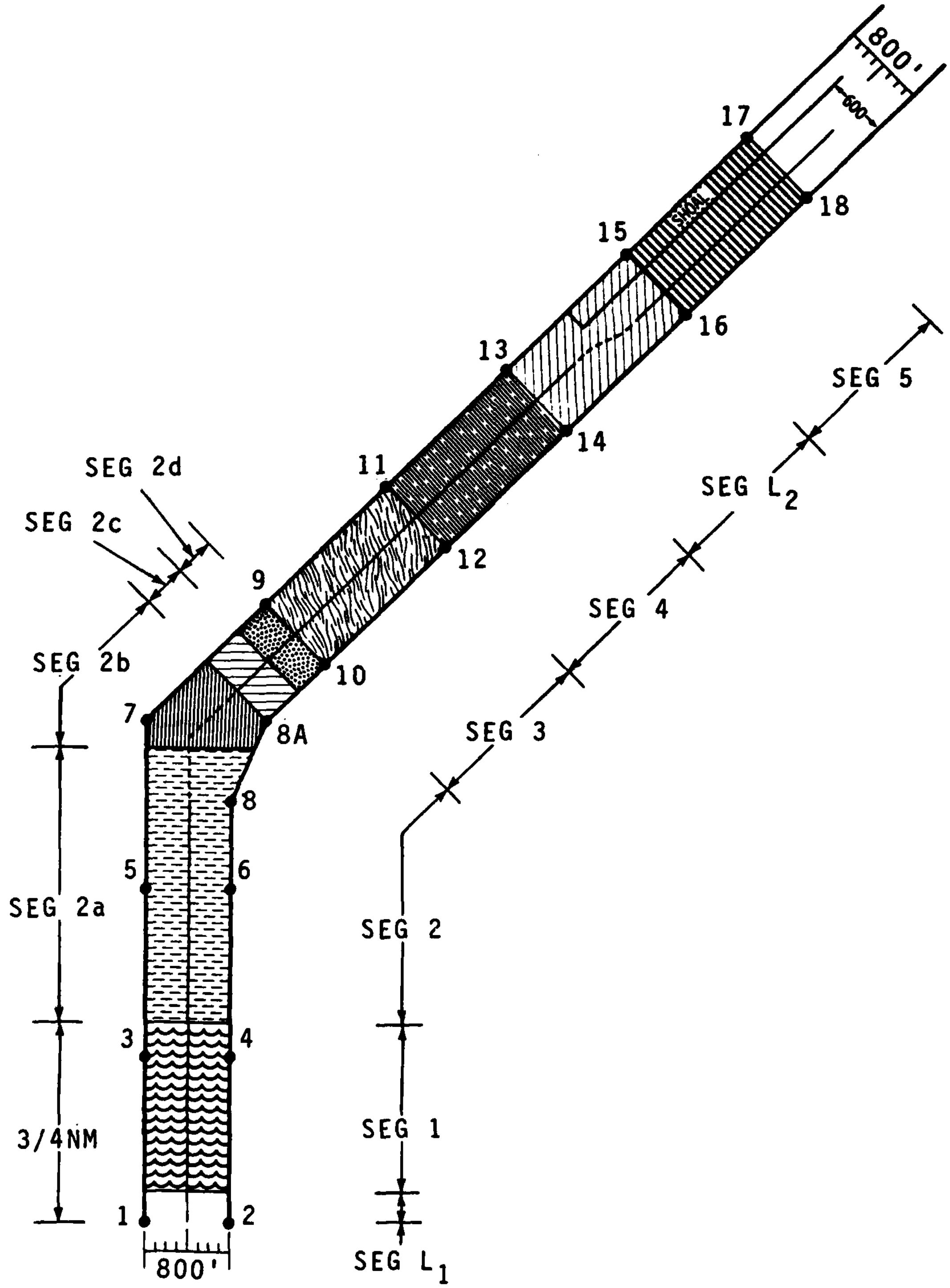


Figure 2-1. Basic Scenario

TABLE 2-3. SCENARIO CONDITIONS, TANKER RUNS

	Leg	Wind Magnitude (kn)	Wind Direction True (deg)	Wind Direction Rel (deg)
Starboard Conditions 2, 4, 6	L_1	10	90	90
	1	X[1]	105	105
	2A	X	120	120
	2B	X	165	165 [2]
	2C	X	155	110
	2D	X	145	100
	3	X	135	90
	4	X	180	135
	L_2	10	135	90
	5	X	150	105
Port Conditions 3, 5, 7	L_1	10	270	-90
	1	X	255	-105
	2A	X	240	-120
	2B	X	285	-75 [3]
	2C	X	295	-110
	2D	X	305	-100
	3	X	315	-90
	4	X	270	-135
	L_2	10	315	-90
	5	X	300	-105

1)

Condition	X	Perturbation
2, 3	40 knots	3%
4, 5	50 knots	3%
6, 7	65 knots	3%

2) 165° then +120° after turn.

3) -75° then -120° after turn.

TABLE 2-4. SCENARIO CONDITIONS, LNG CARRIER RUNS

	Leg	Wind Magnitude (kt)	Wind Direction True (deg)	Wind Direction Rel (deg)
Starboard Conditions 8, 10, 12	L_1	10	90	90
	1	X [1]	105	105
	2A	X	120	120
	2B	X	165	165 [2]
	2C	X	155	110
	2D	X	145	100
	3	X	135	90
	4	X	105	60
	L_2	10	135	90
	5	X	150	105
Port Conditions 9, 11, 13	L_1	10	270	-90
	1	X	255	-105
	2A	X	240	-120
	2B	X	285	-75 [3]
	2C	X	295	-110
	2D	X	305	-100
	3	X	315	-90
	4	X	345	-60
	L_2	10	315	-90
	5	X	300	-105

1)

Condition	X	Perturbation
8, 9	40 knots	3%
10, 11	50 knots	3%
12, 13	65 knots	3%

2) 165° then 120° after turn.

3) -75° then -120° after turn.

897 foot long LNG, an 80,000 DWT 763 foot long tanker, and a 30,000 DWT 595 foot long tanker) were incorporated into the CAORF simulator for this purpose. The primary ship maneuvering characteristics for these three vessels are shown in Figures 2-2, 2-3, and 2-4 respectively.

2.4 TEST SUBJECTS

This experiment required a total of 24 full branch harbor pilots experienced with the type of vessel that they were to handle at CAORF. Eighteen of these subjects (six for 30,000 DWT tankers, six for 80,000 DWT tankers, and six for LNGs) were used with the bank effects scenario while six of them (for the 80,000 DWT tanker) were used with a scenario which did not contain vertical banks. Since the LNG grouping consisted of pilots inexperienced with the CAORF simulator, it was highly desirable that the other 18 test subjects also have little or no experience with the simulator.

No special requirements were imposed for helmsmen. Each helmsman was an experienced AB seaman, having previously performed turns at sea as well as at CAORF. It should be noted at this point that helm orders were given only as rudder commands by the pilots. This procedure has been used in the past at CAORF to eliminate "helmsman effects" and to ensure that the control of the vessel is entirely due to the test subject's performance. Therefore, the standard grouping of helmsman used for most CAORF experiments was adequate for the current study.

2.5 PROCEDURES

The simulator runs for this experiment were spread over a three month time frame. Rigorous and consistent control had to be maintained over the complete period to ensure that spurious confounding experimental effects due to differences in the procedural handling of the twenty-four test subjects were minimized. A sequential listing of test subject activities was used for this purpose and is presented for reference in Appendix D as part of "Experiment Responsibilities and Sequential Schedule Check List For Test Subjects." The procedures follow a pattern of familiarization, experimental runs, and final debriefing.

2.5.1 Test Subject Familiarization

2.5.1.1 CAORF Familiarization

As indicated above, test subjects arriving at CAORF for this experiment were, in the main, not familiar with the facility and therefore needed a complete familiarization. They initially viewed the indoctrination movie in the lounge area, after which a research staff member discussed various relevant items with them including the relationship of CAORF to NMRC to MarAd to GDS to Sperry, the CAORF research program, the types of research which have been run in the past, test subject ID numbers and schedules, and the form and usage of research results.

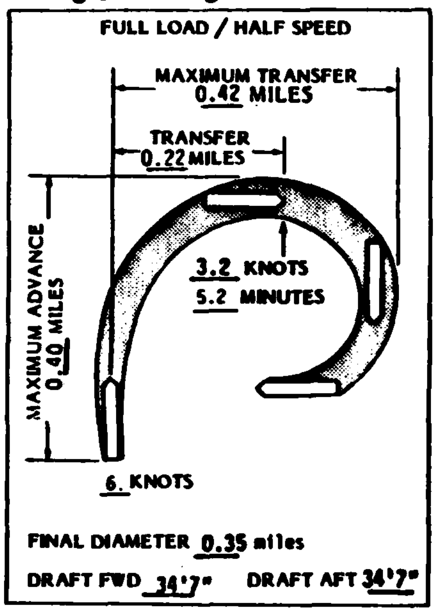
As an aid towards familiarization the test subjects were given the CAORF orientation manuscript to read. (See Appendix D.)

The general CAORF familiarization was then brought into more detailed focus with an explanation of the system's ability to simulate the characteristics of different vessels. The ship to be handled by the test subjects was described, as were the availability of an experienced helmsman and the

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES S.S. THIRTY KAY

Turning Circle Diagram



Length	595.0' (181.4 m)
Beam	84.0' (25.6 m)
Draft	34.8' (10.6 m)
Displacement	37,700 tons
Capacity	30,000 DWT

Maximum Rudder Angle	Starboard	Port
	Right	Left
	35 degrees	35 degrees

TIME AND DISTANCE TO CRASH STOP		
Engine Order	Full Load	
	Time (Minutes)	Distance Miles
Full Sea Speed	7.6	.87
Full Ahead	5.2	.37
Half Ahead	3.8	.19
Slow Ahead	2.3	.06

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	120	17.4
Full Ahead	60	8.7
Half Ahead	40	5.8
Slow Ahead	20	2.9
Dead Slow Ahead	10	1.6
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	Time Full Ahead RPM to Full Astern 150 sec

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

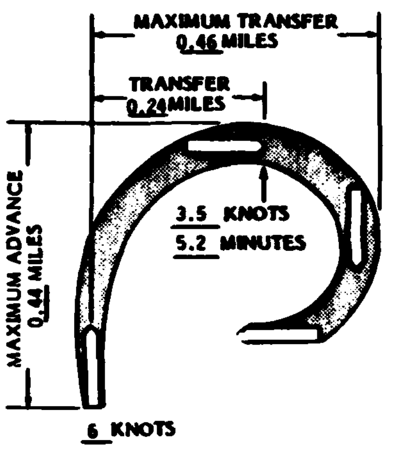
1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 2-2. Vessel Characteristics, 30,000 DWT Tanker

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES S.S. EIGHTY KAY

Turning Circle Diagram



Length	763.0' (232.6 m)
Beam	125.0' (38.1 m)
Draft	39.9' (12.2 m)
Displacement	87,142 tons
Capacity	80,000 DWT

	Starboard	Port
Maximum Rudder Angle	Right 35 degrees	Left 35 degrees

TIME AND DISTANCE TO CRASH STOP		
Engine Order	Full Load	
	Time (Minutes)	Distance Miles
Full Sea Speed	13.7	1.65
Full Ahead	9.7	.68
Half Ahead	7.3	.36
Slow Ahead	4.2	.11

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	120	17.7
Full Ahead	60	8.8
Half Ahead	40	5.9
Slow Ahead	20	2.9
Dead Slow Ahead	10	1.5
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	Time Full Ahead RPM to Full Astern 150 sec

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

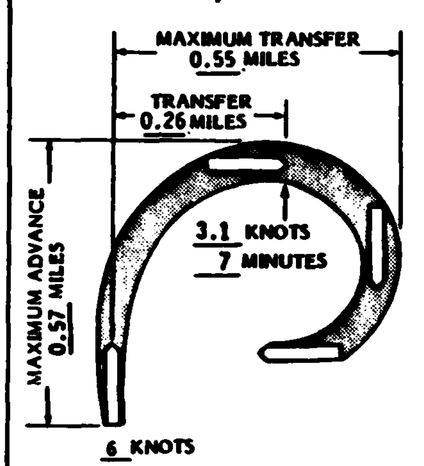
1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 2-3. Vessel Characteristics, 80,000 DWT Tanker

DEEP WATER MANEUVERING CHARACTERISTICS

CAORF LINES S.S. EL ENCEE

Turning Circle Diagram



FINAL DIAMETER 0.44 miles

DRAFT FWD 36'0" DRAFT AFT 36'0"

Length	897.0' (273.4 m)
Beam	143.5' (43.7 m)
Draft	36.0' (11.0 m)
Displacement	93,200 tons
Capacity	125,000 m^3

Maximum Rudder Angle	Starboard Right 35 degrees	Port Left 35 degrees

TIME AND DISTANCE TO CRASH STOP		
Engine Order	Full Load	
	Time (Minutes)	Distance Miles
Full Sea Speed	9.3	1.44
Full Ahead	7.5	.76
Half Ahead	5.8	.41
Slow Ahead	3.3	.13

ENGINE ORDER / R.P.M. / SPEED		
Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	100	20.5
Full Ahead	60	12.0
Half Ahead	40	8.0
Slow Ahead	20	4.0
Dead Slow Ahead	10	2.0
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	40	
Full Astern	60	Time Full Ahead RPM to Full Astern 150 sec

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather - 10 knots or less, calm sea.
2. No current.
3. Water depth three times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less Advance.
2. There is no appreciable difference in the time or distance of ADVANCE and TRANSFER when making a turn to port or starboard. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same, regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 2-4. Vessel Characteristics, LNG Carrier need for rudder orders rather than course orders. It was pointed out that several runs would be made in a realistic channel under varying and extreme environmental conditions, with winds but not currents present. It was explained that at the start of each run a weather forecast would be read to the test subject (see Figure 2-5). It was also explained that the purpose of the study was to determine the manner in which the ships were brought through the channel under the prevalent conditions and that a more detailed discussion of the objectives of the experiment would be postponed until completion of all runs (i.e., during a final debriefing).

The appropriate deep water vessel characteristics of length, beam, draft, vessel turning circles, crash stop information and ship speed vs. rpm (no wind) were shown to the test subject (Figures 2-2, 2-3, and 2-4). This information was also left on the bridge during the experiment runs.

2.5.1.2 Bridge Familiarization

Although the test subjects used in this experiment were experienced pilots, they were not familiar with the CAORF bridge and its specific equipment, the handling characteristics of Ownship, the properties of the visual scene, or the specific procedures that would be used. A brief period of familiarization or training was given to each test subject prior to his baseline run. On the bridge, the bridge console, steering stand, radars, relative wind instruments, phones, peloruses, etc. were shown to him. The turn rate indicator was also pointed out, and the fact that its readout is in degrees per second was emphasized.

The signal telegraph control was indicated, including the fact that "bridge control" would be used during the experiment. A mate was always present on the bridge during the familiarization and maneuvering run to describe bridge equipment, answer questions, and to introduce conditions of

1022302 VIA WSL
NOAA WX ADVISORY

0700 AMBROSE TOWER REPORTS TEMPERATURE 69 DEGREES/BAROMETRIC PRESSURE 29.72 INCHES. WESTERLY WINDS 35 TO 45 KNOTS. SEAS 2 TO 3 FT. SKIES ARE CLEAR-VISIBILITY 10 MILES IN LIGHT HAZE. SEA WATER TEMPERATURE 60 DEGREES.

FORECAST FOR CAPE MAY TO BLOCK ISLAND INCLUDING LONG ISLAND SOUND, THE LONG ISLAND SOUTH SHORE BAY AREA, NEW YORK HARBOR AND THE LOWER HUDSON RIVER - CLEAR AND SEASONABLY WARM OVERNIGHT WITH TEMPERATURES IN THE LOW TO MID 60's. WINDS VARIABLE AT LESS THAN 10 KNOTS - SEAS RUNNING 0 TO 2 FEET. VISIBILITY GENERALLY GREATER THAN 5 MILES EXCEPT LOWERING TO LESS THAN 1 MILE IN PATCHY DENSE FOG. THERE IS A SMALL CRAFT ADVISORY IN EFFECT AT THIS TIME.

Figure 2-5. Typical Weather Forecast

the actual experiment runs. The need to maintain five knots of Ownship speed in the experiment was introduced at this point.

2.5.1.3 Ship Handling Familiarization

A preliminary maneuvering run was made by the test subject through a special scenario, shown in Figure 2-6. The vessel that would be used by each subject in his experiment runs was used for the maneuvering run. This allowed the test subject to become familiar with the ship's bridge, the visual scene, the handling characteristics of the vessel, the helmsman, etc., prior to the acquisition of experimental data. The maneuvering run scenario consisted of four anchored ships placed as shown in Figure 2-6, clear visibility, and open sea, deep water conditions.

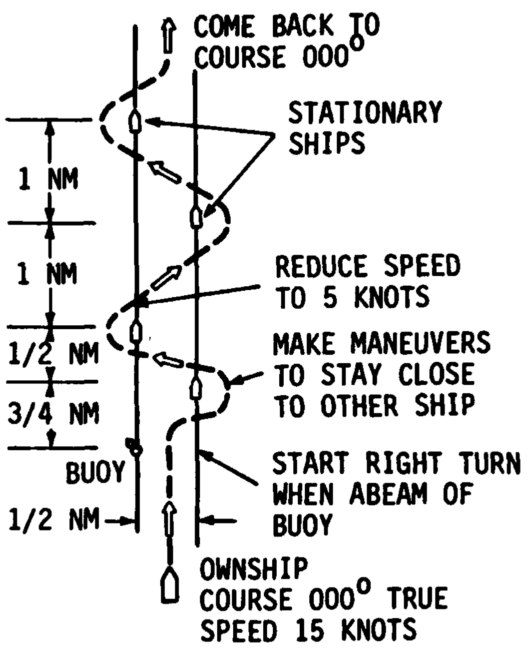


Figure 2-6. Maneuver Familiarization Diagram

The maneuvering run was accomplished by the test subject transiting past the first two anchored ships at 15 knots. The vessel was then brought down to the appropriate engine rpm for five knots by the pilot/mate. No winds or currents were present during this maneuvering training.

The maneuvering training terminated at the pilots' discretion after Ownship's speed had actually come down to five knots and at least one additional anchored ship had been passed. This was normally at a point after the completion of the turn around the third vessel, where the turn rate had decreased to zero.

2.5.2 Experiment Runs

Each test subject transited through the channel scenario seven times (Figure 2-1). The first experiment run was designated a baseline run (under low wind conditions), while the following six runs occurred at three different wind magnitudes from the port side and the same three magnitudes from the starboard side. The required combinations of conditions for this experiment (13 in number) are described in Section 2.3.1.

Prior to the baseline run a CAORF research staff member described the channel to the test subject. The subject then conned the vessel through the baseline run (at low wind conditions) and became familiar with the channel characteristics.

After the baseline run was completed a CAORF research staff member discussed the channel with the test subject and attempted to elicit his transit plan (desired-track) for "heavy" wind conditions. It had been expected that most subjects would prefer a desired centerline track or one slightly to windward. Most did give that type of response but, as indicated previously, there was sufficient evidence to cast doubt on the reliability of these responses. Figure 2-7 was used to obtain the desired-track information.

Wind ratio was one of the major variables in this experiment. The effects of wind magnitude on Ownship's characteristics change with Ownship speed, and, though the experimenter could impose a true wind magnitude for each experimental run, it was really the ratio of wind magnitude/ship speed which should have been held at its correct value. It was therefore a prime requisite that all portions of all runs be made at the desired ship speed of five knots so that the aforementioned ratio was correctly maintained. This requirement was emphasized by the staff researcher prior to each run, as well as by the mate on the bridge during the run if Ownship's speed became excessive.

Ownship was equipped with a normal complement of bridge instrumentation. The test subjects received no explicit instruction as to which instruments should be used or, for that matter, not used. A member of the CAORF operations staff was present on the bridge, serving as a mate during all runs. The role of the mate was to respond to any questions that the pilot might have concerning the ship. They were instructed not to offer any unsolicited information but rather to respond only to the pilot's inquiries. The mate was also responsible for executing the pilot's engine orders and for monitoring and recording the pilot's helm commands.

A quartermaster was present for each run to man the helm. To minimize the quartermaster's contribution to ship handling, all test subjects were asked to issue only rudder and not course commands to the helm.

Each of the test subjects transited the channel six times after the base line run. All subjects received the following instructions prior to their experimental runs:

> Ownship will be travelling at a speed of five knots with light winds when the transit begins.
>
> This speed should be maintained through the channel. The weather forecast for this run is indicated by the following weather forecast ---.
>
> No traffic will be present in the channel to hinder your passage. You should follow the desired path that you have indicated whenever possible.
>
> As you conn the vessel in the transits of this experiment we would like you to carry out an additional task. As you conduct your bridge activities try to "think-out-loud." Assume you are instructing an apprentice on the bridge, and in that context explain the reasons underlying and forming the basis for your commands.

The instruction to the subjects regarding verbal reporting was supplemented by an audio tape which demonstrated a mariner actively engaged on the bridge and generating a "think-out-loud" report. This activity occurred just prior to the baseline run and served as an instructional aid for the subjects.

The "think-out-loud" procedure had been part of an earlier experiment in narrow channel passages to determine if the activity actually diverted the

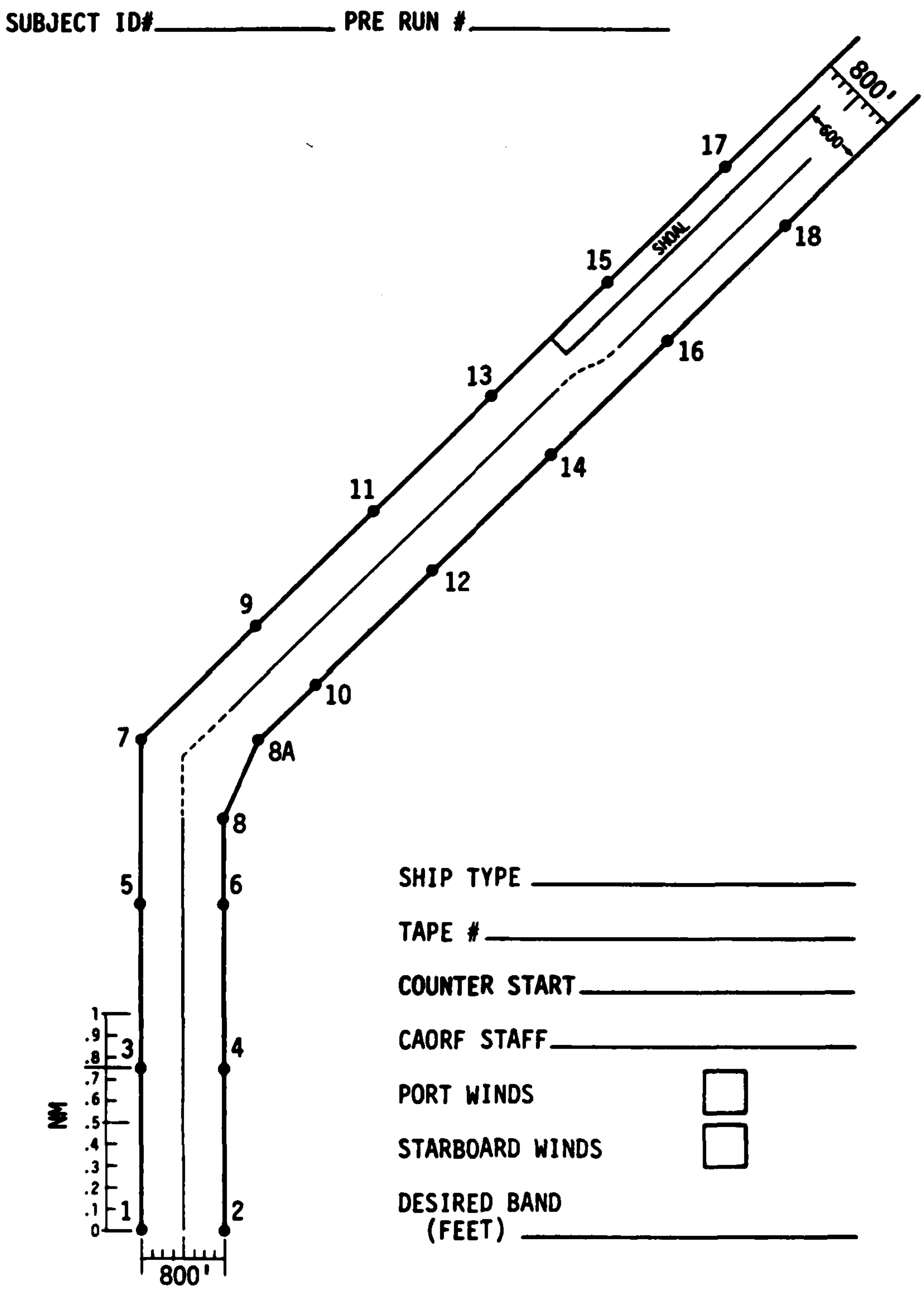


Figure 2-7. Desired Track Sheet

mariner from his prime task of pilotage. It was found that it did not interfere and was used during this experiment as a subjective analytical tool to determine when (or which) pilots were encountering difficulties. No formal analyses were performed on this "measure."

2.5.3 Final Debriefings

At the conclusion of the last run a final debriefing was held with each test subject by a member of the CAORF research staff. This was taped on a small audio recorder and followed a structured format. Questions regarding the subjective reactions to the overall experiment, vessel handling, and actual experience under severe wind conditions by the pilot were explored. Table 2-5 is a summary listing of questions.

2.6 DATA COLLECTION

A variety of sources were used for data collection during the running and analyses of the experiment. The major performance measures were obtained from computer summary datalogs, ship's bridge data sheets, precise navigational data printouts, and debriefings. The primary source for all objective data during the actual experiment runs was the "playback tapes." This is a magnetic recording of each run, taken at a fixed time interval, of important computer and ship parameters (numbering well over 1,000 items). The recording rate for the experiment was once every 10 seconds.

2.6.1 Computer Summary Datalogs

Computer summary datalogs are printouts from the playback tapes. A small number of parameters were made available to research personnel monitoring the experimental runs. These were called up on command at the Control Station Digital Display. This information was then available as hard copy printouts at the end of groups of runs. A listing of the items obtained on the printouts is shown in Table 2-6.

2.6.2 Precision Navigation Data Printouts

During the actual runs, stored parameters as well as specially computed parameters were made available to research personnel monitoring the experimental runs. These were called up on command at the Control Station Digital Display. This information was then available as hard copy printouts at the end of groups of runs. A listing of the items obtained on the printouts are shown in Table 2-7.

2.6.3 Summary Plots

The analyses of the experimental data were conducted primarily with five segments: a 3/4 nm segment followed by a one nm segment prior to the turn; two 3/4 nm 800 foot wide segments after the turn; and a 3/4 nm 600 foot wide segment containing a shoal. Within these segments summary plots were made to graphically demonstrate the trends caused by the experimental variables. At 1/8 nm points along these segments the ship position of all six test subjects per wind condition per ship were averaged and displayed. In addition, the maximum and minimum value off-track at each 1/8 nm were also shown as well as plus or minus one standard deviation. The summary plots are contained in the Results & Discussion section of this report.

TABLE 2-5. SUMMARY OF FINAL DEBRIEFING QUESTIONS

At the conclusion of the last run a final debriefing will be held with each test subject by a member of the CAORF research staff. This should be taped on the small audio recorder and should follow a structured format:

- o Do you have any comments about the experience you've just undergone?
- o Do you feel that the vessel handled normally, i.e., realistically in the first base line run? In the subsequent high wind runs?
- o Have you ever experienced wind conditions of this type in your actual piloting activities? How often?
- o What are the environmental criteria for your suggesting/insisting that the ship anchor and wait for calmer conditions?
- o Are there track keeping clues or cues in your home area that were missing here?
- o Do you feel that you handled the vessels in a realistic manner, i.e., the way you would have in your own areas. (This is different than the ship "feel" question since it is aimed more towards Pilot Performance rather than Ship Performance.)
- o Was the channel width approximately the same size as your home area? Does that area have bank effects? Did you try to use them here? Did they seem proper/realistic here, based on the first run in light winds?
- o Do you feel that your performance was constant; improved as a function of time spent on simulator; varied as a function of wind speed?
- o Did the verbal reporting interfere with your job?
- o What instruments did you use? Did your use here represent your typical use of instruments in your home area?
- o Did you have difficulty holding down your speed? What techniques did you use to accomplish this? Would you ever reverse engines to reduce speed, under like conditions, in your owm area? Do you attempt to hold down speed in home area? How?
- o Do you normally (ever) find that you can locate a "slot" for a ship while operating in a channel which allows for movement of the ship along a leg without change of rudder or minimum change of rudder?
- o Do you normally give course orders or rudder orders?
- o Please do not discuss the experiment with anyone for 3 months.

TABLE 2-6. COMPUTER SUMMARY DATALOG PARAMETERS

1. Bridge Time
2. Playback Tape Number
3. Ownship Ground Speed (knots)
4. Ownship North Coordinate (nm)
5. Ownship East Coordinate (nm)
6. Rudder Angle (degrees)
7. Engine Propeller Speed (rpm)
8. Water Depth (feet)

TABLE 2-7. PRECISION NAVIGATION DATA PARAMETERS

1. Playback Tape Number
2. Channel Leg Number
3. Distance to Way Point (nm)
4. Distance Off-Track (feet)
5. Speed Along Track (knots)
6. Speed Across Track (feet/minutes)
7. Incremental Distance Along Track (feet)
8. Crab Angle (degrees)
9. Yaw Rate (degrees)
10. Ownship Heading (degrees)
11. Rel. Wind Speed/Ship Speed (knots/knots)
12. Rel. Wind Angle (degrees)

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 INTRODUCTORY SUMMARY

3.1.1 Chapter Contents

The major purposes of the experiment were to determine the narrow channel ship-handling performance differences between three classes of ships under heavy wind conditions, and to discern the effects of wind-based inherent ship instabilities on the performances exhibited by experienced pilots while conning these vessels. The experimental data has been subjected to a variety of analyses and the findings are presented and discussed within this chapter.

Paragraph 3.2 contains the results of five sets of statistical analyses which make use of seven performance measures in defining performance differences which had been demonstrated under the environmental conditions examined.

Summary ground tracks are presented and discussed in paragraph 3.3. The ground tracks that are shown have been generated from performance data which has been averaged over each pilot grouping. They indicate the nature of the average tracks as well as the variability of the tracks within the five key legs of the scenario. These tracks are presented for all ship groups at all wind conditions.

Each of the groupings in the primary statistical comparison (the LNG, the 80K tanker, and the 30K tanker group) was comprised of randomly selected samples of pilots experienced with and conning a particular vessel under given wind and channel-with-banks conditions. These samples were derived from so-called parent populations and, by using standard analytical techniques, estimates of these population distributions can be derived from the characteristics (i.e., statistics) of their representative samples. The confidence interval of the population means, as well as probable range of standard deviations, were developed for several primary performance measures used in this experiment. These findings are presented in paragraph 3.4.

A performance and stability discussion which draws on the findings of paragraphs 3.2 and 3.3 is included in paragraph 3.5. This includes comments on the effects of wind instabilities on ship-handling performance. Additional ship characteristics data for the three vessels are also presented as part of the discussion.

3.1.2 Summary

A summary assessment of the experiment's findings indicates that LNG carrier pilots consistently had a more difficult time controlling their vessels than did the tanker pilots. When differences in tanker ship-handling performance surfaced from the analyses it was usually the 80K tankers that were found to be under better control. This in no way reflects upon the capabilities of the pilots, since all pilots that were used for the experiment had many years of experience and were randomly selected from various pilot organizations. Variability in control capabilities should therefore have been uniformly distributed throughout the three classes of vessels that were examined. Instead, the findings indicate differences in ship-handling difficulty which are imposed on the mariner by the inherent characteristics of the vessels themselves.

Of further interest, difficulties in ship-handling performance did not correlate in the expected manner with inherent wind-based ship instabilities. The LNG vessel was shown to have less wind-induced instabilities and yet demonstrated a higher level of controllability difficulties. The tanker pilots were able to overcome their vessels' instabilities and transited the channel with less problems.

When transits were made through a channel with vertical banks, the pilots experienced less problems than when the waterway had gentle sloping sides (i.e., no bank forces). The pilots used the banks as an aid to make their channel passages safer, since fewer penetrations of the channel boundaries by any portion of the hull were evidenced when bank forces were present.

Differences in channel width affected the pilots on the LNG vessel to a greater degree than those pilots that conned the tankers. The LNG pilots perceived that the narrower, 600 foot wide portions of the channel would be dangerous, that is difficult, and substantially increased their speed during this portion of the passage to acquire a greater degree of control over their vessel. The use of speed to maintain controllability, by LNG pilots in particular, was evidenced throughout the experiment, especially at the highest wind levels. The LNG pilots found that their rudder was not effective under the wind conditions they encountered, and therefore used kick turns as well as increased ship speed to develop the necessary turning capability.

Estimating techniques using the findings developed from the experiment's sample groupings resulted in indications of the manner in which all pilots would handle these classes of vessels under comparable real world environmental conditions. These results strongly indicate that such passages through 600 to 800 foot wide channels by LNG vessels without outside assistance (e.g., tugs) would be difficult. This would be especially true if vessels speeds could not be set at levels greater than 10 knots.

Overall, the pilots were shown to be capable of overcoming the wind-based instabilities of their vessels and therefore differences in performances that were noted were due to other causes, such as other ship characteristics. The LNG vessel was shown to have an exceptionally high level of directional stability at high wind levels.

3.2 STATISICAL ANALYSES OF PERFORMANCE MEASURES

The experiment was structured so that the experimental data was capable of being efficiently analyzed from a variety of viewpoints. The purpose of the statistical analyses was to determine if differences existed in the performance exhibited by sample groups of experienced pilots under various controlled conditions. Performance was evaluated by means of a set of seven measures, three of which were concerned with the pilot actions (pilot performance measures) and four with the results of the actions (system performance measures). Five sets of comparisons were performed on the data:

- o Main
- o Bank/No Bank
- o Channel Width
- o Rudder Effects
- o Special Experience

The primary performance comparisons (i.e., main comparisons) were made between pilotage exhibited on different classes of ships under different wind conditions during passages through a narrow, shallow, vertically banked waterway. The comparisons were based on the total performance during the straight legs of the channel.

The remaining four sets of analyses were refinements of secondary issues concerned with the basic comparisons. A bank/no bank comparison investigated the question of the effects and/ or usage of bank forces during the total passage through the channel. This was done with only one ship type, the 80K tanker. A channel width comparison analyzed the difference in performance on the three classes of ships within an 800 foot wide channel leg and a 600 foot wide channel leg. One of the vessels, the LNG carrier, exhibited an unusual rudder characteristic under conditions of heavy wind forward of the ship's beam. An examination of the effects of this phenomenon was also conducted. The last comparison was based on an experience factor; one group was selected for actual experience with a particularly long and narrow waterway, while its comparitive group did not necessarily have this type of background.

Subparagraphs 3.2.1 through 3.2.5 present the results of these five statistical sets of comparisons, discussing only those performance measures within each comparison which indicate the differences that exist between the specific groups under study. When performance differences were not determined to be present, they were not discussed. A complete presentation of all statistical findings (both significant and non-significant differences) are contained in Appendix C for reference purposes.

3.2.1 Main Comparisons

The main comparisons are based on data obtained from eighteen test subjects assigned to three groups. Each group handled one type of vessel: an LNG carrier, an 80K tanker, or a 30K tanker. Ship was therefore the major variable, with wind magnitude (40, 50, or 65 knots) and wind side (starboard or port) two additional variables. The data was obtained from six channel transits for each test subject consisting of all combinations of wind magnitude and side. The data base for the main comparisons consists of 108 transits through the channel with bank effects present. The statistics for five of the seven performance measures analyzed were based on data obtained from Legs 1, 2, 3, 4, and 5 (Figure 2-1), while the remaining two measures of rudder crossings and consistency also include the turn legs.

3.2.1.1 Absolute Value of Off-Track Deviation, $\overline{|X|}$ (M.C.)

Significant differences were found between the means of absolute magnitude of off-track deviation, $\overline{|X|}$, in the main comparisons. These are shown in Table 3-1, with Xs given in feet from the channel centerline. The trend of the data indicates that the LNG pilots on average obtained a larger magnitude of distance off-track than pilots conning the other two vessels under like wind conditions. Under starboard wind conditions the off-track deviation obtained for the LNG was larger

TABLE 3-1. ABSOLUTE MAGNITUDE OF DISTANCE OFF-TRACK, $\overline{|X|}$ (MAIN COMPARISON)

Wind Side	Wind Speed (kt)	$\overline{|X|}$ (ft)		
		LNG	80K	30K
Starboard	40	111	56	62
	50	121	73	51
	65	144	63	73
Port	40	143	99	83
	50	195	96	109
	65	169	96	160

$p < 0.05$

for 65 knots (144 feet) than for 40 knots of wind (111 feet). This trend, however, was not significantly apparent with the other two ships. For port wind conditions the $\overline{|X|}$s for the 30K tanker pilots increased with wind magnitude while $\overline{|X|}$s were substantially the same for the 80K tanker runs. For the LNG, $\overline{|X|}$ for 50 knot winds was significantly larger than for 40 knot winds (195 feet vs. 143 feet), but for 65 knot winds ($\overline{|X|}$ = 169 feet) the pilots appeared to buck the trend of increasing $\overline{|X|}$ with increasing levels of wind. The difference of 195 vs. 169 feet was not found to be significantly different in a statistical sense, though. A general trend of larger values of $\overline{|X|}$ for port wind conditions compared with those observed under conditions of starboard winds was also apparent.

Based on this measure and as noted above, it would appear that the pilots who conned the LNG carriers had more difficulty controlling their vessels than pilots of the other two ships.

3.2.1.2 Consistency of Off-Track Deviation, C (M.C.)

Consistency (C) of off-track deviation is another figure of merit of the level of difficulty that the pilots exhibited while transiting the channel. It is a function of the variation in actual track line measured in feet around the mean track line during each transit. A larger variation around the mean track line would normally be attributed to a higher level of difficulty encountered in the controllability of the vessel since a vessel that is well controlled would not "wander" about its mean track line as much as one experiencing greater difficulty.

Significant differences were found for the mean values of C across all conditions (Table 3-2). Again it can be seen

TABLE 3-2. CONSISTENCY, C (MAIN COMPARISON)

Wind Side	Wind Speed (kt)	Consistency, C (ft)		
		LNG	80K	30K
Starboard	40	130	79	93
	50	132	86	95
	65	183	81	104
Port	40	120	72	83
	50	174	77	100
	65	169	84	112

$p < 0.01$

that the pilots on the LNG carriers had more difficulty than the pilots of the tankers for the starboard wind conditions. The LNG showed less consistency than either of the other two vessels. For 40 and 50 knot winds the tankers exhibited similar consistencies, but more trouble was encountered at the 65 knot wind condition by the 30K tanker pilots compared with those on the 80K vessel.

The same general trends are seen in the port wind results. LNG C values are larger than those for tankers, and when the performance of the tanker pilots differed it was the 30K pilots that had more difficulty. Once again it appears that controllability is either the same or worse with larger winds, and though this is true for the LNG pilots when they transited the channel under starboard wind conditions, the 50 and 65 knot port winds for LNG did not cause the same types of differences in consistency in performance (132 vs. 183 feet for starboard winds and 174 vs. 169 feet for port winds).

3.2.1.3 Ship Speed, S (M.C.)

All pilots were requested to maintain a five knot ship speed during the channel transits, speeding up or slowing down engine rpm as necessary. When vessel safety became questionable because of potential penetration of the channel limits by the ship's skin, changes in engine rpm were permitted to maintain controllability. At times this took the form a "kick turn," i.e., increased propeller rpm causing increased propeller wash against a "hard over" rudder, resulting in a large turn rate. A true "kick turn" was then completed by the reduction of propeller rpm to its initial setting. If an increase in rpm was maintained for too long a period of time a change in the ship's speed resulted. Therefore, S is also a measure of difficulty in piloted controllability for this experiment, with small variations about five knots indicating good control, i.e., good pilot controllability, and large variations indicating poorer control.

The average ship speeds that were found for the different experimental conditions are presented in Table 3-3. The results again reinforce the evidence that pilots handling the LNG had more difficulty controlling their vessels than those on the tankers. While tanker pilots needed little more than six knots of speed for only the highest wind condition, this occurred only once for the LNG pilots and then only at the lowest, 40K wind conditions.

For both port and starboard wind conditions the LNG pilots found that on average they had to maintain a speed of close to 11 knots (10.8 and 11) during the highest wind conditions of 65 knots. In general, for all wind conditions they were found to substantially increase their ship's speed to maintain control of their vessels.

3.2.1.4 Boundary Penetrations (M.C.)

The primary objective for all pilots during the experimental runs was to safely conn the vessel through the channel without allowing any portion of the ship to penetrate the channel boundary, strike buoys, or transit over the shoal area. This was to be accomplished at a speed which was maintained as close to five knots as wind conditions would permit. The level of winds had been selected so that differences in performance would be evidenced, and it was therefore not surprising to find instances of multiple incidents (penetrations) during a single run. The spread in number of incidents therefore became a clear indication of differences in controllability difficulties.

There were significant differences in such incidents and the results are presented in Table 3-4. The data presented in this table are total incidents

TABLE 3-3. SHIP SPEED, S (MAIN COMPARISON)

Wind Side	Wind Speed (kt)	Ship Speed, S (kt)		
		LNG	80K	30K
Starboard	40	6.9	5.1	5.3
	50	8.9	5.4	5.4
	65	11.0	6.8	6.0
Port	40	9.4	5.4	5.3
	50	9.0	5.7	5.5
	65	10.8	6.6	6.0

$p < 0.05$

TABLE 3-4. NUMBER OF BOUNDARY PENETRATIONS (MAIN COMPARISON)

Wind Side	Wind Speed (kt)	Boundary Penetrations (Number)		
		LNG	80K	30K
Starboard	40	13	0	1
	50	11	1	2
	65	24	0	1
Port	40	14	0	1
	50	28	1	4
	65	23	3	8

$p < 0.05$

per ship per wind condition, as contrasted with the earlier tables which presented mean values of the relevant performance measures for each ship and wind condition. This data substantiates the trends previously discussed. The number of incidents was significantly larger for pilots conning the LNG vessel (as compared with the tankers) for all wind levels and both sides. Although the number of incidents occurring at each level of wind appears larger for the 30K tanker than for the 80K, this did not show up as a significant statistical difference.

There was no apparent difference in number of incidents as a function of wind speed for either the 80K tanker pilots or for the starboard wind conditions for the 30K vessel. Port winds, however, caused a significant number of incidents at 65 knots, compared with 40 knots for the 30K tankers. The LNG pilots consistently found that the 65 knot condition was more difficult to handle than the 40 knot wind condition. Although incidents in the port wind 50 knot condition for the LNG were more numerous (28) than those occurring at 65 knots (23), statistical analyses did not substantiate a significant difference.

3.2.1.5 Factored Absolute Magnitude of Off-Track Deviation, $\overline{|X|}_F$ (M.C.)

As indicated in paragraph 2.3.2.1, an additional analysis was performed on the distance off-track data. The $\overline{|X|}$ was modified by a factor to increase the value as a function of increased ship speed and decrease it by a function of its consistency or standard deviation. This measure, factored $\overline{|X|}$, was an attempt to "unbias" the value obtained for $\overline{|X|}$ caused by the pilots' variable efforts to gain control by increasing speed as well as inflation of the $\overline{|X|}$ measure when pilots transited the channel under good control (small value for C) but a steady large off-track value.

Table 3-5 contains the factored $\overline{|X|}$ data for all conditions of wind level and side. The factored $\overline{|X|}$s for LNG vessels were clearly larger than for the tankers. There were no differences as a function of level of wind condition for the 80K tanker, but the 30K tanker pilots did have more trouble with the highest wind than with the lowest. The higher winds also caused the LNG pilots more difficulty than they experienced with the 40 knot winds. The trends are identical to those noted previously (3.2.1.1).

The results in Table 3-5 are significant at a higher probability level than those for $\overline{|X|}$ (Table 3-2), which means that the differences indicated by the factored $\overline{|X|}$ data could have occurred by chance in only one in a thousand times, compared with five times out of a hundred for the basic $\overline{|X|}$. Therefore, the factoring of $\overline{|X|}$ tended to underscore the differences previously discussed in paragraph 3.2.1.1. This indicates that the experimental problems associated with pilot tendencies to speed up the vessels to maintain control, or their selection of a desired track position other than the channel centerline, did not substantially obscure the differences that were inherent in pilot performances as shown by the basic $\overline{|X|}$ analyses. In fact, the differences were made more pronounced.

3.2.1.6 Rudder Effects (M.C.)

3.2.1.6.1 Rudder Angle. Pilot use of rudder control showed significant differences as a function of wind level and type of ship (Table 3-6).

These results indicate differences between pilot use of rudder on the 80K tanker compared to the other two vessels. With the higher winds more rudder was used by the pilots on the larger tanker, while at 40 knots the value for the 80K tanker rudder usage fell between that of the other two

TABLE 3-5. FACTORED X FOR SPEED AND CONSISTENCY, $\overline{|X|}_F$ (MAIN COMPARISON)

Wind Side	Wind Speed (kt)	$\overline{|X|}_F$ (ft) LNG	80K	30K
Starboard	40	76	10	15
	50	105	27	18
	65	226	28	56
Port	40	99	10	13
	50	217	20	36
	65	229	38	74

$p < 0.001$

TABLE 3-6. ABSOLUTE MAGNITUDE OF RUDDER ANGLE (MAIN COMPARISON)

Wind Level (kt)	Absolute Value of Rudder Angle (deg)		
	LNG	80K	30K
40	19	15	7
50	19	22	11
65	20	23	17

$p < 0.001$

vessels. Differences between the average rudder angle used by pilots on the LNG vessel, as compared with those on the 30K tanker, were also perceived.

An interesting finding can be seen in the trends for each vessel as winds increased. With the 30K tanker rudder usage increased with wind level. For the 80K tanker, a change in average rudder angle used occurred between 40 and 50 knots but not between 50 and 65 knots. With the LNG vessel the pilots tended to use the same average amount of rudder without regard to the level of the wind. As previously shown, winds did affect overall pilot performance. The amount of average rudder used is one of the primary control elements available to the pilots, and yet in the two situations noted above the pilots did not use more rudder with higher wind levels even though other performance measures indicated that they needed more control. This most probably is due to the fact that they found additional rudder was not effective and that rudder "saturation" took place prior to 35°, the maximum level of physically available rudder. Paragraph 3.5 contains further discussion regarding this finding.

3.2.1.6.2 Zero Rudder Crossings. Rudder zero crossings were also observed during the experiment. Differences in number of rudder reversals could be indicative of control difficulties, i.e. more rudder crossings indicate a loss of control. Major difference between pilots with regard to this measure were not apparent. All pilots on all ships performed in a similar manner. Not surprisingly though, since most measures indicated increased ship handling difficulties with increased wind speed, it was found that more reversals occurred on average under conditions of 65 knots than appeared at the other two wind levels (see Table 3-7).

3.2.2 Bank/No Bank Comparisons (B/NB)

The bank/no bank comparisons are based on data that were obtained from twelve test subjects, all of whom conned the 80K tankers. The pilots were placed in two groups and each of them transited the channel described in paragraph 2.3.1 six times. For six of the pilots no bank effects were present in the channel during their runs. For the remaining six pilots, the bank forces were present and affected

TABLE 3-7. NUMBER OF ZERO RUDDER CROSSINGS (MAIN COMPARISON)

Wind (kt)	Number of Rudder Crossings
40	13
50	13
65	16

$p < 0.001$

the ship's track. The data needed for this second group were obtained from the 80K tanker group data pool used in the main comparisons, since all conditions were identical to those necessary for these comparisons. To obtain the data for the 80K tanker without banks (the first group), an additional set of 36 transits were run using six different (additional) pilots. Wind level and direction of wind were again variables and for these analyses bank effects were also used as a variable. Ships, of course, was not a variable since only the performances on the 80K tanker were investigated. Significant differences were found as a result of the statistical analyses but the differences appeared in only four of the seven measures that were examined. When differences were found, performance with bank effects present was usually superior to no bank performance results. The pilots conning the 80K tankers sensed, used, and were aided by the banks during their transits through the narrow waterway.

3.2.2.1 Factored Absolute Magnitude of Off-Track Deviation $\overline{|X|}_F$ (B/NB)

No differences in performance were found for the basic measure of absolute value of off-track deviation in the bank/no bank comparison. As noted in paragraph 3.2.1.5, however, factoring of $\overline{|X|}$ for ship speed and consistency biases does tend to "sharpen" any real differences that may exist and this was found to be true during these bank/no bank analyses. Table 3-8 shows that the means of factored $\overline{|X|}$ increased with wind level in both the bank and no bank cases and were larger under transit conditions without banks for a given wind magnitude.

3.2.2.2 Ship Speed and Boundary Penetrations (B/NB)

Differences in performance were found for both the ship speed and boundary penetration measures. Pilots that transited the channel when bank effects were present did so at a speed that was slightly larger on average than transits that had no bank effects (5.9 knots vs. 5.5 knots, $p < 0.05$). This difference in speed was less than 0.5 knots, and, though it was found to exist statistically, from a practical sense could not be the cause for differences noted in the number of boundary penetrations. Table 3-9 presents the latter findings and indicates the number of incidents of boundary penetrations as a function of wind magnitude, wind side, and bank/no bank conditions.

TABLE 3-8. FACTORED $|X|_F$ (BANKS/NO BANKS)

Wind (kt)	$\|X\|_F$ (ft)	
	Banks	No-Banks
40	10	16
50	23	30
65	23	70

$p < 0.05$

TABLE 3-9. NUMBER OF BOUNDARY PENETRATIONS (BANKS/NO BANKS)

Wind Side	Wind Speed (kt)	Boundary Penetrations (Number)	
		Banks	No-Banks
Starboard	40	0	3
	50	1	1
	65	0	7
Port	40	0	0
	50	1	6
	65	3	3
Total		5	20

$p < 0.05$

The incidents of boundary penetrations by any portion of the vessel during transits under bank conditions show no significant differences for either port or starboard wind side as wind speed increases. The number of boundary penetrations by pilots conning the 80K tankers through the channel under no bank 65 knot starboard wind and 50 knot port wind conditions was larger than for comparable wind conditions when bank effects were present. The total number of incidents under no banks without regard to wind level or side (20) was larger than for transits with banks (5). The ultimate figure of merit for piloted controllability is really the incidence of boundary penetrations since this is a direct measure of safety. The experimental findings indicate that the pilots were aided by the presence of the banks and transited the channel more safely when bank forces were present.

3.2.2.3 Rudder Effects (B/NB)

The bank/no bank analyses did not indicate any differences in the number of rudder crossings between pilots transiting the channel when no bank effects were available compared with the conditions when the bank forces were present. Rudder angle, however, showed a small significant effect and the findings are presented in Table 3-10.

The bank/no bank comparison at the 65 knot wind condition showed that larger rudder angle was used on average by pilots transiting without bank effects (27° vs. 23°). There was also a no bank general trend of increasing average rudder angle with increased level of wind. As discussed earlier in 3.2.1.6.1 there was no significant increase in the average rudder used by the 80K tanker pilots as the level of wind increased from 50 to 65 knots when bank effects were present.

From the average rudder angle trends noted above and the controllability difficulties stated earlier (Paragraphs 3.2.2.1 and 3.2.2.2) it would appear that the pilots of the 80K tankers used more average rudder when they were having difficulty in an effort to maintain better control.

3.2.3 Channel Width Comparisons (C.W.)

The channel width comparisons are based on a portion of the data pool used for the main comparisons, namely 18 pilots divided into three groups (LNG, 80K tanker, and 30K tanker). They compare performance in the first and the last leg of the channel transit, legs 1 and 5, respectively. Conditions for leg 1 and leg 5 of any single transit were identical in all respects save one, the channel width. In the first leg the width was 800 feet while the fifth leg width was 600 feet. A two hundred foot wide shoal had been placed on the side of the channel in leg 5, causing the pilots to move their vessels towards the starboard bank as the channel narrowed (see Figure 2-1).

Both leg 1 and leg 5 were preceeded by low wind magnitude transition segments. Within the legs the wind direction was either plus or minus 105° relative, depending on the wind side

TABLE 3-10. RUDDER ANGLE (BANKS/NO BANKS)

Wind (kt)	Rudder Angle (deg)	
	Banks	No-Banks
40	15°	14°
50	22°	22°
65	23°	27°

$p < 0.05$

condition for the particular channel transit. The level of wind for the two legs was the same for each passage, and bank forces were present and affected the ship's track in both of the legs.

Since the objective of these channel width comparisons was to determine if the difference of 200 feet in width caused a substantial difference in pilot performance, only differences caused by channel width will be reported within this section. Other differences that were found that didn't reflect legs 1 and 5 differences were reported under the main comparisons. These were common to both legs, and when they arose within these channel width comparisons were only ramifications of the basic differences previously reported for the complete transit.

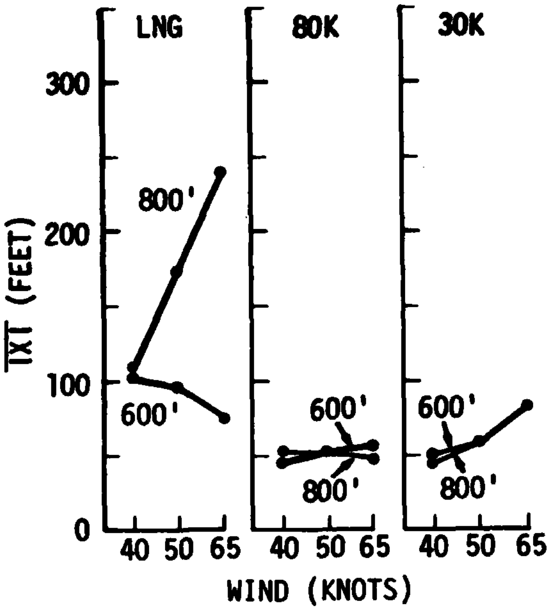


Figure 3-1. Channel Width Comparison, Absolute Value of Off-Track Deviation

3.2.3.1 $\overline{|X|}$ and Factored $\overline{|X|}$ (C.W.)

The average magnitudes of off-track deviations are shown in Figure 3-1. They indicate that the pilots on the LNG vessels were the only group that showed a significant difference in performance between the passages in the two legs. There were no differences for the 80K and 30K tankers at any wind magnitude or between channel legs.

The LNG pilots had significantly different performance results for different wind levels in the 800 foot portion of the channel. In the 600 foot leg, though, they took measures to conn their vessels with a higher degree of control, with no differences found between levels of wind. When the half channel width was 400 feet they allowed their 897 foot long vessel to go an average of 240 feet from the channel centerline (65 knots), but when the half channel width was reduced to 300 feet they brought this parameter down to just over 75 feet. Their experience with controllability difficulties in the wider channel area forced them to attempt to improve their performance near the shoal, and on average they succeeded. Figure 3-2 is a presentation of the $\overline{|X|}$ data which has been factored for S and C and reinforces the previous statements regarding LNG pilot perceptions. The factored $\overline{|X|}$ for the LNG in the 800 foot leg shows an even larger range of values as a function of wind magnitude than did $\overline{|X|}$. The factored $\overline{|X|}$ performance in leg 5 was also substantially the same for all levels of wind. Again, no performance differences were found between tanker pilots at any wind level.

3.2.3.2 Consistency, C (C.W.)

The average consistency of the actual ship track within each leg (Figure 3-3)

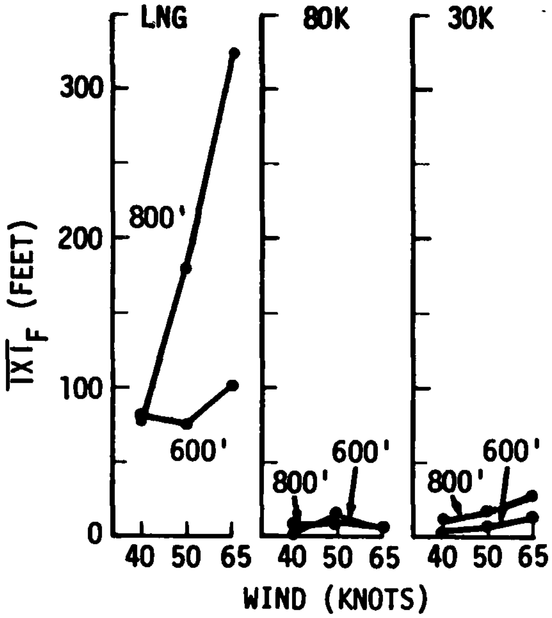


Figure 3-2. Channel Width Comparison, Factored Value of Off-Track Deviation

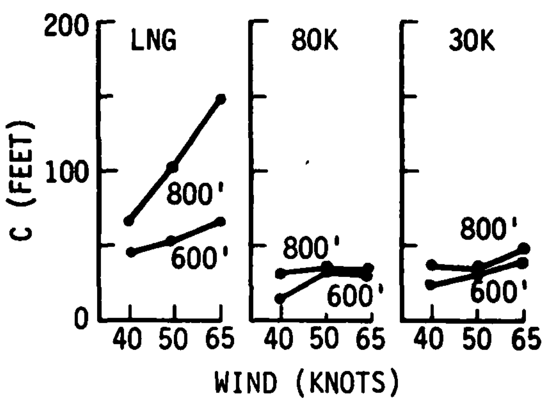


Figure 3-3. Channel Width Comparison, Consistency

effectively mirrors the $\overline{|X|}$ and factored $\overline{|X|}$ results. The LNG pilots tended to be less consistent, i.e., with larger variation in off-track deviation as a function of wind speed in the wider section of the channel. The measures that were taken in the narrow leg to lessen controllability difficulties also lessened the variation in distance off centerline. The average values of C for leg 5 in fact were smaller than those for leg 1 and did not show any significant difference as the wind increased. The results once again showed no significant differences between pilots on the different tankers in either leg, or at different wind levels.

3.2.3.3 Ship Speed, S (C.W.)

From the main comparison, the measure of ship speed was found to increase with wind magnitude, with the LNG pilots on average increasing their speed over the desired level of five knots to a greater degree than the tanker pilots. Figure 3-4, however, shows the manner in which the average speed of the vessels varied during

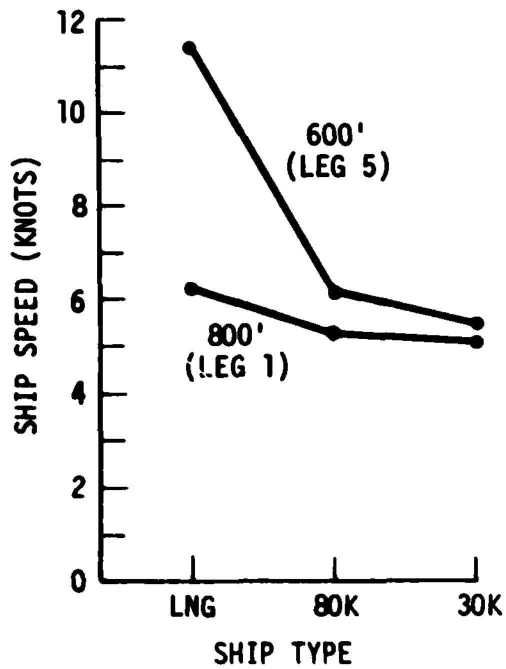


Figure 3-4. Channel Width Comparison, Ship Speed

the passages as a function of channel leg (i.e., leg 1 vs. 5). Although the average speed attained by the LNG pilots was significantly larger than was required by the tanker pilots under all conditions of channel width, it was in the narrower channel area that the pilots of the LNG vessels found that a substantial increase of speed was necessary for control. On average the LNG pilots went almost twice as fast in the 600 foot segment as in the 800 foot segment. The pilots that conned the 80K tankers showed an increase in average speed when they transited the narrow leg as compared with the wider one, but the increase was far smaller than the LNG pilots exhibited.

3.2.3.4 Boundary Penetrations (C.W.)

The boundary penetration findings are shown in Figure 3-5. No incidents were recorded for tanker pilots in either of the two legs. The pilots that were conning the LNG vessels experienced considerable difficulties in both legs and found that their control difficulties in the wider channel segment increased substantially as a function of wind; i.e., many more penetrations of the boundary occurred at 65 knots than at 50 knots, as well as at 50 knots compared with 40 knots. There were more incidents at 40 knots in the narrower section of the channel than in the wider section, indicating that the pilots believed they had control in the narrow section/lower wind conditions, but didn't. The pilots gained some measure of control with the greater levels of wind in the 600 foot leg by increasing speed (as noted previously), keeping the number of incidents relatively constant as a function of wind magnitude.

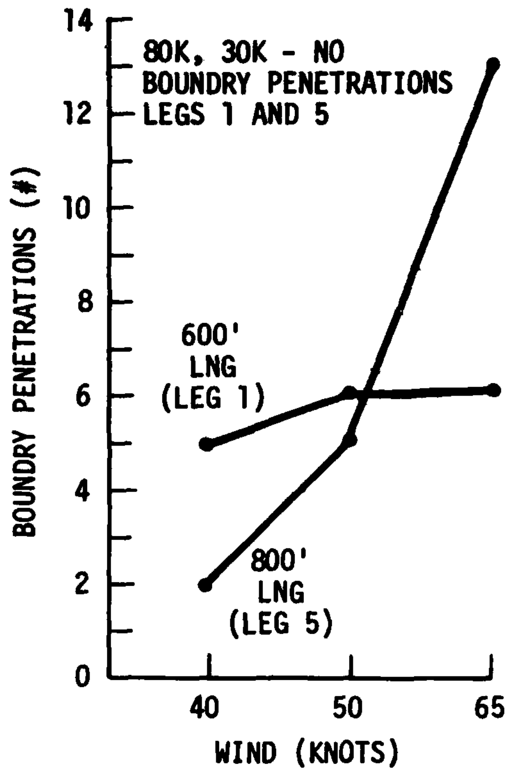


Figure 3-5. Channel Width Comparison, Boundary Penetrations

3.2.3.5 Rudder Effects (C.W.)

Table 3-11 and Figure 3-6 are indications of the way the pilots varied their rudder usage within the two legs studied in the channel width comparisons. Less rudder was used on average by all pilots for all wind levels in the narrower leg when starboard winds were present (Table 3-11). This was most probably due to the fact that the bank forces tended to aid the pilot's efforts to combat the starboard wind forces when they were forced by the shoal to move closer to the starboard bank. They therefore tended to move to the right of center track under both conditions of wind direction.

TABLE 3-11. AVERAGE RUDDER ANGLE (CHANNEL WIDTH)

Channel Width (ft)	Starboard Winds	Port Winds
800 (leg 1)	18	19
600 (leg 5)	16	19

$p < 0.05$

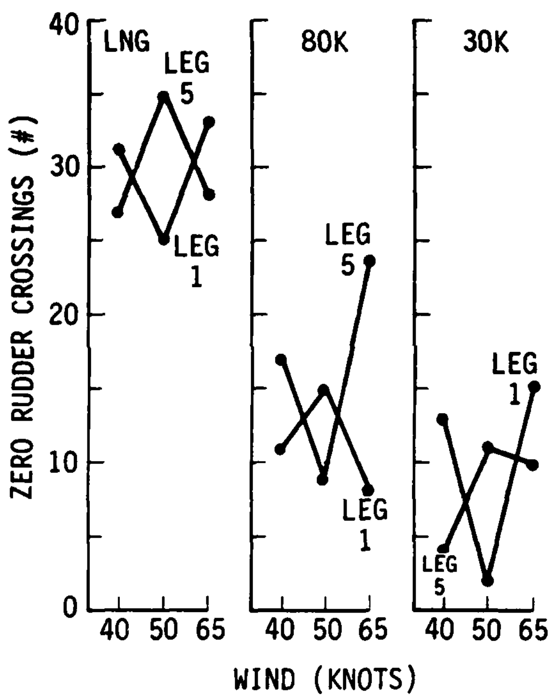


Figure 3-6. Channel Width Comparison, Rudder Crossings

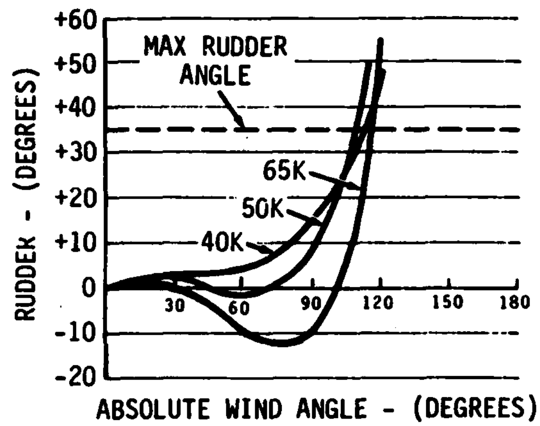


Figure 3-7. Steady State Rudder Angle, LNG Carrier

The number of zero rudder crossings for the LNG pilots (Figure 3-6) was always larger than for the 30K tanker pilots but varied somewhat with wind magnitude and channel width when LNG performance was compared to that of the 80K tanker pilots. No real differences in rudder crossings for the LNG pilots were found as a function of wind magnitude or channel width. This no doubt was due to the increased level of control attained on the LNG vessels with the use of the higher ship speeds at higher wind levels.

3.2.4 Rudder Effects Comparisons (R.E.)

The rudder effects analyses are based on portions of the data used for the main comparisons. Comparisons are made between the LNG, 80K tanker, and 30K tanker groupings of pilots for performance in leg 1 vs. leg 4 for each transit (Figure 2-1). Normally a starboard wind would cause a tendency for clockwise rotation of the vessel which is then counteracted by a "left," i.e., positive rudder. As shown in Figure 3-7 an anomaly exists for the LNG vessel for certain wind levels and wind angles because the rudder effect reverses; that is, negative rudder is needed to counteract a starboard wind. Similar "rudder reversal" occurs for port winds.

Figure 3-8 and 3-9 are comparable plots of rudder angle vs. wind angle for the two tankers. No rudder reversal occurs for either tanker at any wind angle. The objective of the rudder effects comparisons was to see if any differences could be discerned between the controllability demonstrated with the LNGs (when this effect was occurring) and the controllability exhibited by the pilots on the tanker runs. If there was a difference, it might be attributed to the rudder reversal effect. Therefore, in leg 1 the direction of the wind was either ±105° (relative to centerline track) for all vessels. For leg 4, the relative wind angle was set at ±135° for the tanker runs and ±60° for those in which the LNG vessel was involved.

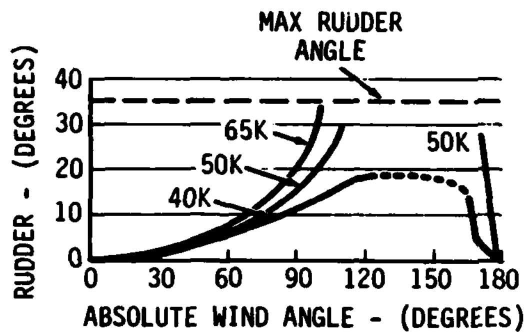


Figure 3-8. Steady State Rudder Angle, 80,000 DWT Tanker

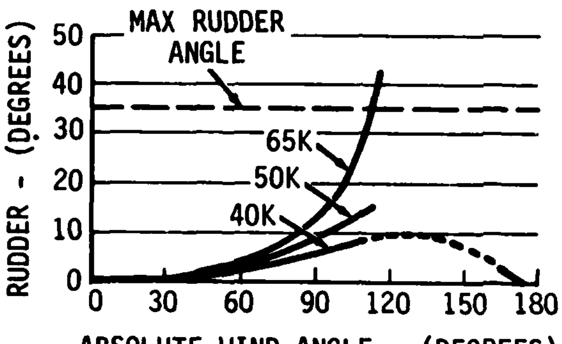


Figure 3-9. Steady State Rudder Angle, 30,000 DWT Tanker

To draw conclusions regarding the objectives of these analyses, comparisons must be made between legs for the LNG vessel to find if performance "deteriorated" in leg 4 compared with leg 1, and also between the LNG and the tankers for each leg under study. The findings for the seven performance measures are presented in summary form in Figures 3-10 and 3-11 and in more detail in Appendix C. Figure 3-10 contains the results for legs 1 and 4 for the LNG vessel alone. Figure 3-11 presents the findings for comparable measures for both tankers and both legs of interest.

3.2.4.1 Absolute Value of Off-Track Deviation, $\overline{|X|}$ (R.E.)

Comparison of Figures 3-10 and 3-11 indicates that pilot performance on the LNG vessel, compared with the tankers, was poorer for all levels of winds studied. This was true for both leg 1 and leg 4. In leg 4, all values of $\overline{|X|}$ for each ship were larger than the values exhibited for equivalent wind conditions in leg 1 (except for the LNG/65 knot condition). This latter difference will be discussed as part of the ship speed (S) performance measure, paragraph 3.2.4.4.

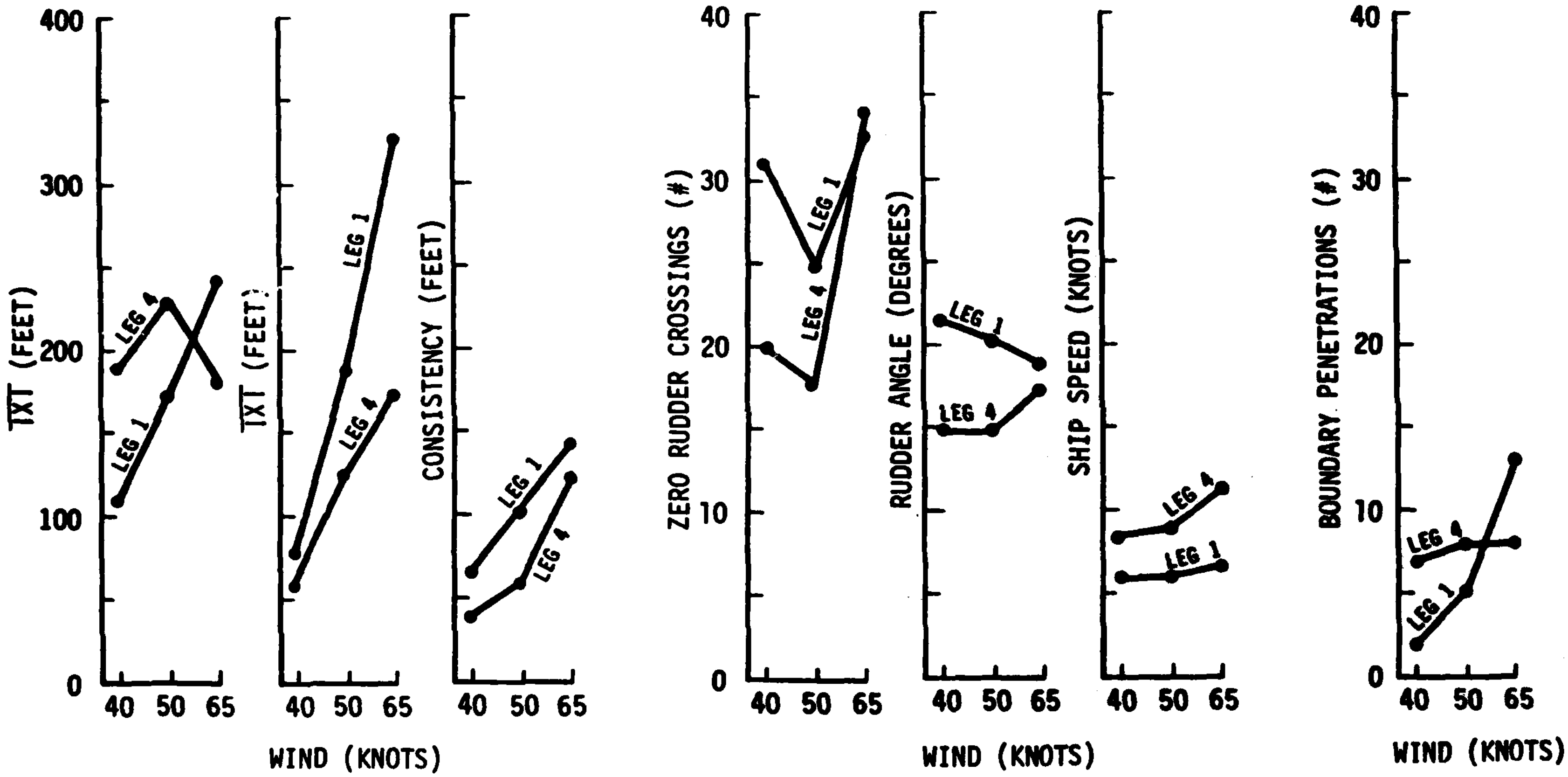


Figure 3-10. Rudder Effects Comparison, LNG Carrier

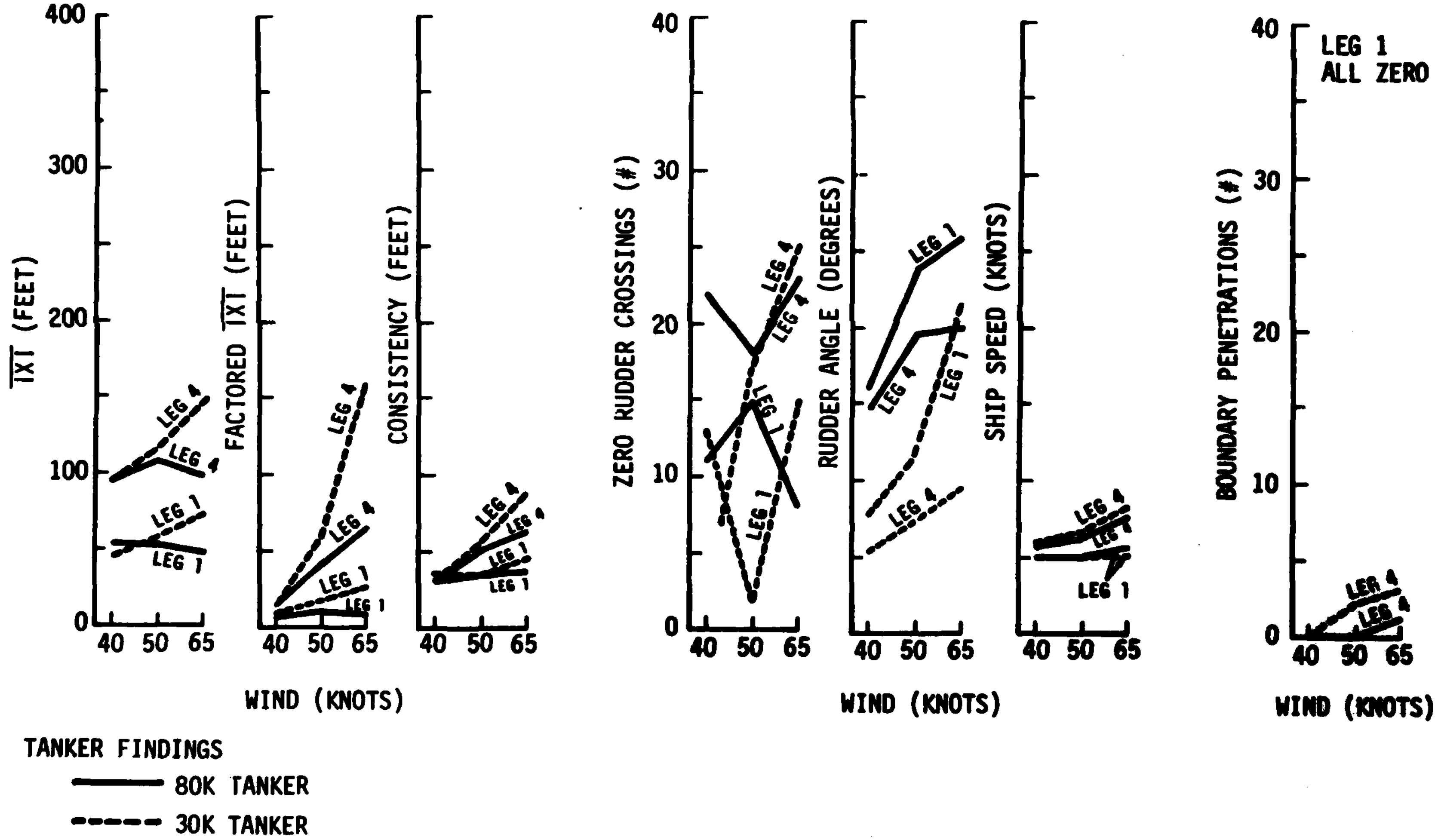


Figure 3-11. Rudder Effects Comparison, 80,000 and 30,000 DWT Tankers

3.2.4.2 Factored Absolute Value of Off-Track Deviation, $\overline{|X|}_F$ (R.E.)

Performance exhibited by the LNG pilots, as indicated by the $\overline{|X|}_F$ measure was poorer (larger) in leg 1 compared to either leg 1 or 4 for either tanker pilot grouping. This comparison was for like wind conditions.

The LNG pilots used more speed and maintained a more consistent track in leg 4 than in leg 1 and the resultant factored $\overline{|X|}$ for leg 4 appears to be superior to their leg 1 findings at all levels of wind. As measured by factored $\overline{|X|}$, however, the LNG pilots' performance for leg 4 was still poorer than that of the tanker pilots under comparable leg 4 wind conditions.

3.2.4.3 Consistency, C (R.E.)

The consistency of performance in leg 4 did not differ between the three vessels for any wind condition. For leg 1, the LNG pilots' controllability for like wind conditions was poorer (less consistent) than the tanker pilots' performance. As indicated in 3.2.4.2, the LNG pilots' consistency of performance improved in leg 4 compared to leg 1.

3.2.4.4 Ship Speed, S (R.E.)

For equivalent wind magnitudes, the pilots of all three vessels on average increased their speed during leg 4 compared with leg 1. For the higher wind conditions in leg 1 the LNG pilots attained approximately six knots of ship speed compared with tanker pilot speeds of approximately five knots. In leg 4, the LNG pilots substantially increased their speed to maintain controllability, reaching an average speed of over 11 knots at 65 knots of wind. With this increase of speed they were able to decrease the $\overline{|X|}$ for leg 4, 65 knot conditions (see Figure 3-10) and maintain better consistency throughout leg 4 compared to leg 1.

3.2.4.5 Boundary Penetrations (R.E.)

The inferences contained in the previous paragraph regarding speed are shown most clearly when boundary penetrations are examined. In leg 1, LNG pilots had more control difficulty and penetrated the channel boundaries more frequently than did the tanker pilots.

In leg 4, under 40 and 50 knot wind conditions, the control situation for the LNG pilots deteriorated, even with the higher speeds that were used. During the leg 4 portion of the 65 knot runs the LNG pilots stabilized their control and penetrated the channel boundaries fewer times (leg 4 - 8, compared with leg 1 - 13). This increase in controllability was only attained by substantially increasing ship speed by more than 67% (6.7 vs. 11.2 knots).

3.2.4.6 Rudder Crossings and Rudder Usage (R.E.)

Average rudder angle and number of rudder crossings for the LNG pilots at various wind levels are shown in Figure 3-10. Once again the higher ship speeds in leg 4 compared with leg 1 probably account for the trends shown. At higher ship speed, less rudder was needed because the rudder became more effective. With higher speed the LNG vessel becames more controllable, and therefore less zero rudder crossings were exhibited.

3.2.4.7 Rudder Effect Conclusions

It is difficult to draw definitive conclusions from this particular set of comparisons. Without question, the LNG pilots had more difficulty with controllability than the tanker pilots did, but this was true in most of the analyses performed within this experiment.

With this type of research, using practicing mariners in realistic environments, the investigator can request that the test subjects/pilots maintain given levels of the controlled variables. However, when the pilot's perceptions of vessel safety come into play, the experienced mariner "does what has to be done," even if it means breaking some of the experiment's ground rules. All subjects were told to maintain their ship speed at five knots, with most of the tanker pilots varying somewhat from this level as anticipated. The LNG pilots, however, departed radically at times from the required level, forcing the investigator/analyst to make inferences in an attempt to discern the motivation for such action.

Leg 4 for the LNG vessel was designed as the portion of the channel requiring a reversed rudder effect, and average LNG ship speed in this leg was substantially higher than leg 1 for all wind levels. Also, ship speed increased in each leg as wind level increased. Since the LNG pilots felt that they needed more speed when the wind was coming from 60° (leg 4) compared with 105° (leg 1), and that they needed even more as wind velocities increased to 65 knots, it would appear that the rudder reversal effect did actually influence the controllability and decision-making process of the pilots of the LNG vessel.

When the leg 4 trends for $\overline{|X|}$ and number of boundary penetrations are examined for the 65 knot wind condition, it appears that the average 11+ knots used at the highest level of wind by the LNG pilots was adequate to gain a measure of control over the vessel. That is to say, the trends in $\overline{|X|}$ and boundary penetrations were reversed somewhat at the highest wind level investigated because of the excessive speeds that were used.

3.2.5 Special Experience Comparison (S.E.)

To obtain the necessary data for the previously discussed analyses, test subjects were randomly selected from numerous pilot associations. The main criterion was that the test subjects were full branch pilots with experience on the class of vessel which each would conn during the experiment. During the experimental runs it seemed to the investigators that the performance of pilots obtained from one particular pilot organization was "better" than from all other organizations. This was a subjective evaluation based on aperiodic observations. The particular pilot organization involved was heavily experienced in a long, very narrow channel, and the question arose as to whether or not this experience was contributing to the apparent performance level. There was also the question as to whether or not the "superior" performance actually existed or was merely a subjective anomaly based on incomplete observations.

A mini-analysis suggested itself and two additional subjects were selected from that pilot organization to make an additional grouping of six pilots. This "specialized experience" group consisted of three pilots who conned the 80K tanker, one who conned a 30K tanker, and two an LNG vessel. The data for this group were for transits under bank conditions, i.e., conditions identical to transits studied in the main comparison. From the remaining main subject data pool a similar group of six pilots (three 80K, one 30K, and two LNG) was randomly selected and their performance results were compiled for comparison with the specialized experience group. The objective of these comparisons was to determine if the S.E. group performance was truly significantly better, since this could have interesting possibilities regarding experience and training ramifications, especially for narrow channel passages.

Four performance measures were analysed as part of the S.E. comparisons: $\overline{|X|}$, S, C, and boundary penetrations. The only significant difference in performance between the two groups was for the $\overline{|X|}$ measure, and the findings for the mean values are shown in Table 3-12. A trend "favoring" the S.E. group is apparent but quite weak. All other measures show no differences between the groups.

Based on the results of this sampling it would appear that specialized experience was of no consequence as a factor in the demonstrated piloted performance. It may very well be, though, that the mixing of the data for all ship types together in one group may have lessened the differences that could have been exhibited between the groups. Pilots were obtained at random from various pilot organizations, with only four originally drawn from the S.E. pilot organization. These latter pilots had been assigned to different vessels; therefore, without a large number of additional test subjects a ship comparison was not possible in the S.E. set of analyses. This would suggest that future S.E. experimentation could address the issue of ship comparison from the outset of the experimental

TABLE 3-12. ABSOLUTE MAGNITUDE OF DISTANCE OFF-TRACK, $\overline{|X|}$ (S.E. COMPARISON)

Wind Side	Wind Speed (kt)	Specialized Experienced Group	Other Group
Starboard	40	84	77
	50	87	106
	65	93	99
Port	40	75	144
	50	118	129
	65	114	126

$p < 0.05$

design and planning, with the possibility of drawing stronger or even different conclusions.

3.3 SUMMARY GROUND TRACKS

The data of the sample groupings of pilots discussed in paragraph 3.2.1 have also been assembled and presented within this section as graphical representations of the average ship ground tracks for channel transits for each wind condition with bank forces in effect. The basic chart for the presentation of this information is shown in Figure 3-12, which represents the four 800 foot wide legs and the final 600 foot wide leg. Legs 1 and 2 are continuous segments, as are legs 3 and 4. The turn, which falls between legs 2 and 3, has been eliminated from the graph, as has the transition segment between legs 4 and 5. Data are presented at one-eighth mile increments, and are based on the results obtained from each subject grouping under the given wind conditions. For example, the six LNG pilots each transited the channel under 65 knots of starboard wind. For each position along the track the six values of off-track deviation were averaged, a standard deviation was computed, and the largest and smallest values of off-track deviation were noted. At the correct position along the track this average value of distance off-track was plotted relative to the channel centerline and a line, centered at the average with a total length equal to two standard deviations, was also drawn. Ship passage is from left to right on the graph, with starboard deviation off-track displaced below the centerline and port deviation plotted above the center. The maximum and mean values at each position were indicated by small circles. The repetitive plotting of the pertinent data for each 1/8

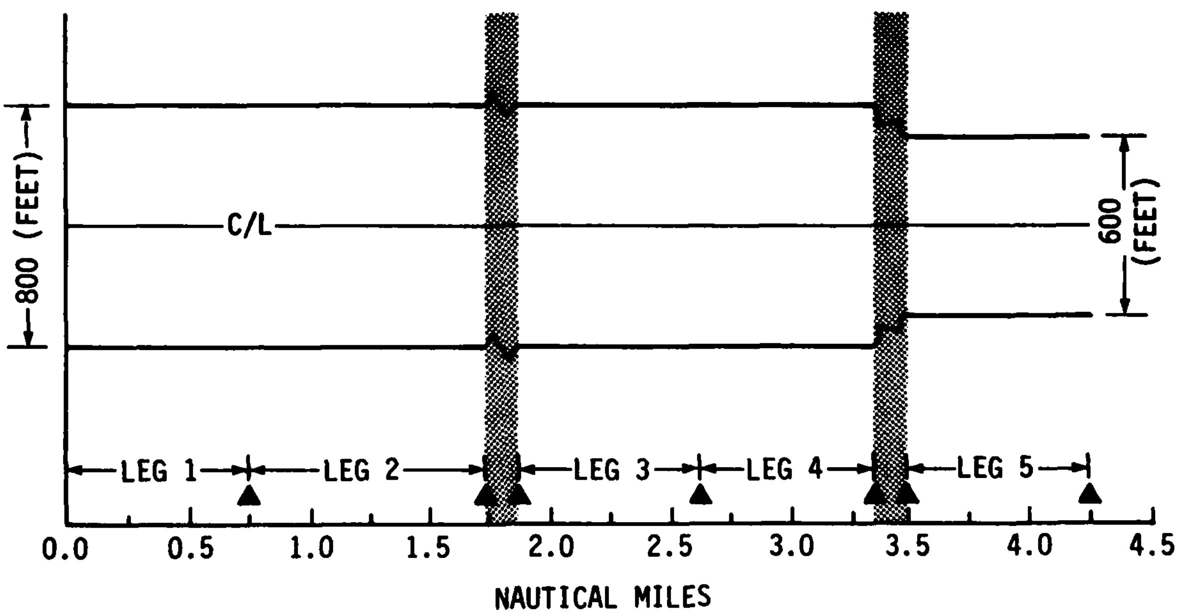


Figure 3-12. Basic Summary Ground Track Chart

mile position in the five legs allows for an overview of each group's performance under the given wind conditions. These plots have been assembled for all six wind conditions and for all three groupings of pilots. The data used were based on the track of the center of gravity of each vessel in each run, and do not account for the length or width of the ships themselves.

3.3.1 80K Tanker

The graphs for the six wind level conditions for the 80K tanker runs are shown in Figure 3-13. The average track for starboard winds are slightly to port, i.e., to leeward, and for port winds are also slightly, though to a greater degree, towards the leeward side. The variability (two standard deviation lines) appears to be smaller with both port and starboard winds for the 600 foot leg than for the 800 foot legs. Maximum and minimum off-track deviations, with almost no exception, fall within plus or minus 200 feet of the centerline of the channel.

3.3.2 30K Tanker

The graphs for the 30K tanker runs are shown in Figure 3-14. The trends noted for performance demonstrated by the 80K tanker pilots are also seen with the 30K tankers. The average off-track deviations for the 65 knot port wind/30K tanker passages were somewhat larger than that found for starboard winds or with the 80K/65 knot wind conditions for either wind side. The variability for the port wind/30K tanker condition was larger than when starboard winds were encountered. With a narrower channel leg, the pilots again maintained a more controlled performance. The range between maximum and minimum values for the higher port wind levels was almost the full channel width and, in fact, the ship's center of gravity for one 30K tanker run actually went outside of the channel boundary under the 65 knot port wind condition.

3.3.3 LNG Carrier

The summary graphs for the performance of the LNG pilots are shown in Figure 3-15. Upon examination, several overall trends emerge. The average tracks become poorer (larger distance off-track) as a function of increased winds. Performance under conditions of port winds tends to mirror the starboard wind effects.

Variability of performance as shown by the length of the two standard deviation lines and the maximum and minimum off-track deviation "traces" are large (200 to 400 feet) for all wind conditions shown. The pattern that was noted for the other vessels regarding performance in the narrower leg (leg 5) is no longer present; i.e., there is no apparent improvement in performance when the LNG pilots perceived that the channel width requirements were more stringent.

The scenario had been designed to allow settling-in (transition) segments prior to legs 1, 3, and 5 by reducing wind levels in the transition segments to a nominal level of 10 knots. It can be seen at all levels of wind, and most strikingly at 65 knots, that the LNG pilots entered each of these three legs (1, 3, and 5) in either good position or at least heading toward a better position relative to the channel center track. As progress was made into the legs, however, the wind tended to dominate the situation and push the vessels to leeward. As ship position deteriorated the pilots took other measures to correct the situation.

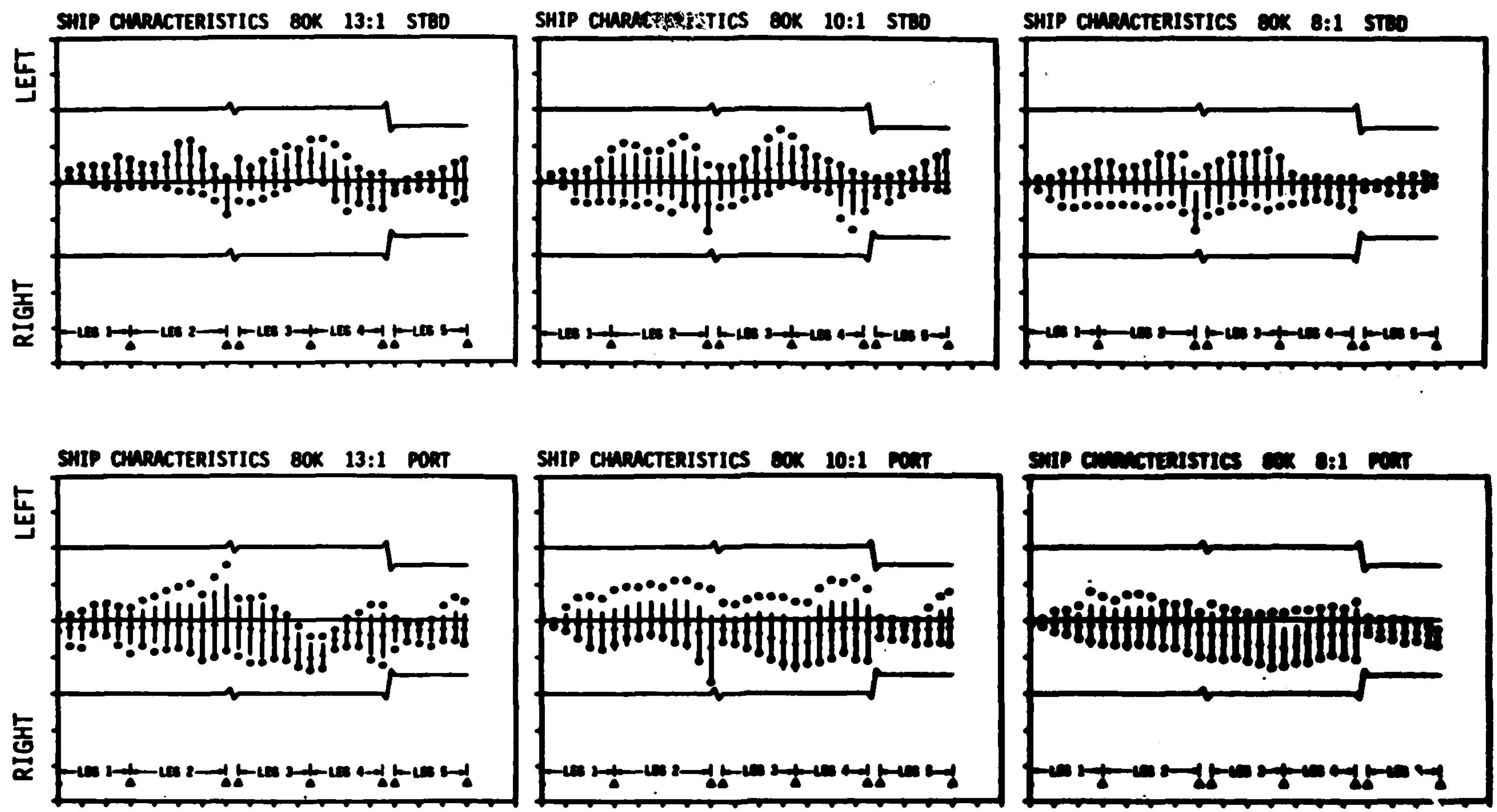


Figure 3-13. Summary Ground Tracks, 80,000 DWT Tanker

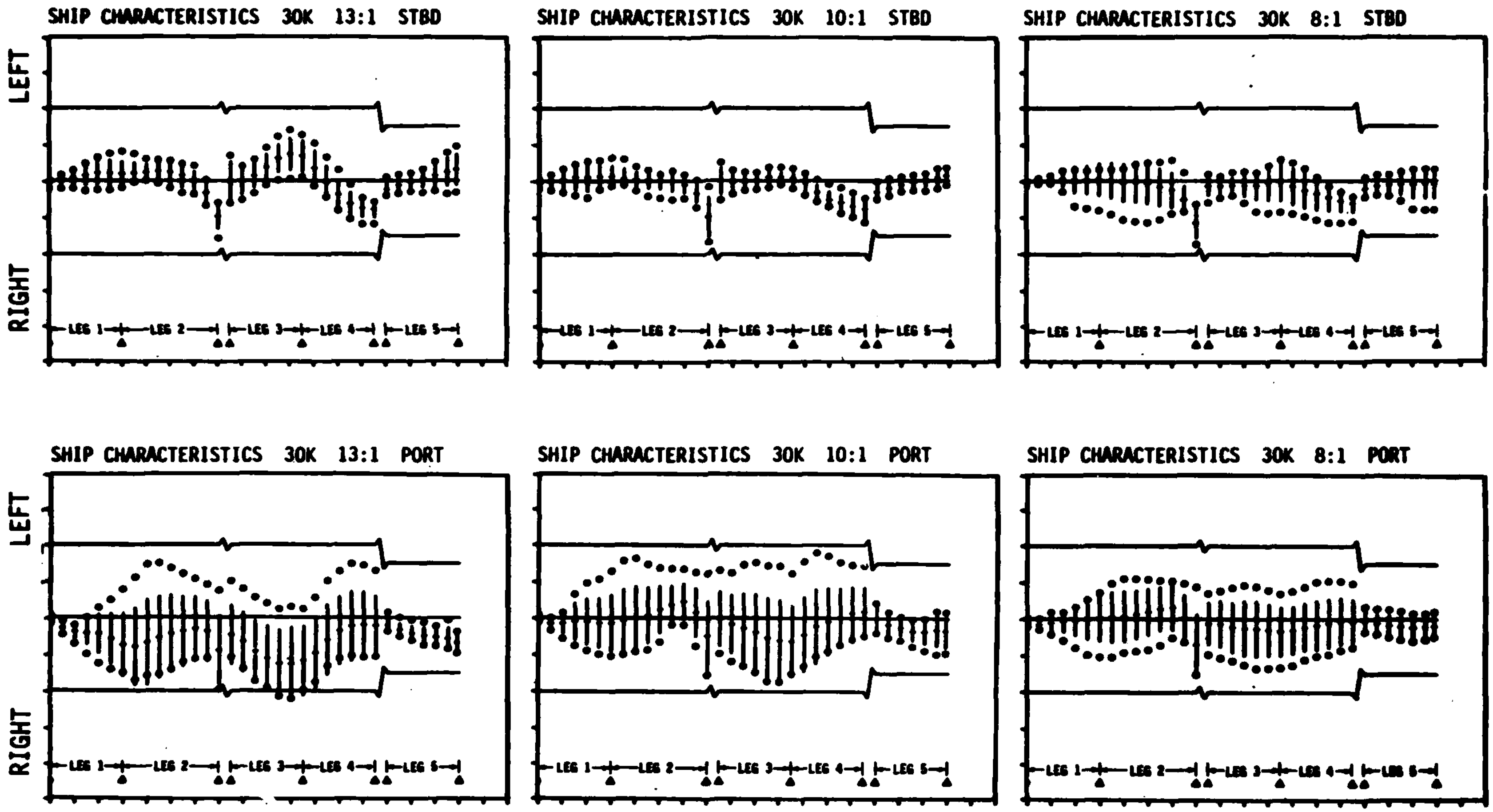


Figure 3-14. Summary Ground Tracks, 30,000 DWT Tanker

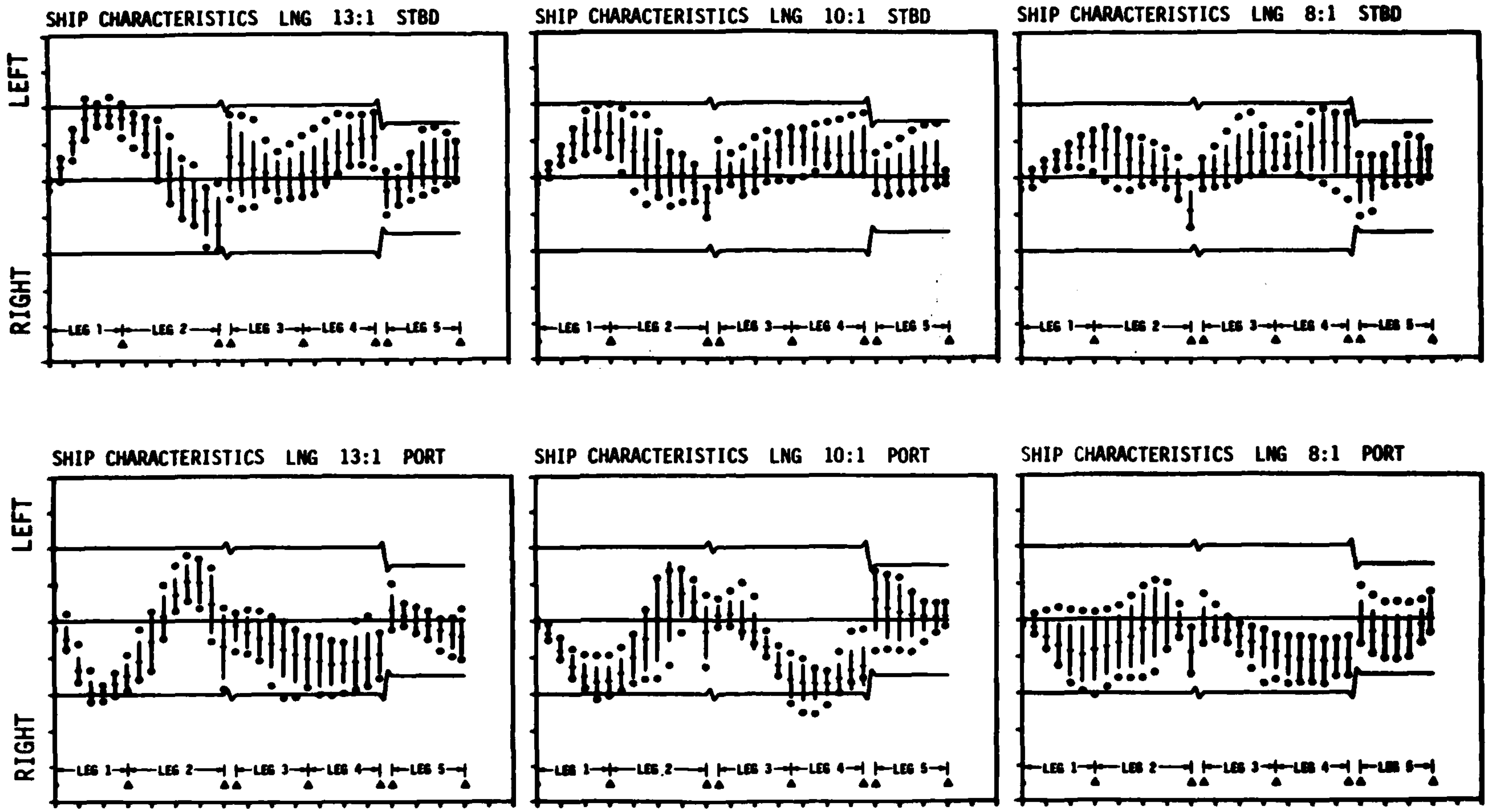


Figure 3-15. Summary Ground Tracks, LNG Carrier

These measures, as noted previously, included kick turns which resulted in increases in vessel speed as pilots sought to maintain control. Overall, the average positions of ship track indicate that the LNG pilots were having great difficulties maintaining a steady course, especially under the higher level wind conditions.

3.3.4 Summary Ground Track Conclusions

The results shown in Figures 3-13, 3-14, and 3-15 display the same data that was used for the statistical analyses discussed in the main comparisons of paragraph 3.2.1, but in the graphical manner used give more insight into the trends and the variations that occurred within the legs themselves. The 80K tanker pilots appeared to have somewhat better control than did the 30K tanker pilots, but both groups showed less problems compared with the performance displayed by the pilots conning LNG vessels. Especially at the higher wind levels, the plots indicate that the latter group was seen to be fighting the wind as their vessels headed towards the channel boundaries.

3.4 PILOT POPULATION PARAMETER ESTIMATIONS

The previous sections (3.2 and 3.3) presented the performance findings for sample groupings of pilots transiting a narrow waterway under various wind conditions. These mariners were grouped in accordance with the vessels that were conned, and statistical comparisons were made between their group performances. Inferences were then drawn regarding comparative group controllability difficulties.

The pilots in each ship group were randomly selected and were representative of the parent pilot populations from which they were drawn; namely, pilot organizations with personnel experienced on at least one of the three vessels studied, (LNG carrier, 80K tanker, and 30K tanker). It is, of course, desirable to extrapolate from the sample group to the parent population itself. The experimental data were therefore subjected to additional analyses which allowed further inferences to be made. These were not so much group-to-group comparisons, but comparisons relative to the populations from which the samples were drawn. By statistical manipulation of the sample data, estimations were made of the parent populations with regard to various performance measures.

Within a given probability of error, estimations were made for <u>all</u> experienced pilots that might transit narrow channels under similar wind conditions. By studying the composite parent population parameters obtained, further inferences were possible regarding channel width requirements for the different ships under severe wind conditions. The performance measures that were used for these estimations were absolute magnitude of off-track deviation and consistency (variability) of ship track around the average track of the passage. Estimations of the range of the population means were calculated from the sample statistics and took the form of confidence intervals; that is, the interval in the distribution of the performance measure within which the population mean ( ) would be expected to be found at a 90% confidence level.

The estimation of the range of values for for the absolute value of off-track deviation, $\overline{|X|}$, is presented in summary graphical form in Figure 3-16 for each of the three ships

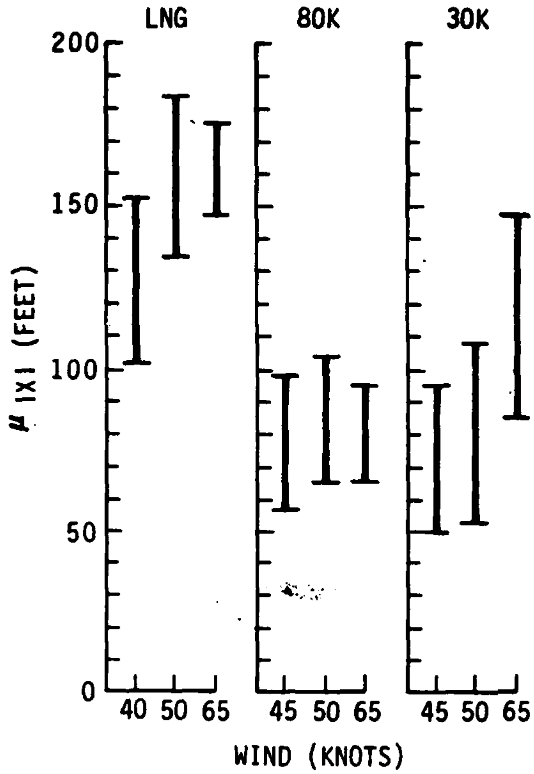


Figure 3-16. $\mu_{\overline{|X|}}$ Intervals (90% Confidence Level)

studied at each of the wind levels that was investigated. The data are presented in more complete tabular form for this measure, as well as all measures discussed in this section, in Appendix C. The upper limit of the confidence interval for the LNG population mean is 182 feet for a 50 knot wind condition and somewhat smaller, 177 feet, for the 65 knot condition. For the 80K tanker the upper limit is approximately 100 feet while the 30K tanker has an upper limit at 65 knots of 148 feet. The lower limit, or "lowest" average in the interval for the larger winds is approximately 145 feet for the LNG, 65 feet for the 80K tanker, and 85 feet for the 30K tanker.

The mean for the measure of $\overline{|X|}$ is always greater or equal to that of the actual "signed" off-track deviation, X. Therefore these values of the population means are more conservative (greater) than would be estimated from the actual off-track deviation values. Based on these more conservative figures, the average position of the center of gravity for the LNG vessel would be expected to be less than 200 feet from the center in an 800 foot wide channel while the tankers would be less than 100 feet. This is for winds up to and including 50 knots.

These latter values do not tell the whole story, however, since they represent at best only the average magnitude of vessel track. Consistency or variability around the mean track must also be considered. Figure 3-17 indicates the estimation of consistency of the parent populations. The upper limit of population means for this measure varies from approximately 170 to 180 feet for LNG/large winds, 90 feet for 80K tankers/large winds, and 110 to 120 feet for 30K tankers/large winds. Considering the conservative estimates of the mean values of off-track deviation and consistency, it appears that the tanker pilots would use approximately half (200 feet) of the leeward side of an 800 foot channel under these wind conditions that were studied. Although in the final analysis the decision is always the prerogative of the mariner on the bridge, the results imply that under these extreme conditions tankers of this type could be moved if necessary in an 800 foot channel with winds in the 50 to 65 knot range. Pilots on the LNG carrier, however, would find that they needed practically the whole available half channel width of 400 feet for winds in

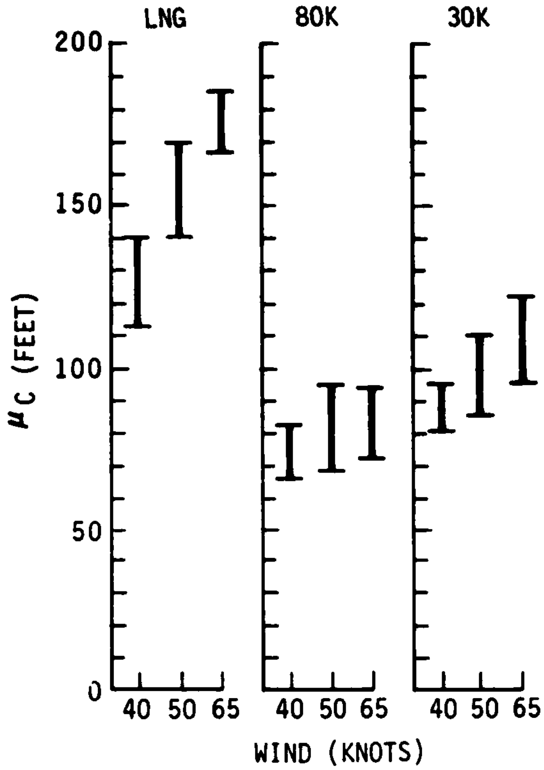


Figure 3-17. μ_C Intervals (90% Confidence Level)

this range, and would therefore be forced to wait for a change in wind conditions when faced with transits which couple low ship speed and high winds.

3.5 PERFORMANCE VS. WIND STABILITY

A summary assessment of the performance exhibited by the three groupings of pilots indicates that those pilots who conned the LNG carriers consistently had a more difficult time handling their vessels than did the tanker pilots. This was apparent with the performance measures of magnitude of off-track deviation ($\overline{|X|}$, both factored and unfactored) as well as consistency (C) and ship speed (S). When wind levels were increased to 65 knots, the LNG pilots increased their ship speed by more than 2:1 over the requested five knots in order to maintain some level of control. In spite of this attempt to maintain controllability, they obviously had far more difficulty with their vessels than either group of tanker pilots did. The net result of these difficulties in a narrow channel passage must be measured against safety, in this case the number of times a portion of the vessel penetrated the channel boundaries and shoal area. The LNG pilots' difficulties were manifested by the large number of such incidents and the fact that these incidents also increased with the higher levels of wind.

Inherent wind instabilities for the three vessels were investigated by means of off-line computer analyses, with the findings presented earlier in the report (paragraph 1.2). The wind angles used in this experiment lie in the range between 90° and 135° off the bow for the tankers and 60° and 120° for the LNG vessel. Both tankers had been shown to be inherently unstable in this range of wind angle at wind-to-ship-speed ratios of 8, 10, and 13 to 1. These were the ratios designed into the experiment, and the instabilities were indicated in the appropriate figures by the positive nature of the real part of the roots, i.e., the eigenvalues. The LNG vessel, on the other hand, had negative eigenvalues for the wind levels and directions used, and therefore any oscillations that occurred due to spurious forces acting on the LNG tended to quickly dampen out. That is to say, the LNG vessels were operating under conditions that were inherently stable as far as wind instability criteria are concerned.

An inspection of the composite findings of performance and inherent ship instabilities leads to an extremely interesting conclusion: pilots had more difficulty controlling the more stable vessel. Conversely, as demonstrated by performance, the less stable vessels were more easily controlled. This points to the fact that the basic wind instability of the vessels was not the predominent factor influencing controllability for the wind conditions that were investigated. The pilots were capable of overcoming the wind-induced inherent ship instabilities, and therefore other factors contributed to the poorer performances evidenced on the LNG vessel.

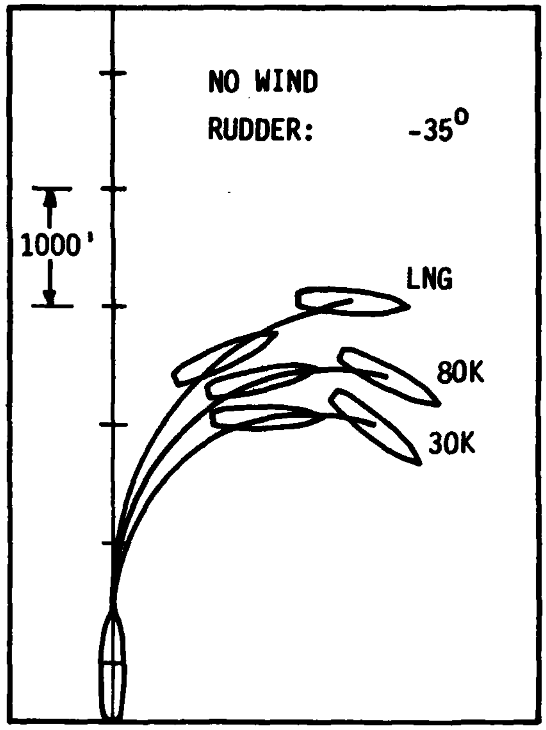


Figure 3-18. Ship Turn Rates, No Wind

What these factors might be is certainly a question of interest and could be adequately addressed in a future research project. This experiment was primarily structured to examine shiphandling performance and questions concerning wind stabilities vs. performance. However, some off-line computer simulations were run after the five analyses had been completed to pursue, if only on a preliminary basis, the question of the difficulties that the pilots had experienced controlling the LNG vessel. A summary of these findings are contained in Appendix B. They address the nature of the difficulties that the LNG pilots were confronted with while trying to turn into the wind. Figure 3-18 indicates the turning capability of the three vessels with no wind, full 35° rudder, and constant engine rpm. The rpm on each vessel was set at the value required for five knots of ship speed under constant straight course conditions. Figure 3-19 contains comparable curves for 65 knot starboard wind conditions with the indicated rudder angles applied and engine rpm for each vessel maintained at the level used for no wind. It can be seen that the tankers are capable of building up a positive turn rate (with starboard winds), and that the turn can be controlled by the amount of rudder applied. The LNG vessel, on the other hand, is seen to be incapable of turning into the wind, or at best has only an extremely small turning capability, even with the application of a maximum 35° of rudder. The LNG displayed an extremely high degree of directional stability under these wind conditions and there was little difference in turning capability between 0 and 35° of rudder. Therefore, the rudder for these conditions could be referred to as "saturated," i.e., having little effect. As indicated in Appendix B, this turning capability is considerably improved by the use of a kick turn, i.e., an increase of engine RPM for a short period to increase rudder

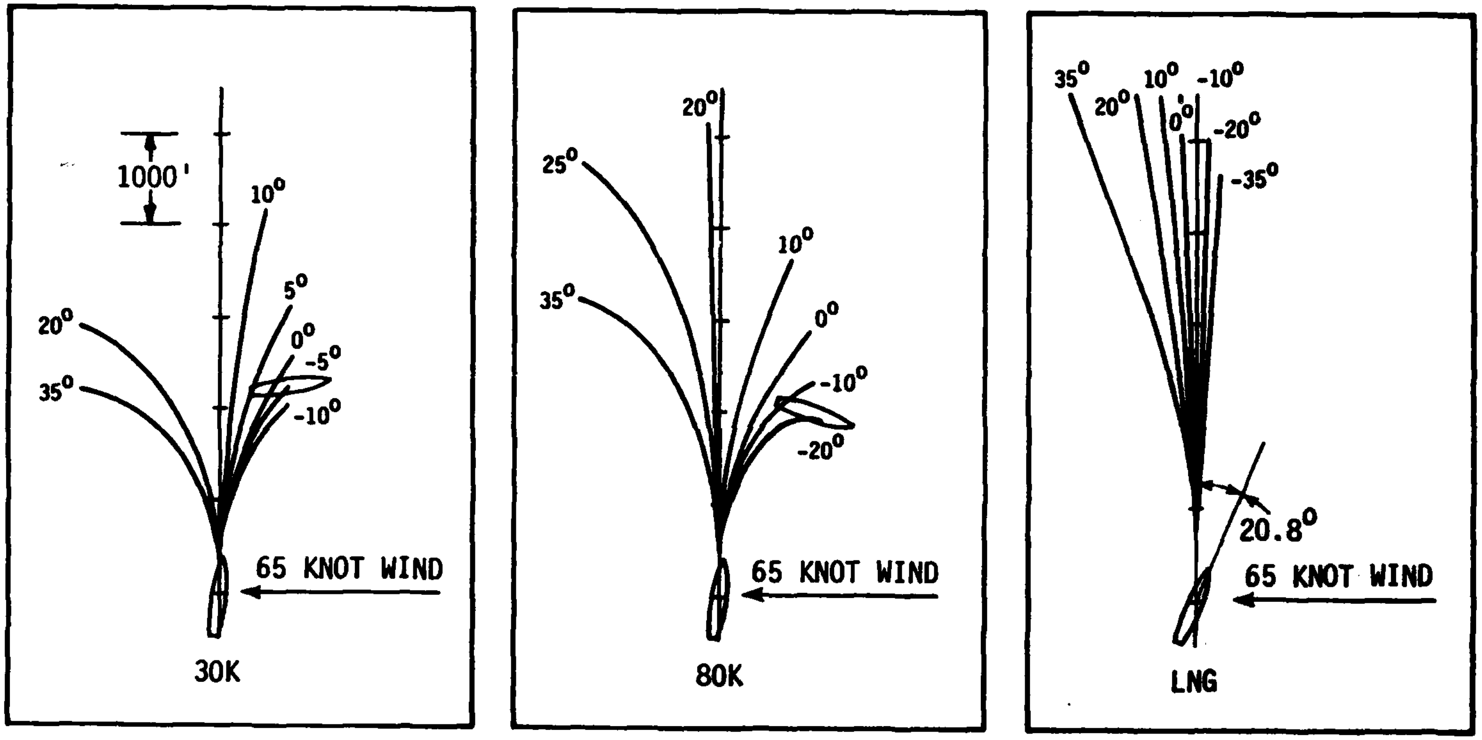


Figure 3-19. Ship Turn Rates, 65 Knot Wind

effectivity. The LNG pilots recognized this characteristic of their vessel and consistently made use of engine speed changes to regain control; that is, to turn the vessel to windward. "Kicking," so as to turn to windward, and the resultant increase in their ships' speed were major characteristics of the ship-handling procedures used by the LNG pilots. This explains to a large degree the reason that the average rudder angle did not change significantly as a function of wind magnitude in the analysis discussed in paragraph 3.2.1.6.1. The LNG pilots found that they were burdened with a "saturated" rudder and therefore relied mostly on kick turns, as well as increased speed, to control their ships.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

- The experiment clearly showed a marked difference in narrow channel ship-handling performance by pilots conning the LNG carriers as compared with those conning the tankers. Under some conditions of winds, banks, channel widths, etc., differences between the performances by pilots on the 80K tankers and 30K tankers were also in evidence. Overall, the pilots assigned to the LNG carriers exhibited the largest degree of control difficulties under the extreme wind conditions used in the experiment. When differences existed between performance on tankers, the mariners on the 80K tankers exhibited better controllability.

- The experimental design as well as the scenario itself were structured to impose high levels of stress on the men and the ships used in the experiment so as to discern more clearly differences in performance which might exist. As a consequence, numerous penetrations of the shoal area and channel boundaries occurred, and these became a sensitive measure of control difficulties encountered. The pilots on the LNG had a larger number of such incidents than did the tanker pilots, and there were more of these incidents occurring at higher winds then at the 40 knot condition. The 30K tanker pilots also had a greater number of incidents at the highest wind level, but still far fewer than the pilots conning the LNG carrier.

- Ship control difficulties did not correlate in a positive manner with inherent wind-based ship instabilities. The inference that the more unstable vessel would be more difficult to control was not borne out and, in fact, the reverse was found to be true. The LNG vessel was shown to have a lower level of wind induced instabilities, yet the pilots that conned that ship had the most difficulty with the channel passage. Tanker pilots were able to overcome their vessels' instabilities and transited the channel with less problems. It was apparent, therefore, that ship characteristics other than instability caused by high wind levels were more dominant in the determination of controllability.

- The LNG pilots found that their rudder was not effective under the wind conditions that they encountered. They were forced to increase engine rpm to counter the control problems that they were experiencing and, in an attempt to maintain control, increased the speed of their vessel through the water by more than 100% over the desired speed.

- Based on the sampling techniques and analyses that were used in this expeiment, estimations of probable LNG ship-handling performance by any experienced pilot indicate that it would be highly injudicious to make an actual passage in a 600 to 800 foot waterway without tug assistance under any of the wind conditions that were studied. This would especially be true if the vessels, for any reason, were unable to have their speed through the water increased to more than 10 knots.

- o The 80K tanker pilots made use of the channel banks as an aid during the passages through the narrow waterway. Transits through a channel with banks was safer (fewer boundary penetrations) than those passages which occurred in a channel that had no banks. The pilots also progressed through the banked channels at a slightly higher speed then when no banks were present.

- o The 600 foot channel width affected the LNG pilots to a greater degree than it did those who conned the tankers. The trend of decreased safety with increased wind levels that was observed for the 800 foot wide channel segment did not occur when the channel was only 600 feet wide. The LNG pilots perceived that the narrower channel would be more difficult/dangerous and substantially increased their ship's speed during that portion of the passage to acquire a greater degree of control over their vessel.

- o Prior experience with a very narrow channel did not surface as a significant factor in the performance exhibited in 800 and 600 foot wide channel segments. This finding was most probably caused by the structuring of the samples used in the mini-analysis of this particular issue since the "experience factor" was investigated as an afterthought, i.e., after the experiment had commenced. The question of specific types of experiences affecting performance in a narrow channel would benefit from a more thorough detailed investigation.

- o On most ships, including an LNG vessel, a positive rudder causes a turn to port. For certain particular wind directions and magnitudes, an anomoly occurs in the ship-handling characteristics of the LNG, resulting in a positive rudder causing a turn to starboard. The effects on performance of this "rudder reversal phenomenon" were studied during the experiment but the findings were inconclusive. The general difficulties that the LNG pilots faced with ship controllability overshadowed any "special effects" differences in ship handling that might exist. By increasing their speed in the "reverse rudder" portion of the channel the pilots attained much better control, thereby masking any difficulties that existed because of a lack of familiarity with this phenomenon. This question, related to "reverse rudder effects," would also benefit from more detailed future research.

- o Pilots were shown to be capable of overcoming the wind-based instabilities of their vessels, and therefore differences in performance in heavy winds were caused by other ship characteristics. An example of one such ship characteristic is the development of a turn rate. Analyses have shown that the LNG vessel exhibits an extremely limited capability for the development of a turn rate into the wind caused by exceptional levels of directional stability. Further research could address issues of which characteristics dominate the controllability problems for the LNG in winds and how shiphandling performance can be better managed in narrow waterways.

APPENDIX A

THE COMPUTER AIDED OPERATIONS RESEARCH FACILITY (CAORF)

A.1 DESCRIPTION OF CAORF

CAORF is the sophisticated ship-maneuvering simulator operated by the U.S. Maritime Administration for controlled research into man-ship-environment problems. Controlled experiments, which might require several vessels, cannot be performed readily in the real world and would certainly be ruled out for testing situations that involve potential danger. Such experiments can be performed safely and easily at CAORF. A simplified cutaway of the simulator building is shown in Figure A-1 and the relationships among the major subsystems are illustrated in Figure A-2.

All actions called for by the watch officer on the bridge are fed through a central computer that alters the visual scene and all bridge displays and repeaters in accordance with the calculated dynamic response of ownship and the environmental situation being simulated. CAORF has the capability of simulating any ship, port, or area in the world. The major subsystems are:

- **Wheelhouse,** which contains all equipment and controls needed by the test subject watch officer to maneuver ownship through a scenario, including propulsion and steering controls, navigational equipment and communication gear.

- **Central Data Processor,** which computes the motion of ownship in accordance with its known characteristics, models the behavior of all other traffic ships, and drives the appropriate bridge indicators.

- **Image Generator,** which constructs the computer-generated visual image of the surrounding environment and traffic ships that is projected onto a cylindrical screen for visual realism.

- **Radar Signal Generator,** which synthesizes video signals to stimulate the bridge radars and collision avoidance system for the display of traffic ships and surrounding environment.

- **Control Station,** from which the experiment is started and stopped, traffic ships and environment can be controlled, mechanical failures can be introduced, and external communications with ownship's bridge can be simulated.

- **Human Factors Monitoring Station,** from which unobtrusive observation and video recording of test subject behavior can be carried out by experimental psychologists.

A.2 SIMULATED BRIDGE

The simulated bridge consists of a wheelhouse 20 feet (6.1 m) wide and 14 feet (4.3 m) deep. The equipment on the CAORF bridge is similar to that normally available in the merchant fleet and responds with realistically duplicated time delays and accuracy. The arrangement is based on contemporary bridge design and includes the following equipment:

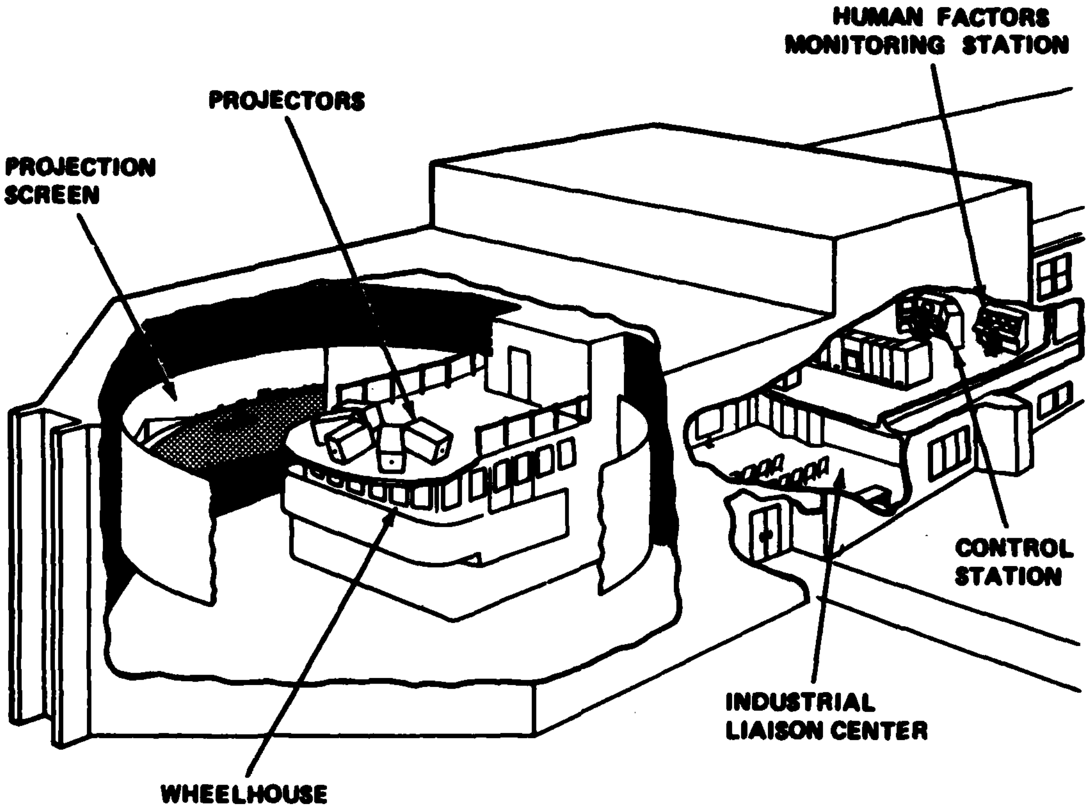


Figure A-1. Cutaway of CAORF Building

- **Steering Controls And Displays** - a gyropilot helm unit with standard steering modes, rate of turn indicator, rudder angle/rudder order indicators, and gyro repeaters.

- **Propulsion Controls and Displays** - an engine control panel (capable of simulating control from either bridge or engine room) containing a combined engine order telegraph/throttle, an rpm indicator and a switch for selecting the operating mode, such as finished with engine, warm up, maneuvering and sea speed.

- **Thruster Controls and Displays** - bow and stern thrusters and their respective indicators and status lights.

- **Navigation Systems** - two radars capable of both relative and true motion presentations, plus a collision avoidance system. Capability exists for future additions such as a digital fathometer, Radio Direction Finder, and Loran C and Omega systems.

- **Communications** - simulated VHF/SSB radio, docking loudspeaker (talkback) system, sound powered phones and ship's whistle.

- **Wind Indicators** - indicate to the bridge crew the true speed and direction of simulated wind.

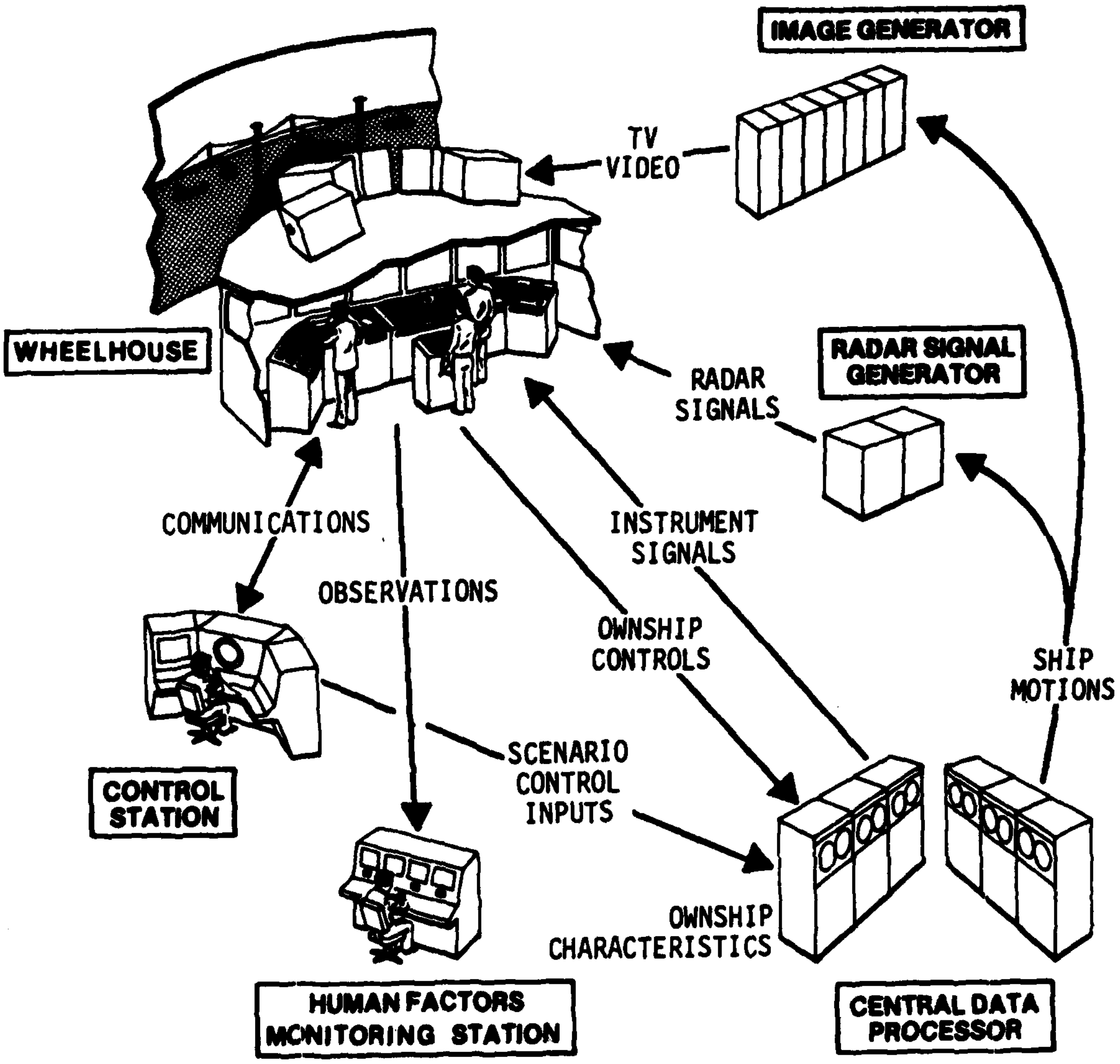


Figure A-2. Major CAORF Subsystems

A.3 OWNSHIP SIMULATION

Any ship can be simulated at CAORF. The computerized equations of motion are adapted to the ship by changing specific coefficients, among which are hydrodynamic, inertial, propulsion, thruster, rudder, aerodynamic, etc. Wind and currents realistically affect ship motion according to draft (loaded or ballasted) and relative speed and direction. Ownship's computer model was validated by comparing various simulated maneuvers (e.g., zig-zag, turning circle, spiral, crash stop, and acceleration tests) with sea trail data.

A.4 IMAGE GENERATION

The visual scene is generated at CAORF to a degree of realism sufficient for valid simulation. The scene (Figure A-3) includes all the man-made structures and natural components of the surrounding scene that mariners familiar with the geographical area deem necessary as cues for navigation.

Thus, bridges, buoys, lighthouses, tall buildings, mountains, glaciers, piers, coastlines, and islands would be depicted in the scene. In addition, the closest traffic ships and the forebody of

Figure A-3. Typical Simulated Visual Scene at CAORF ownship appear. All elements in the scene appear to move in response to ownship's maneuvers. The sky is depicted without clouds and the water without waves.

For enhanced realism the scene is projected in full color. The perspective is set for the actual bridge height above waterline for the simulated ship. Shadowing can be varied according to the position of the sun at different times of day.

Environmental conditions also affect the scene. The lighting can be varied continuously from full sun to moonless night. At night, lights can be seen on traffic vessels, buoys, piers, and other points ashore. Visibility in the day or night can be reduced to simulate any degree of fog or haze.

A.5 RADAR SIGNAL GENERATION

The Radar Signal Generator produces real-time video signals for driving the two radar PPIs. The items displayed are synchronized with the visual scene and include navigation aids, ships, shorelines and other topographical features with appropriate target shadowing, clutter, range attenuation, and receiver noise. The radar gaming area, which covers an area of 150 by 200 miles, extends beyond the visual gaming area, which is 50 by 100 miles. Within the radar gaming area, as many as 40 moving traffic ships can be displayed. The radar signal generator also drives the collision avoidance system, which can be slaved to either of the master PPIs.

A.6 CONTROL STATION

The Control Station (Figure A-4) is the central location from which the simulator experiment is controlled and monitored. An experiment can be initiated anywhere within the visual gaming area with any ship traffic configuration. The Control Station enables the researchers to interface with the watchstanding crew on the bridge, to simulate malfunctions, and to control the operating mode of the simulator. The Control Station is also capable of controlling motions of traffic ships and tugs in the gaming area and simulating telephone, intercom, radio (VHF, SSB) and whistle contact with the CAORF bridge crew.

A.7 HUMAN FACTORS MONITORING STATION

The Human Factors Monitoring Station (Figure A-5) is designed to allow collection of data on crew behavior. Monitoring data is provided by five closed-circuit TV cameras and four microphones strategically located throughout the wheelhouse to record all activities, comments and commands.

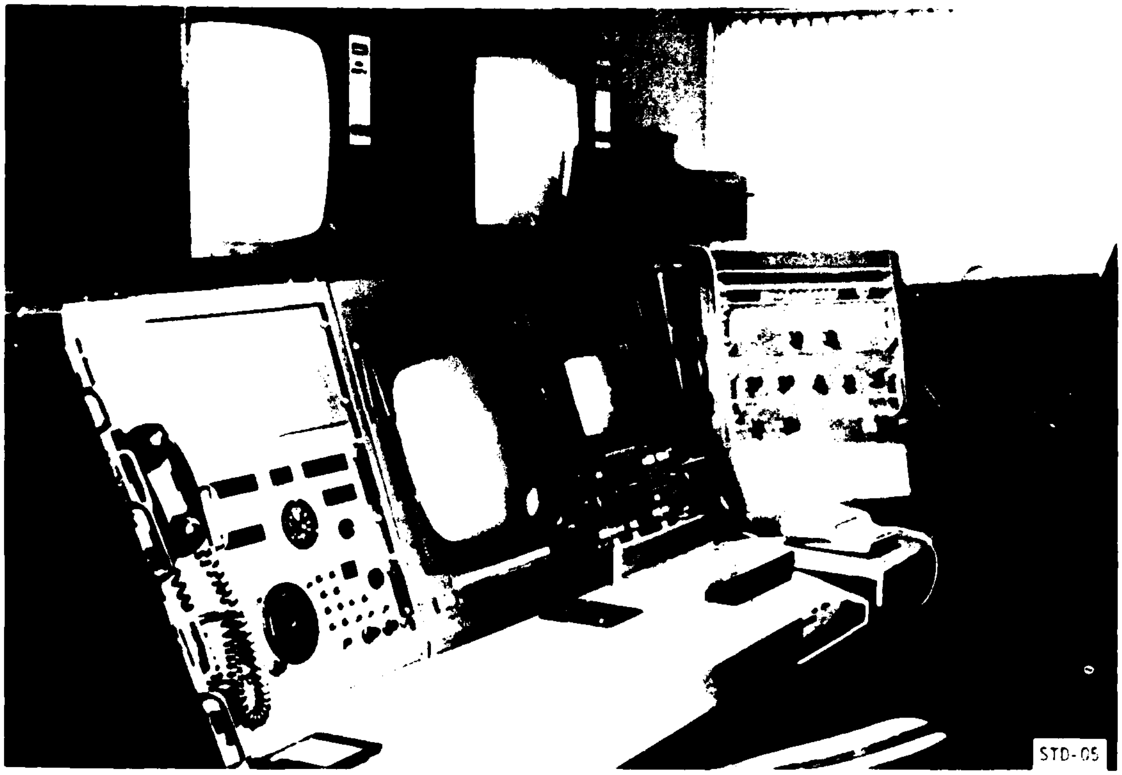


Figure A-4. Control Station

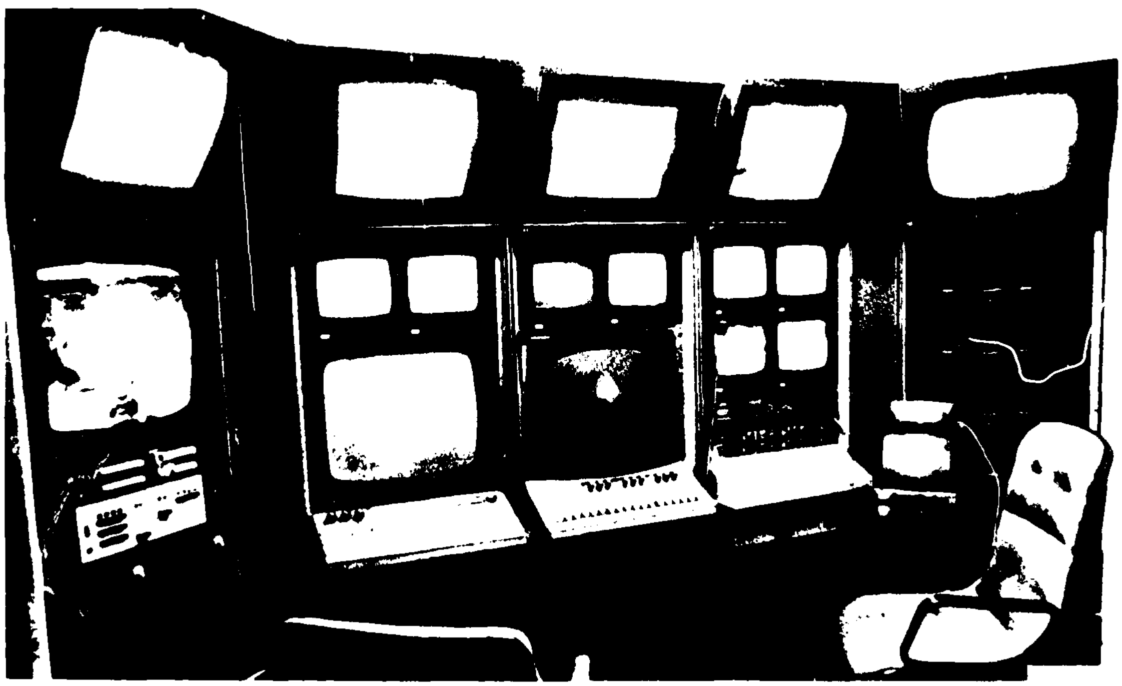


Figure A-5. Human Factors Monitoring Station

APPENDIX B

EFFECT OF WIND ON SHIP CONTROLLABILITY, STABILITY AND MANEUVERABILITY

The CAORF on-line Simulator is presently investigating pilot controllability and ship maneuverability for several classes of ships passing through restricted waterways. These studies are designed to investigate the difficulties encountered by experienced pilots while conning different classes of ships through a narrow channel. The pilot's task is normally complicated with the presence of disturbances due to changes in the local winds and tides and is further burdened with changing hydrodynamic effects due to variations in depth/draft ratio and bank effects throughout the passage. The on-line study presents the pilots with a single 45° turn channel which must be transited at a moderately low ship speed of five knots, under wind conditions which reach the level of 65 knots. At these severe wind magnitudes different vessels exhibit differential levels of wind-based inherent ship instabilities, and the study is designed to investigate the manner in which pilots can adjust to these difficulties during their channel passages. Since a complete stability analysis was not available for the CAORF ship models considered for these studies it was requested that Grumman Research augment the off-line Optimal Ship Maneuvering Program to determine ship stability (or instability) for given wind strengths and directions.

The maneuvering program was extended with additional subroutines to evaluate the stability eigenvalues associated with the perturbation equations which arise from linearizing the non-linear ship dynamics about the equilibrium cruise condition. The approach is similar to that used by Eda(1) in 1968 to analyze the low speed controllability of the Mariner-class vessel in wind. Eda investigated the stability of these ships for both the unsteered and the automatically steered modes of operation. His findings are summarized in Figure B-1 where the real part of the dominate eigenvalues are plotted for various wind conditions. He concludes that "Comparison of the figures shows the great improvement in stability in wind can be achieved by the introduction of a control system (or an experienced helmsman)."

Wind stability was examined for two different CAORF tankers and one liquidfied natural gas ship. Table B-1 indicates the ship type, tonnage, and wind conditions studied.

Additional subroutines were included to determine the trim conditions for the rudder angle, sideslip angle, and propeller RPM required to maintain a straight track when ship speed, course, and wind speed and direction are given.

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(1) Eda, H., Low Speed Controllability of Ships in Wind, Journal of Ship Research, Sept. 1968, p. 181-200.

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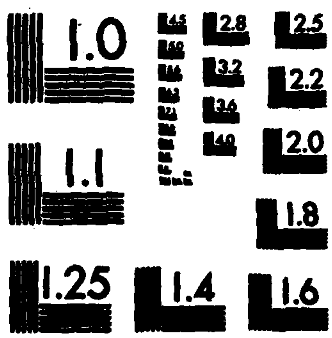

MICROCOPY RESOLUTION TEST CHART
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TABLE B-1 CONDITIONS STUDIED

Ship Type	Ship	Wind/Ship Speed Ratio
Tanker	30,000 DWT	5, 8, 10, 13
Tanker	80,000 DWT	5, 8, 10, 13
LNG	125,000 m^3	5, 8, 10, 13

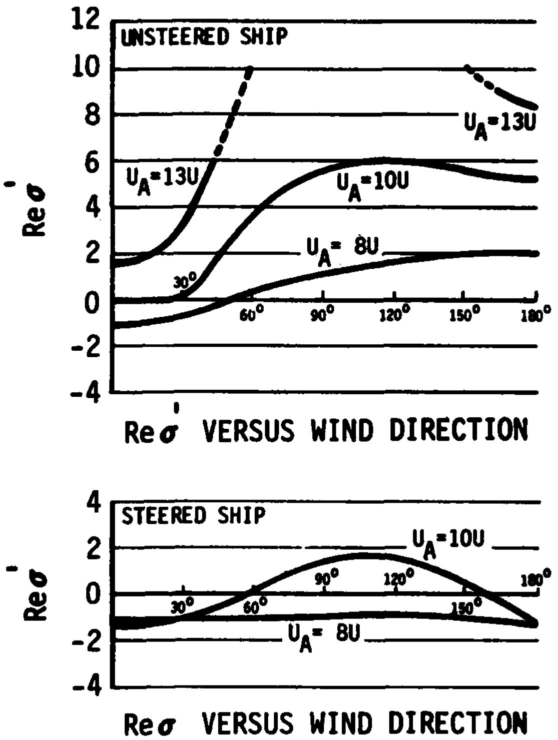

Figure B-1 Stability Analysis of Mariner-Class Vessels by Eda

The salient features of the results of this investigation for the three ships are given in Figures B-2 through B-11. Summarized are the equilibrium rudder angles and the eigenvalues (real part only) of the perturbation equations indicative of the degree of stability for an unsteered ship.

30,000 DWT Tanker

The equilibrium or trim value of the rudder angle is given in Figure B-2 for various relative wind strengths and directions. For this ship very little trim rudder is required for winds from the bow ($\psi_A \leq 60^\circ$); note that only 4° of port rudder is needed to balance a strong wind (U_A = 13U) at $\psi_A = 60^\circ$. This figure summarizes the common ship characteristic which requires increasing trim angles for beam winds of increasing strength and only minor rudder angles for winds from the bow or stern. For the moderate wind of U_A = 8U blowing from the stern quarter (ψ_A = 125° -165°) the curve is shown dotted to indicate wind conditions for which the wind/ship speed ratio cannot be maintained at eight with a positive value of propeller rpm (N), that is, trim or equilibrium can only be attained with reverse propeller rpm. Another common handling characteristic is the loss of ship controllability which occurs when the trim value for the rudder reaches its maximum deflection. This usually occurs for strong winds from the beam which create significant lateral forces and cause sideslip and a resulting hydrodynamic moment which can only be counteracted with large rudder deflections.

This tanker would lose controllability if operated in wind/ship speed ratios of 12 or greater and with wind direction of 110° or more. To regain control of the ship if these wind conditions were ever encountered, the helmsman would either have to increase propeller rpm and thereby reduce the wind/ship speed ratio or he would have to steer another course direction resulting in a more favorable relative wind direction.

The equilibrium subroutine determines the trim values for the rudder angle, the sideslip and the propeller rpm for prescribed values of ship speed and heading, and wind speed and direction. Therefore, in addition to the trim rudder angles given in Figure B-2 similar plots are available for trim values of sideslip angle and propeller rpm.

Associated with the controllability of a ship is its longitudinal directional stability or its ability to maintain a given course when wind perturbations cause the ship to deviate from the equilibrium conditions. To analyze directional stability, subroutines were developed to evaluate the eigenvalues of the perturbation equations which result from linearizing the non-linear ship dynamics. It should be recognized that the perturbation analysis is valid for only small disturbances away from the equilibrium conditions. The nature of the solution to the perturbation equations can be determined by plotting the eigenvalues on a root locus plot for variations in wind speed and direction. These plots indicate whether the responses are stable or unstable, and provide data on frequency of oscillation and the time constants or damping coefficients from the real and imaginary parts of the eigenvalue. To investigate the question of stability it is only necessary to know the sign of the real parts of the roots. Therefore the same convention as Dr. Eda's of plotting only the real part of the critical eigenvalue for variations in wind is used. It is evident from Figure B-3 that the unsteered ship is stable for all winds from the bow quarter (ψ_A = 0° -75°) and exhibits a damped oscillatory response to a wind disturbance due to the negative real part of the eigenvalues and the fact that it is indicatedas a complex root. For winds from the beam (ψ_A = 75° -120°) the ship exhibits an unstable response for changes in wind

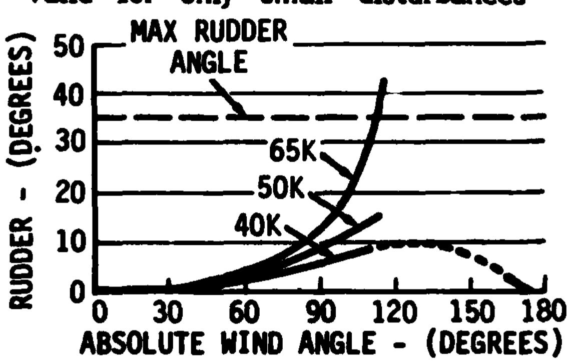

Figure B-2 ***Equilibrium Rudder Angles Versus Wind and Direction for 30,000 DWT Tanker***

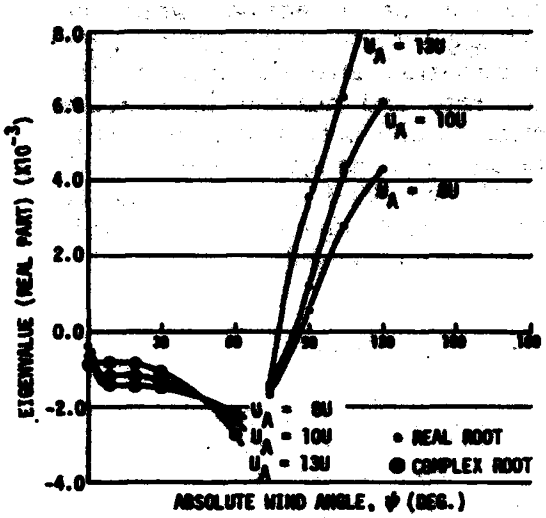

Figure B-3 ***Eigenvalue (Real Part) Versus Wind Speed and Direction for 30,000 DWT Tanker*** strength or direction when no steering action is taken, that is, the perturbation analysis predicts the yaw rate and heading to increase exponentially unbounded. In reality the ship will change its heading until a relative wind angle is reached (bow or stern) which causes a stable response for the ship.

80,000 DWT Tanker

Figure B-4 indicates that the rudder trim required for wind disturbances by the 80,000 DWT tanker has the same general character as that for the 30,000 DWT tanker (Figure B-2). There is a quantitative difference though; the 80,000 DWT tanker requires about twice the rudder angle to trim for the same wind condition. Again for moderate winds (U_A = 8U) from the stern quarter, reverse propeller rpm is required to maintain the wind/ship speed ratio. Rudder saturation accompanied with a loss of controllability occurs for strong winds (U_A = 13U) at a beam wind direction of 100°.

Unlike the 30,000 DWT tanker, the 80,000 DWT tanker is directionally unstable for winds directly from the

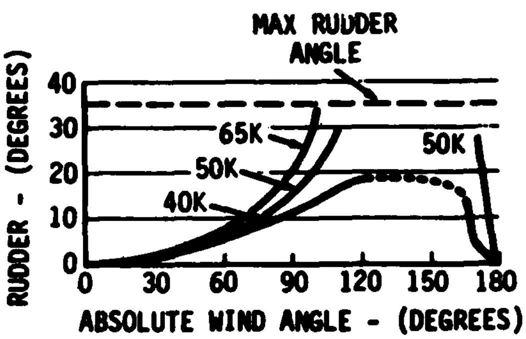

Figure B-4 ***Equilibrium Rudder Versus Wind Speed and Direction for 80,000 DWT Tanker***

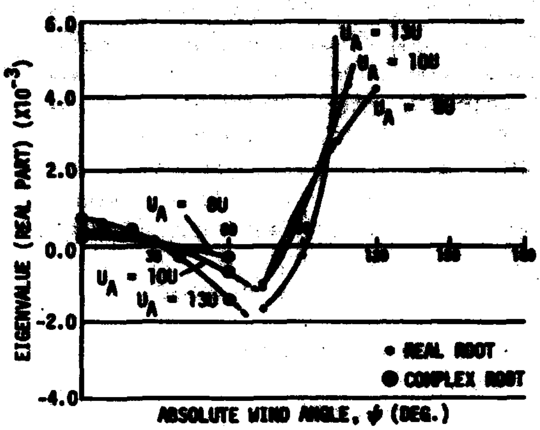

Figure B-5 ***Eigenvalue (Real Part) Versus Wind Speed and Direction for 80,000 DWT Tanker***

bow (0° - 30°) as shown in Figure B-5. For small perturbations from trim, the yaw rate for the ship would oscillate with ever increasing amplitude if no action were taken by the helmsman. The ship becomes stable for winds from the bow quarter (ψ_A = 30° - 80°) and exhibits the characteristic of improved stability for greater wind strength in this region. For winds from the beam (ψ_A = 80° - 120°), the ship is unstable and responds with an exponentially increasing yaw rate.

To verify the stability of these ships predicted by the perturbation analysis, trajectories were generated with the Ship Maneuvering Program using the non-linear dynamic equations. In particular, for the 80,000 DWT tanker three wind conditions were considered; strong winds (U_A = 13U) blowing from the (absolute) directions of 10°, 60° and 120°. Figure B-5 predicts an unstable, stable, and an unstableresponse for these wind conditions. For the simulations the ship was initialized with the necessary trim values for rudder angle and propeller rpm. The required sideslip angles to maintain the ship on a 0° course-made-good are .75°, 5.5°, and 2°, respectively. To provide a perturbation from the wind equilibrium conditions the ship was initialized with 0° sideslip rather than the above trim values. The time histories for the ship's heading for the three wind conditions are shown in Figure B-6 where the nature of the solution is of the form predicted by the analysis. With the wind from the bow (ψ_A -10°) the heading is an unstable increasing oscillatory response; for a wind from the bow quarter (ψ_A = 60°) the response is a stable damped oscillatory motion; and for a wind from the beam the heading increases in an exponentially unstable manner.

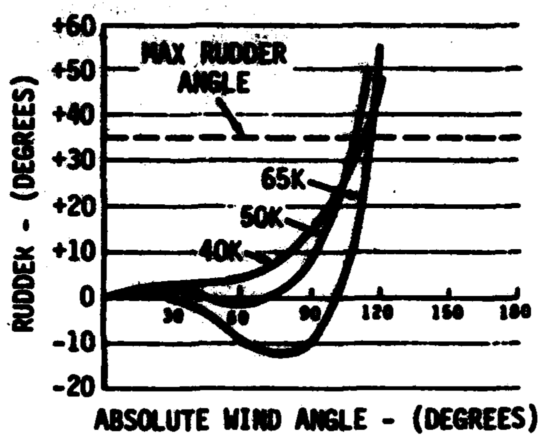

Figure B-7 Equilibrium Rudder Angles Versus Wind Speed and Direction for LNG Carrier

LNG 125,000 m³ Carrier

This ship has very different aerodynamic characteristics compared to either the 30,000 DWT tanker with a central wheelhouse or the 80,000 DWT tanker with a stern wheelhouse design. The LNG has large tanks which rise well above deck level and present a large sail area over its entire length resembling a lightly loaded tanker or ocean liner.

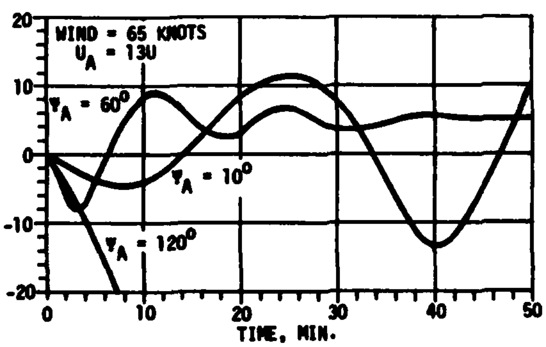

Figure B-6 80,000 DWT Tanker Yaw Response Induced by Small Perturbations

These differences are immediately evident from the trim rudder angles required for various wind conditions shown in Figure B-7. For light winds ($U_A \leq 5U$) the rudder angles are similar to those for the tankers, but for moderate-to-strong winds ($U_A \geq 5U$) from the beam the characteristics vary dramatically. For wind/ship speed ratios greater than 10 the LNG requires a reversed rudder angle, that is, for U_A = 13U and ψ_A = 90° the rudder must be held at 10° starboard to maintain trim. In comparison, for the same wind condition the 30,000 DWT tanker requires a 10° port rudder while the 80,000 DWT tanker needs 20° port rudder for equilibrium. These rudder reversals could cause control problems for inexperienced pilots assigned to the LNG.

The LNG is more unstable than the 80,000 DWT tanker for all winds from the bow, as illustrated in Figure B-8. That is, the magnitude of the real part of the dominate eigenvalue is three to four times that for the 80,000 DWT tanker indicating a corresponding change in the time constant associated with the exponential divergence. In contrast, the LNG exhibits greater stability for all wind strengths from the beam direction (ψ_A = 60° - 120°). The ship becomes unstable and uncontrollable for winds from the stern quarter. In particular, for low wind/ship speed ratios ($U_A \leq 5U$) the ship has unstable eigenvalues as shown. In addition, for higher wind speed ($U_A \geq 8U$) the LNG is not only unstable but is uncontrollable with only rudder control since the maximum rudder angle constraint is violated for these wind conditions.

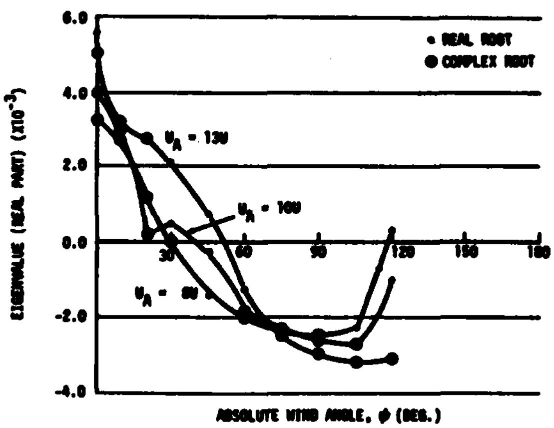

Figure B-8 Eigenvalue (Real Part) Versus Wind Speed and Direction for LNG Carrier

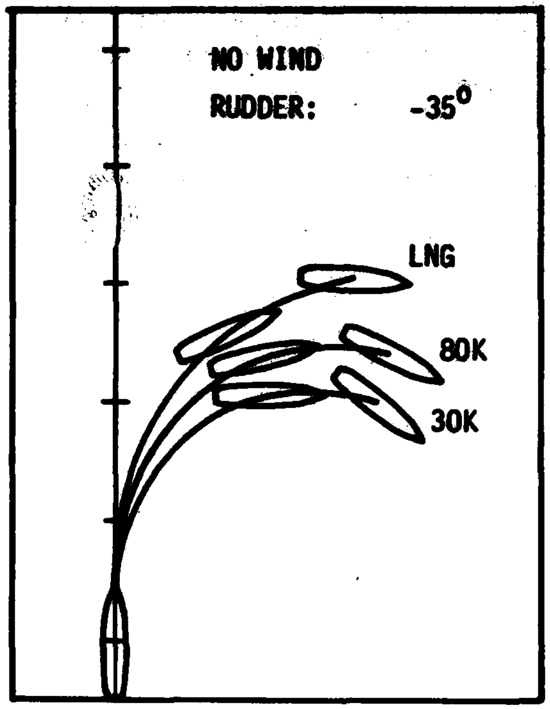

Figure B-9 Turning Circles for Maximum Starboard Rudder

Ship Maneuverability

Because the pilots operating the LNG on the CAORF Simulator commented on the ship's poor handling characteristics in strong winds, a study was made using the off-line simulation code to verify these responses. The response of the three ships to hard over rudder command without wind were studied first. Then the ability of the ships to turn from a wind equilibrium condition (strong winds from the beam) was investigated. Finally the use of a kick rudder maneuver was simulated for the LNG.

The turning circles or maneuvering capabilities for the three ships using maximum starboard rudder (δ = -35°) are shown in Figure B-9. The 10-minute simulated trajectories were generated without wind and show that the 30,000 DWT tanker can maneuver inside the 80,000 DWT tanker which can, in turn, outmaneuver the LNG.

Even though the LNG has the largest turn radius it still has a respectful maneuvering capability for the no-wind situation.

For strong winds from the beam the maneuverability of the LNG is dramatically reduced. The trim or equilibrium conditions for the ships given in Table B-2 were determined for a wind/ship speed ratio of 13 and with the wind blowing from an absolute direction of 90°. The table illustrates the rudder reversal required by the LNG for this wind condition and shows the excessive sideslip angle (20.8°) needed for trim.

All three ships were initialized with the above trim conditions, then variations over the entire range of possible rudder commands ($-35° \leq \delta \leq 35°$) were used to simulate their range of maneuverability. As seen in Figure B-10 both the 30,000 DWT and 80,000 DWT tankers have no problem maneuvering either into or away from the wind with even moderate levels of rudder command. In comparison, the LNG has extremely little capability to "come up into the wind" and only limited ability to even turn away.

Therefore, pilots are expected to have severe handling problems when maneuvering the LNG in strong winds with only rudder commands. This situation led to investigating the potential of using a kick rudder command to improve the LNG maneuverability. A series of kick rudder maneuvers were executed starting from the trimmed conditions for the beam wind given in Table B-1. At the point of control initiation the rudder was commanded to hard over starboard ($\delta = -35°$) while the propeller revolutions were increased above the trim value thereby improving the rudder effectiveness. The improved LNG maneuverability using kick rudder is shown in Figure B-11 for various levels of propeller rpm and in particular for N = 70 rpm

TABLE B-2 TRIM CONDITIONS

Ship Type	Rudder Angle (deg.)	Sideslip Angle (deg.)	Propeller Revolutions N (rpm)
30,000 DWT Tanker	11.9	6.8	55.7
80,000 DWT Tanker	19.5	7.6	58.5
LNG 125,000 m^3 Carrier	-10.4	20.8	44.9

U_A = 65 knots, U_o = 5 knots
ψ_A = 90°, Course-Made-Good = 0°

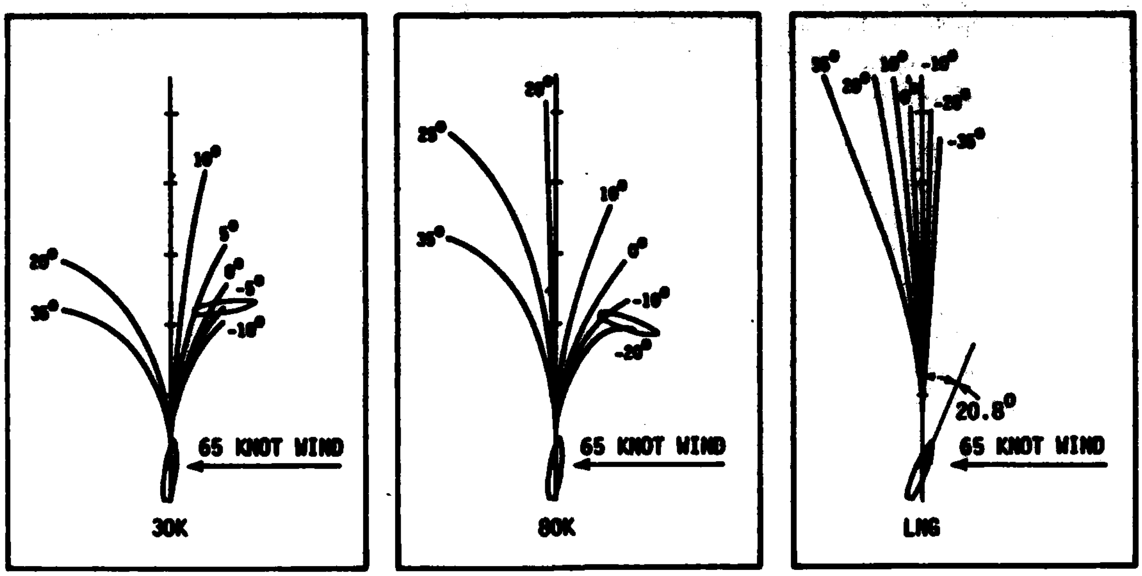

Figure B-10 Maneuver Capability Initiated from a Beam Wind Condition

the kick rudder affords the LNG comparable turning performance to the no-wind case of Figure B-9.

In conclusion, it has been shown that the LNG is less maneuverale than the 80,000 DWT tanker which in turn is worse than the 30,000 DWT tanker for no-wind situations. When the LNG is operated in strong winds from the beam it exhibits extremely limited turning capability for rud der-only commands and must rely on a kick rudder maneuver. This maneuver ultimately reduces the wind/ship speed ratio which in itself increases the LNG's turning performance.

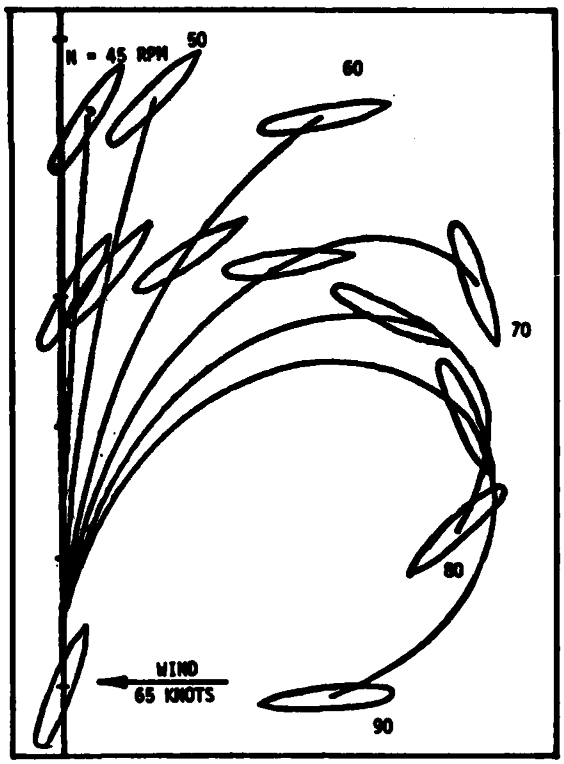

Figure B-11 LNG Carrier Maneuvering Capability Initiated from a Beam Wind Using Kick Rudder

APPENDIX C

EXPERIMENT DESIGN AND STATISTICAL ANALYSIS

The experiment design was structured around three principal independent variables:

A) Ship Type
   1) 125,000 m^3 LNG carrier
   2) 80,000 DWT tanker
   3) 30,000 DWT tanker

B) Wind Ratio
   1) 8:1
   2) 10:1
   3) 13:1

C) Wind Side
   1) Port
   2) Starboard

These variables were combined in a completely factorial, mixed design arrangement (Table C-1). In the mixed design model S_{18} (A_3) B_3 C_2 each of the 18 subjects was observed under only one of the three levels of the between-groups variable A (Ship Type) and under each of the six conditions of variables B (Wind Ratio) and C (Wind Side). A total of 108 runs comprised the main experiment.

The run order matrix is shown in Table C-2. The sequence for testing Ship Type was an alternating one as indicated under the Subject Run Order column; within each level of Ship Type, the order for testing Wind Ratio is counter-balanced with Wind Side alternating on each successive run.

Two supplemental, sub-experiments were conducted as part of the overall investigation. In the first, Ship Type was constant, utilizing only the 80,000 DWT tanker, while Bank Effects (Variable F), Wind Ratio (Variable B) and Wind Side (Variable C) were experimental variables. The experimental design for this study is shown in Table C-3 as a three-factor mixed design with Bank Effects as the between-groups variable and with Wind Ratio and Wind Side as within-subjects variables. Seventy-two runs comprised this sub-experiment with half in each bank effect condition. No attempt was made to counterbalance the bank effects factor since the six subjects participating in the no-banks condition were run in an unstructured random manner.

In the second sub-experiment, Pilot Experience Group (Variable E), Wind Ratio (Variable B) and Wind Side (Variable C) were experimental variables while Ship Type was equally represented for both Experience Groups and, therefore, not treated as an experimental variable. The experiment design for this study is shown in Table C-4 as a three factor mixed design with Pilot Experience Group as the between-groups factor and with Wind Ratio and Wind Side as within-subjects variables. Since this sub-experiment used data from the main experiment no additional counterbalancing of run sequence was necessary.

Data Analyses

Throughout this section frequent reference is made to the "probability" or "level of significance" associated with specific results of statistical analyses. The reported probability value (p) represents the likelihood that results as large or larger than those obtained in the experiment data could be due to random or chance factors outside the scope of the investigation. For example, if one were comparing two sample statistics, e.g., means, and reported that the means differed significantly from one another at the $p \leq 0.05$ level of significance, there is a probability of no greater than 0.05 that the observed difference was due to chance variation. Therefore, there is a 0.95 probability that the difference observed in the sample reflects a difference attributable to some systematic influence, i.e., a factor systematically manipulated in the experiment. Such differences are referred to as "statistically significant."

Data analyses of the performance measures that are discussed in this report utilized the analysis of variance (ANOVA) technique.

Five different ANOVA models were used for data analyses purposes in this investigation:

1. The ANOVA model outlined in Table C-5 enabled significance determinations for effects of Ship Type (Variable A), Wind Ratio (Variable B), Wind Side (Variable C), and all possible interactions of these factors. These are the primary variables examined in the study and, therefore, this can be considered the "Main Analyses".

2. The ANOVA model outlined in Table C-6 enabled significance determinations for Bank Effects (Variable F), Wind Ratio (Variable B), Wind Side (Variable C), and all possible interactions of these factors. There is redundancy in this ANOVA model and the "Main Analyses" for the Wind Ratio and Wind Side factors.

   The Bank Effects factor and its interactions are the primary concern of the analysis and it is referred to as the "Bank-No Bank Analyses."

3. A comparison of ship control performance in two sections of the test channel, Sections 1 and 5, form the basis of the "Channel Width Analyses". The ANOVA model used in this analysis (Table C-7) enabled significance determinations for Channel Width (Variable D) and all possible interactions of this factor with Ship Type (Variable A), Wind Ratio (Variable B) and Wind Side (Variable C).

4. A comparison was conducted to evaluate "Pilot Experience Group" (Variable E) and its interactive effects with Wind Ratio (Variable B) and Wind Side (Variable C). The ANOVA model used for this analysis is outlined in Table C-8.

5. The final ANOVA model used in this investigation is outlined in Table C-9. It enabled a direct comparison to be drawn between ship control performance in two test channel sections, Sections 2 and 8, constituting a "Rudder Effect Analyses," as well as tests of the interactive effects of this factor with Ship Type (Variable A), Wind Ratio (Variable B) and Wind Side (Variable C).

Performance Measures

Seven performance measures were assessed via the Analysis of Variance in this experiment:

1) Absolute Magnitude Off-Track

deviation
2) "Factored" Off-Track Deviation
3) Consistency
4) Boundary Penetrations
5) Ship Speed
6) Rudder Angle
7) Zero Rudder Crossings

In all cases the measures were computed across either five sections of the test channel (Legs 1-5) excluding the turn and transition areas, or across the five legs including the turn area. This is duly noted in the tabular presentation of the data analyses. Two of the seven performance measures, Boundary Penetrations and Zero Rudder Crossings were transformed using a square root transformation ($x^1 = \sqrt{X} + \sqrt{X+1}$) and a logarithmic Transformation (X^1 = Log X + Log X + 1), respectively, prior to application of the Analysis of Variance. These transformations were chosen based on observed relationships between treatment condition means and variances within these measures; tabular presentation of both measures is, however, in non-transformed form, in the interest of clarity of interpretation.

"Main" Analyses

An ANOVA was performed for each of the seven performance measures using the "Main" analyses model (Table C-5). The results of these analyses are presented in Tables C-10 through C-16. A three-way interaction between the treatment conditions, Ship Type (A), Wind Ratio (B), and Wind Side (C) is the highest order interaction possible in the analysis model. The analyses revealed significant three-way interactions for five of the performance measures, therefore, all other significant effects for these measures must be assessed in the context of the three-way interactions. For the two performance measures not indicating a significant three-way interaction (Rudder Angle and Zero Rudder Crossings), the interpretation of the lower order interactions and main effects is less complex.

For each of the seven performance measures mean values are presented for each of the three main effects, Ship Type (Table C-17), Wind Ratio (Table C-18), and Wind Side (Table C-19). The main effects from the analyses of variance as well as the comparisons among means are noted as to their level of significance (e.g., 0.05, 0.01), or non-significance (ns).

Interaction effects are illustrated by presenting peformance measure means for all possible combinations of treatment levels. In each are the interaction significance level as presented as well as significance values for all comparisons (simple main effects) within each interaction.

Absolute Magnitude Off-Track Deviation - The ANOVA performed on this performance measure (Table C-10) revealed significant main effects for each treatment variable and a significant three-way interaction among the three treatment variables. The main effects must therefore be interpreted in the context of this interaction. Table C-20 presents the analysis of the simple main effects in the interaction.

The absolute magnitude off-track deviation was largest for the LNG carrier as compared to the tankers (which did not differ from one another) in all cases except the 13:1 wind ratio/port side. Differences between the three wind ratios occurred only in three instances: for the LNG carrier in both port and starboard winds, and for the 30,000 DWT tanker in only the port wind. Differences between the port and starboard winds were observed for the LNG carrier in the 10:1 wind ratio, the 80,000 DWT tanker for the 8:1 wind ratio and the 30,000 DWT tanker for both the 10:1 and 13:1 wind ratios.

"Factored" Off-Track Deviation -The ANOVA performed on this performance (Table C-11) revealed significant main effects for each of the three treatment variables, significant two-way interactions for Ship Type by Wind Ratio (Table C-21) and Wind Ratio by Wind Side (Table C-22). The presence of a significant three-way interaction (Table C-23) precludes independent discussion of the main effects and the lower order two-way interactions, all of which are contained in the three-way interaction.

As with Absolute Magnitude Off-Track Deviation, "Factored" Off-Track Deviation was larger for the LNG carrier than for the tankers in all treatment conditions. The tankers did not differ from one another except in the 13:1 port side wind ratio. Differences between the three wind ratios were observed only for the LNG carrier and the 30,000 DWT tanker and a wind side difference was observed only for the LNG carrier in the 10:1 wind ratio.

Consistency - The ANOVA performed on the Consistency Measure (Table C-12) revealed significant main effects for the Ship Type and Wind Ratio variables and significant interactions for Ship Type by Wind Ratio (Table C-24), Wind Ratio by Wind Side (Table C-25), and Ship Type by Wind Ratio by Wind Side (Table C-26).

Detailed analysis of the three-way interaction (Table C-26) indicates a greater degree of inconsistency in the LNG carrier performance than in the tanker performance under all conditions. The 30,000 DWT tanker showed some indication of greater inconsistency compared to the 80,000 DWT tanker in the conditions of 13:1 wind ratio and 10:1 port wind ratio. Differences in consistency between wind ratio conditions is evident primarily for the LNG carrier and in the port wind for the 30,000 DWT tanker. A difference between the port and starboard wind is indicated only for the LNG carrier in the 10:1 wind ratio.

Boundary Penetrations - The ANOVA performed on this performance measure revealed significant main effects for each treatment variable and a significant three-way interaction among these variables (Table C-13).

The analysis of the three-way interaction (Table C-27) revealed findings almost identical to those for the Consistency Measure. A greater number of boundary penetrations occurred for the LNG carrier as compared to the tankers in all conditions of the experiment. Differences in this measure due to wind ratio variations occurred primarily in the LNG carrier and to a lesser extent in the 30,000 DWT tanker. Differences due to wind side variation also were limited to these ships.

Ship Speed - The ANOVA performed on Ship Speed revealed that each main effect and each interaction was significant (Tables C-14, C-28, C-29, C-30). In this case the description of the three-way interaction subsumes all others.

The analysis of the three-way interaction (Table C-31) indicates that speed was greater for the LNG carrier than either of the tankers in all experiment conditions. Wind ratio influences on speed occurred primarily for the LNG carrier as was also the case for wind side influences. Increases in wind ratio caused increases in the LNG carrier speed.

Rudder Angle - The ANOVA performed on Rudder Angle indicated significant main effects for the three treatment variables, Ship Type, Wind Ratio, and Wind Side; also a significant Ship Type by Wind Ratio interaction (Table C-15).

The main effect for wind side indicates that greater mean rudder angle was employed in the port wind than in the starboard wind. The other main effects must be interpreted in the context of the Ship Type by Wind Ratio interaction (Table C-32). Rudder angle differed generally among the three ship types with greatest mean angle used for the 80,000 DWT tanker and least for the 30,000 DWT tanker. An exception to this trend is evident for the 8:1 wind ratio condition in which the greatest mean rudder angle was used for the LNG carrier. As wind ratio increased greater rudder angle was employed but only for the 30,000 DWT and 80,000 DWT tankers.

Zero Rudder Crossing - The ANOVA performed on this measure indicated that only the Wind Ratio main effect was significant (Table C-16) with a greater number of zero rudder crossings evident for the 13:1 wind ratio as compared to the other two wind ratios.

Bank Effects Analyses

An ANOVA was performed for each of the seven performance measures using the "Bank/No-Bank" analyses model (Table C-6). The results of these analyses are presented in Tables C-33 through C-39. The Bank Effects variable (F) and its interactions with the Wind Ratio (B) and Wind Side (C) variables are the primary concern of the analysis, therefore, description of the results will focus on these factors.

For each of the seven performance measures, mean values are presented for the Bank Effects variable in Table C-40. Bank effect influences and interactions involving the Bank Effects variable were found to be non-significant in three performance measures, Absolute Magnitude Off-Track Deviation, Consistency, and Zero Rudder Crossings. Ship speed was found to differ significantly with greater speed employed in the presence of bank effects (Table C-40). Significant interactions between the Bank Effects and Wind Ratio variables were found for "Factored" Off-Track Deviation (Table C-41) and for Rudder Angle (Table C-42). In both performance measures, differential effects of banks are evident only for the 13:1 wind ratio. A three-way interaction was found for Boundary Penetrations presented in Table C-43.

Channel Width Analyses

An ANOVA was performed for each of the seven performance measures using the "Channel Width" analysis model (Table C-7). The results of these analyses are presented in Tables C-44 through C-50. The Channel Width variable (D) and its interaction with the variables of Ship Type (A), Wind Ratio (B), and Wind Side (C) are the primary concern of these analyses, therefore, description of the results will focus on these factors.

Main values for each of the seven performance measures for the Channel Width variable are presented in Table C-51. Interactions between the Channel Width variable and other variables are presented in Tables C-52 through C-65.

Rudder Effect Analyses

An ANOVA was performed for each of the seven performance measures using the "Rudder Effect" analysis model (Table C-9). The results for these analyses are presented in Tables C-66 through C-72. The Rudder Effect Variable (R) and its interactions with the variables of Ship Type (A), Wind Ratio (B), and Wind Side (C) are the primary concern of these analyses and are presented in Tables C-73 through C-95.

Pilot Experience Group Analyses

An ANOVA was performed for four of the performance measures using the "Pilot Experience Group" analysis model (Table C-8). The results of these analyses are presented in Tables C-96 through C-99. The main effect for Pilot Experience Group and its interaction with the Wind Ratio (B) and Wind Side (C) variables are presented in Tables C-100 and C-101.

Confidence Intervals

In research one is frequently interested in drawing inferences about population parameters when only sample statistics are available. A technique useful for this purpose is the generation of confidence intervals.

When a sample statistic is computed, e.g., a sample mean ($\bar{X}$), a confidence interval can be calculated around this mean. The confidence interval is a prediction of the limits within which the actual population parameter (mean, μ) is likely to fall. Furthermore it is stated probabilistically, reflecting the degree of certainty in the prediction, e.g., 90% or 95% certainty or confidence.

Ninety percent confidence intervals were computed for both the mean and standard deviation for the Absolute Magnitude Off-Track Deviation and the Consistency measures (Table C-102). The procedures used are described in Snedecor and Cochran, 1967.

TABLE C-1. EXPERIMENTAL MATRIX FOR MIXED DESIGN (ONE BETWEEN/TWO WITHIN)

	Subject	8:1 Ratio		10:1 Ratio		13:1 Ratio		
		Starboard	Port	Starboard	Port	Starboard	Port	
LNG	1 2 3 4 5 6							36
80K	7 8 9 10 11 12							36
30K	13 14 15 16 17 18							36
		18	18	18	18	18	18	108 Total

TABLE C-2. RUN ORDER MATRIX FOR MIXED DESIGN

	Subject Run Order	8:1 Ratio		10:1 Ratio		13:1 Ratio	
		Starboard	Port	Starboard	Port	Starboard	Port
LNG	1	2	5	6	3	4	1
	4	1	4	5	2	3	6
	7	6	3	4	1	2	5
	10	5	2	3	6	1	4
	13	4	1	2	5	6	3
	16	3	6	1	4	5	2
80K	2	2	5	6	3	4	1
	5	1	4	5	2	3	6
	8	6	3	4	1	2	5
	11	5	2	3	6	1	4
	14	4	1	2	5	6	3
	17	3	6	1	4	5	2
30K	3	2	5	6	3	4	1
	6	1	4	5	2	3	6
	9	6	3	4	1	2	5
	12	5	2	3	6	1	4
	15	4	1	2	5	6	3
	18	3	6	1	4	5	2

TABLE C-3. RUN ORDER WITHIN EXPERIMENTAL DESIGN MATRIX FOR MIXED DESIGN TEST OF BANK EFFECTS

	Subject	8:1 Ratio		10:1 Ratio		13:1 Ratio		
		Starboard	Port	Starboard	Port	Starboard	Port	
Banks (From Main Experiment)	2	2	5	6	3	4	1	36
	5	1	4	5	2	3	6	
	8	6	3	4	1	2	5	
	11	5	2	3	6	1	4	
	14	4	1	2	5	6	3	
	17	3	6	1	4	5	2	
No Banks	19	2	5	6	3	4	1	36
	20	1	4	5	2	3	6	
	21	6	3	4	1	2	5	
	22	5	2	3	6	1	4	
	23	4	1	2	5	6	3	
	24	3	6	1	4	5	2	
		12	12	12	12	12	12	72 Total

TABLE C-4. EXPERIMENTAL DESIGN MATRIX FOR MIXED DESIGN (ONE BETWEEN/TWO WITHIN)

	8:1 Ratio		10:1 Ratio		13:1 Ratio	
	Starboard	Port	Starboard	Port	Starboard	Port
"Narrow Channel" Experience (6 Subjects)						
"Other" Experience (6 Subjects)						

TABLE C-5. ANALYSIS OF VARIANCE SOURCE TABLE ANOVA MODEL VI, "MAIN ANALYSIS"

Source of Variance	df	Mean Squares	F
A (Ship Type)	2	SS_A/df_A	$MS_A/MS_{S(A)}$
S(A)	15	$SS_{S(A)}/df_{S(A)}$	—
B (Wind Ratio)	2	SS_B/df_B	$MS_B/MS_{S(A)B}$
C (Wind Side)	1	SS_C/df_C	$MS_C/MS_{S(A)C}$
AB	4	SS_{AB}/df_{AB}	$MS_{AB}/MS_{S(A)B}$
AC	2	SS_{AC}/df_{AC}	$MS_{AC}/MS_{S(A)C}$
BC	2	SS_{BC}/df_{BC}	$MS_{BC}/MS_{S(A)BC}$
ABC	4	SS_{ABC}/df_{ABC}	$MS_{ABC}/MS_{S(A)BC}$
S(A)B	30	$SS_{S(A)B}/df_{S(A)B}$	—
S(A)C	15	$SS_{S(A)C}/df_{S(A)C}$	—
S(A)BC	30	$SS_{S(A)BC}/df_{S(A)BC}$	—
TOTAL	107		

TABLE C-6. ANALYSES OF VARIANCE SOURCE TABLE ANOVA MODEL #2, "BANK EFFECTS ANALYSES"

Source of Variance	df	Mean Squares	F
F (Bank Effects)	1	SS_F/df_F	$MS_F/MS_{S(F)}$
S(F)	10	$SS_{S(F)}/df_{S(F)}$	—
B (Wind Ratio)	2	SS_B/df_B	$MS_B/MS_{S(F)B}$
C (Wind Side)	1	SS_C/df_C	$MS_C/MS_{S(F)C}$
FB	2	SS_{FB}/df_{FB}	$MS_{FB}/MS_{S(F)B}$
FC	1	SS_{FC}/df_{FC}	$MS_{FC}/MS_{S(F)C}$
BC	2	SS_{BC}/df_{BC}	$MS_{BC}/MS_{S(F)BC}$
FBC	2	SS_{FBC}/df_{FBC}	$MS_{FBC}/MS_{S(F)BC}$
S(F)B	20	$SS_{S(F)B}/df_{S(F)B}$	—
S(F)C	10	$SS_{S(F)C}/df_{S(F)C}$	—
S(F)BC	20	$SS_{S(F)BC}/df_{S(F)BC}$	—
TOTAL	71		

TABLE C-7. ANALYSES OF VARIANCE SOURCE TABLE ANOVA MODEL #3, "CHANNEL WIDTH ANALYSIS"

Source of Variance	df	Mean Squares	F
A (Ship Type)	2	SS_A/df_A	MS_A/MS Error 1
B (Wind Ratio)	2	SS_B/df_B	MS_B/MS Error 2
C (Wind Side)	1	SS_C/df_C	MS_C/MS Error 3
D (Channel Width)	1	SS_D/df_D	MS_D/MS Error 4
AB	4	SS_{AB}/df_{AB}	MS_{AB}/MS Error 2
AC	2	SS_{AC}/df_{AC}	MS_{AC}/MS Error 3
AD	2	SS_{AD}/df_{AD}	MS_{AD}/MS Error 4
BC	2	SS_{BC}/df_{BC}	MS_{BC}/MS Error 5
BD	2	SS_{BD}/df_{BD}	MS_{BD}/MS Error 6
CD	1	$SS_{CD}df_{CD}$	MS_{CD}/MS Error 7
ABC	4	SS_{ABC}/df_{ABC}	MS_{ABC}/MS Error 5
ABD	4	SS_{ABD}/df_{ABD}	MS_{ABD}/MS Error 6
ACD	2	SS_{ACD}/df_{ACD}	MS_{ACD}/MS Error 7
BCD	2	SS_{BCD}/df_{BCD}	MS_{BCD}/MS Error 8
ABCD	4	SS_{ABCD}/df_{ABCD}	MS_{ABCD}/MS Error 8
S(A) Error 1	15	$SS_{S(A)}/df_{S(A)}$	—
S(A)B Error 2	30	$SS_{S(A)B}/df_{S(A)B}$	—
S(A)C Error 3	15	$SS_{S(A)C}/df_{S(A)C}$	—
S(A)D Error 4	15	$SS_{S(A)D}/df_{S(A)D}$	—
S(A)BC Error 5	30	$SS_{S(A)BC}/df_{S(A)BC}$	—
S(A)BD Error 6	30	$SS_{S(A)BD}/df_{S(A)BD}$	—
S(A)CD Error 7	15	$SS_{S(A)CD}/df_{S(A)CD}$	—
S(A)BCD Error 8	30	$SS_{S(A)BCD}/df_{S(A)BCD}$	—
TOTAL	215		

TABLE C-8. ANALYSES OF VARIANCE SOURCE TABLE ANOVA MODEL #4, "PILOT EXPERIENCE GROUP ANALYSES"

Source of Variance	df	Mean Squares	F
E (Experience Group)	1	SS_E/df_E	$MS_E/MS_{S(E)}$
S(E)	10	$SS_{S(E)}/df_{S(E)}$	—
B (Wind Ratio)	2	SS_B/df_B	$MS_B/MS_{S(E)B}$
C (Wind Side)	1	SS_C/df_C	$MS_C/MS_{S(E)C}$
EB	2	SS_{EB}/df_{EB}	$MS_{EB}/MS_{S(E)B}$
EC	1	SS_{EC}/df_{EC}	$MS_{EC}/MS_{S(E)C}$
BC	2	SS_{BC}/df_{BC}	$MS_{BC}/MS_{S(E)BC}$
EBC	2	SS_{EBC}/df_{EBC}	$MS_{EBC}/MS_{S(E)BC}$
S(E)B	20	$SS_{S(E)B}/df_{S(E)B}$	—
S(E)C	10	$SS_{S(E)C}/df_{S(E)C}$	—
S(E)BC	20	$SS_{S(E)BC}/df_{S(E)BC}$	—
TOTAL	71		

TABLE C-9. ANALYSES OF VARIANCE SOURCE TABLE ANOVA MODEL #5, "RUDDER EFFECT ANALYSIS"

Source of Variance	df	Mean Squares	F
A (Ship Type)	2	SS_{A}/df_{A}	MS_{A}/MS Error 1
B (Wind Ratio)	2	SS_{B}/df_{B}	MS_{B}/MS Error 2
C (Wind Side)	1	SS_{C}/df_{C}	MS_{C}/MS Error 3
R (Rudder Effect)	1	SS_{R}/df_{R}	MS_{R}/MS Error 4
AB	4	SS_{AB}/df_{AB}	MS_{AB}/MS Error 2
AC	2	SS_{AC}/df_{AC}	MS_{AC}/MS Error 3
AR	2	SS_{AR}/df_{AR}	MS_{AR}/MS Error 4
BC	2	SS_{BC}/df_{BC}	MS_{BC}/MS Error 5
BR	2	SS_{BR}/df_{BR}	MS_{BR}/MS Error 6
CR	1	SS_{CR}/df_{CR}	MS_{CR}/MS Error 7
ABC	4	SS_{ABC}/df_{ABC}	MS_{ABC}/MS Error 5
ABR	4	SS_{ABR}/df_{ABR}	MS_{ABR}/MS Error 6
ACR	2	SS_{ACR}/df_{ACR}	MS_{ACR}/MS Error 7
BCR	2	SS_{BCR}/df_{BCR}	MS_{BCR}/MS Error 8
ABCR	4	SS_{ABCR}/df_{ABCR}	MS_{ABCR}/MS Error 8
S(A) Error 1	15	$SS_{S(A)}/df_{S(A)}$	—
S(A)B Error 2	30	$SS_{S(A)B}/df_{S(A)B}$	—
S(A)C Error 3	15	$SS_{S(A)C}/df_{S(A)C}$	—
S(A)R Error 4	15	$SS_{S(A)R}/df_{S(A)R}$	—
S(A)BC Error 5	30	$SS_{S(A)BC}/df_{S(A)BC}$	—
S(A)BR Error 6	30	$SS_{S(A)BR}/df_{S(A)BR}$	—
S(A)CR Error 7	15	$SS_{S(A)CR}/df_{S(A)CR}$	—
S(A)BCR Error 8	30	$SS_{S(A)BCR}/df_{S(A)BCR}$	—
TOTAL	215		

TABLE C-10. "MAIN ANALYSES" SOURCE TABLE, ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	1,239,530.00	17.52	< 0.001
S(A)	15	70,741.87	-	-
B (Wind Ratio)	2	162,450.40	5.58	< 0.01
C (Wind Side)	1	1,250,842.00	31.50	< 0.001
AB	4	56,896.30	1.96	ns
AC	2	29,153.00	0.73	ns
BC	2	22,313.50	0.99	ns
ABC	4	65,242.95	2.91	< 0.05
S(A)B	30	29,096.33	-	-
S(A)C	15	39,710.53	-	-
S(A)BC	30	22,430.04	-	-
TOTAL	107			

TABLE C-11. "MAIN ANALYSES" SOURCE TABLE, "FACTORED" OFF-TRACK DEVIATION (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	5,107,150.00	67.40	< 0.001
S(A)	15	75,775.19	-	-
B (Wind Ratio)	2	1,147,785.00	46.32	< 0.001
C (Wind Side)	1	252,898.50	6.10	< 0.05
AB	4	283,053.20	11.42	< 0.001
AC	2	126,610.20	3.05	ns
BC	2	79,936.25	6.74	< 0.01
ABC	4	96,033.75	8.09	< 0.001
S(A)B	30	24,778.73	-	-
S(A)C	15	41,466.23	-	-
S(A)BC	30	11,867.79	-	-
TOTAL	107			

TABLE C-12. "MAIN ANALYSES" SOURCE TABLE, CONSISTENCY (LEGS 1-5 PLUS TURN)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	49,987.59	41.52	< 0.001
S(A)	15	1,203.99	-	-
B (Wind Ratio)	2	6,007.45	14.97	< 0.001
C (Wind Side)	1	35.59	0.08	ns
AB	4	1,537.62	3.83	< 0.05
AC	2	227.58	0.52	ns
BC	2	1,020.26	4.84	< 0.05
ABC	4	1,108.54	5.26	< 0.01
S(A)B	30	401.34	-	-
S(A)C	15	435.06	-	-
S(A)BC	30	210.65	-	-
TOTAL	107			

TABLE C-13. "MAIN ANALYSES" SOURCE TABLE, BOUNDARY PENETRATIONS (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	61.74	48.10	< 0.001
S(A)	15	1.28	-	-
B (Wind Ratio)	2	4.22	7.52	< 0.01
C (Wind Side)	1	4.71	6.02	< 0.05
AB	4	0.57	1.01	ns
AC	2	0.38	0.48	ns
BC	2	1.04	2.81	ns
ABC	4	1.56	4.25	< 0.01
S(A)B	30	0.56	-	-
S(A)C	15	0.78	-	-
S(A)BC	30	0.37	-	-
TOTAL	107			

TABLE C-14. "MAIN ANALYSES" SOURCE TABLE, SHIP SPEED (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	3,964.22	49.59	< 0.001
S(A)	15	79.93	-	-
B (Wind Ratio)	2	659.57	56.72	< 0.001
C (Wind Side)	1	70.72	10.91	< 0.01
AB	4	84.67	7.28	< 0.001
AC	2	34.84	5.37	< 0.05
BC	2	66.38	3.47	< 0.05
ABC	4	52.66	2.76	< 0.05
S(A)B	30	11.63	-	-
S(A)C	15	6.48	-	-
S(A)BC	30	19.10	-	-
TOTAL	107			

TABLE C-15. "MAIN ANALYSES" SOURCE TABLE, RUDDER ANGLE (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	20,203.78	50.01	< 0.001
S(A)	15	403.97	-	-
B (Wind Ratio)	2	8,874.00	43.62	< 0.001
C (Wind Side)	1	1,720.91	20.11	< 0.001
AB	4	2,125.61	10.45	< 0.001
AC	2	258.49	3.02	ns
BC	2	21.57	0.27	ns
ABC	4	104.15	1.28	ns
S(A)B	30	203.45	-	-
S(A)C	15	85.56	-	-
S(A)BC	30	81.19	-	-
TOTAL	107			

TABLE C-16. "MAIN ANALYSES" SOURCE TABLE, ZERO RUDDER CROSSINGS (LEGS 1-5 PLUS TURN)

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	0.47	2.01	ns
S(A)	15	0.23	-	-
B (Wind Ratio)	2	0.11	10.03	@ 0.001
C (Wind Side)	1	0.00017	0.009	ns
AB	4	0.02	1.36	ns
AC	2	0.07	3.56	ns
BC	2	0.06	2.04	ns
ABC	4	0.03	0.96	ns
S(A)B	30	0.01	-	-
S(A)C	15	0.02	-	-
S(A)BC	30	0.03	-	-
TOTAL	107			

TABLE C-17. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY PERFORMANCE MEASURE

Performance Measure	LNG (1)	80K (2)	30K (3)	Main Effect p Value	Ship Comparisons 1-2	1-3	2-3
Absolute Magnitude Off-Track Deviation (Feet)	149.00	81.00	90.00	0.001	**	**	ns
"Factored" Off-Track Deviation (Feet)	159.00	22.00	35.00	0.001	**	**	ns
"Consistency" (Feet)	151.39	79.81	97.64	0.001	**	**	**
Boundary Penetrations (Frequency)	3.14	0.14	0.47	0.001	**	**	**
Ship Speed (Kt)	9.24	5.88	5.58	0.001	**	**	ns
Rudder Angle (Degrees)	19.00	20.00	11.00	0.001	ns	**	**
Zero Rudder Crossings (Frequency)	18.11	12.00	12.06	ns	—	—	—

** $p < 0.01$

TABLE C-18. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY PERFORMANCE MEASURE

Performance Measure	8:1 (1)	10:1 (2)	13:1 (3)	Main Effect p Value	Wind Comparisons 1-2	1-3	2-3
Absolute Magnitude Off-Track Deviation (Feet)	93.00	118.00	120.00	0.01	ns	**	ns
"Factored" Off-Track Deviation (Feet)	37.00	71.00	109.00	0.001	**	**	**
"Consistency" (Feet)	96.22	110.61	122.00	0.001	*	**	*
Boundary Penetrations (Frequency)	0.81	1.31	1.64	0.01	*	**	ns
Ship Speed (Kt)	6.20	6.60	7.80	0.001	*	**	**
Rudder Angle (Degrees)	13.00	17.00	20.00	0.001	**	**	**
Zero Rudder Crossings (Frequency)	13.47	13.15	15.50	0.001	ns	**	**

* $p < 0.05$
** $p < 0.001$

TABLE C-19. RELATIONSHIP AMONG MEANS FOR WIND SIDE (C) BY PERFORMANCE MEASURE

Performance Measure	Starboard	Port	Main Effect p Value
Absolute Magnitude Off-Track Deviation (Feet)	85.00	124.00	0.001
"Factored" Off-Track Deviation (Feet)	63.00	82.00	0.05
"Consistency" (Feet)	109.04	110.19	ns
Boundary Penetrations (Frequency)	0.98	1.52	0.05
Ship Speed (Kt)	6.70	5.90	0.01
Rudder Angle (Degrees)	16.00	18.00	0.001
Zero Rudder Crossings (Frequency)	13.96	14.15	ns

TABLE C-20. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY WIND SIDE (C) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
STARBOARD	8:1 (4)	111.00	56.00	62.00	0.05	**	**	ns
	10:1 (5)	121.00	73.00	51.00		**	**	ns
	13:1 (6)	144.00	63.00	73.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	ns	ns	ns				
PORT	8:1 (7)	143.00	99.00	83.00		**	**	ns
	10:1 (8)	195.00	96.00	109.00		**	**	ns
	13:1 (9)	169.00	96.00	160.00		**	ns	**
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	ns	ns	**				
	8-9	ns	ns	**				
Wind Side Comparisons (C)	4-7	ns	**	ns				
	5-8	**	ns	**				
	6-9	ns	ns	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-21. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) FOR "FACTORED" OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	8:1 (4)	88.00	10.00	14.00	0.001	**	**	ns
	10:1 (5)	161.00	23.00	27.00		**	**	ns
	13:1 (6)	227.00	33.00	65.00		**	**	*
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	**				
	5-6	**	ns	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-22. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY WIND SIDE (C) FOR "FACTORED" OFF-TRACK DEVIATION

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
Starboard (4)		34.00	50.00	103.00	0.01	ns	**	**
Port (5)		41.00	91.00	114.00		**	**	**
Wind Side Comparisons (C)	4-5	ns	**	ns				

** $p < 0.01$

TABLE C-23. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY WIND SIDE (C) FOR "FACTORED" OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
STARBOARD	8:1 (4)	76.00	10.00	15.00	0.001	**	**	ns
	10:1 (5)	105.00	27.00	18.00		**	**	ns
	13:1 (6)	226.00	28.00	56.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	**				
	5-6	**	ns	**				
PORT	8:1 (7)	99.00	10.00	13.00		**	**	ns
	10:1 (8)	217.00	20.00	36.00		**	**	ns
	13:1 (9)	229.00	38.00	74.00		**	**	*
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	**	ns	**				
	8-9	ns	ns	**				
Wind Side Comparisons (C)	4-7	ns	ns	ns				
	5-8	**	ns	ns				
	6-9	ns	ns	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-24. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) FOR CONSISTENCY

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	8:1 (4)	125.17	75.58	87.92	0.05	**	**	ns
	10:1 (5)	153.25	81.58	97.00		**	**	ns
	13:1 (6)	175.75	82.25	108.00		**	**	**
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				

** $p < 0.01$

TABLE C-25. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY WIND SIDE (C) FOR CONSISTENCY

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
Starboard (4)		100.39	104.28	122.44	0.05	ns	ns	ns
Port (5)		92.06	116.95	121.56		ns	*	ns
Wind Side Comparisons (C)	4-5	ns	ns	ns				

$p < 0.05$

TABLE C-26. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY WIND SIDE (C) FOR CONSISTENCY

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
STARBOARD	8:1 (4)	130.00	78.50	92.67	< 0.01	**	**	ns
	10:1 (5)	132.33	86.00	94.50		**	**	ns
	13:1 (6)	182.50	80.67	104.17		**	**	*
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
PORT	8:1 (7)	120.33	72.67	83.17		**	**	ns
	10:1 (8)	174.17	77.17	99.50		**	**	*
	13:1 (9)	169.00	83.83	111.83		**	**	**
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	**	ns	**				
	8-9	ns	ns	ns				
Wind Side Comparisons (C)	4-7	ns	ns	ns				
	5-8	**	ns	ns				
	6-9	ns	ns	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-27. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY WIND SIDE (C) FOR BOUNDARY PENETRATIONS

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
STARBOARD	8:1 (4)	2.17	0.00	0.17	< 0.01	**	**	ns
	10:1 (5)	1.83	0.17	0.33		**	**	ns
	13:1 (6)	4.00	0.00	0.17		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
PORT	8:1 (7)	2.33	0.00	0.17		**	**	ns
	10:1 (8)	4.67	0.17	0.67		**	**	ns
	13:1 (9)	3.83	0.50	1.33		**	**	ns
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	*	ns	**				
	8-9	ns	ns	ns				
Wind Side Comparisons (C)	4-7	ns	ns	ns				
	5-8	**	ns	ns				
	6-9	ns	ns	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-28. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) FOR SHIP SPEED

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	8:1 (4)	8.10	5.30	5.30	0.001	**	**	ns
	10:1 (5)	8.90	5.60	5.50		**	**	ns
	13:1 (6)	10.90	6.70	6.00		**	**	*
Wind Ratio Comparisons (B)	4-5	*	ns	ns				
	4-6	**	**	*				
	5-6	**	**	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-29. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY SIDE (C) FOR SHIP SPEED

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
Starboard (4)		5.80	6.80	7.90	0.05	*	**	**
Port (5)		6.70	6.70	7.80		ns	**	**
Wind Side Comparisons (C)	4-5	*	ns	ns				

*p @ 0.05
** p @ 0.01

TABLE C-30. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY SIDE (C) FOR SHIP SPEED

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
Starboard (4)		8.90	5.90	5.50	0.05	**	**	ns
Port (5)		9.70	5.90	5.60		**	**	ns
Wind Side Comparisons (C)	4-5	**	ns	ns				

** p @ 0.01

TABLE C-31. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY WIND SIDE (C) FOR SHIP SPEED

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
STARBOARD	8:1 (4)	6.10	5.10	5.30	< 0.05	**	**	ns
	10:1 (5)	8.90	5.40	5.40		**	**	ns
	13:1 (6)	11.00	6.80	6.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	**	ns				
	5-6	**	*	ns				
PORT	8:1 (7)	9.40	5.40	5.30		**	**	ns
	10:1 (8)	9.00	5.70	5.50		**	**	ns
	13:1 (9)	10.80	6.60	6.00		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	**	ns	ns				
	8-9	**	ns	ns				
Wind Side Comparisons (C)	4-7	**	ns	ns				
	5-8	ns	ns	ns				
	6-9	ns	ns	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-32. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) FOR RUDDER ANGLE

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	8:1 (4)	19.0	15.0	7.0	0.001	**	**	**
	10:1 (5)	19.0	22.0	11.0		*	**	**
	13:1 (6)	19.5	23.0	17.0		**	ns	**
Wind Ratio Comparisons (B)	4-5	ns	**	**				
	4-6	ns	**	**				
	5-6	ns	ns	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-33. "BANK EFFECTS ANALYSES" SOURCE TABLE, ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	143,219.70	2.03	ns
S(F)	10	70,497.84	-	-
B (Wind Ratio)	2	36,394.35	2.44	ns
C (Wind Side)	1	80,245.50	1.88	ns
FB	2	40,432.72	2.71	ns
FC	1	178,517.70	4.19	ns
BC	2	8,099.66	0.37	ns
FBC	2	43,824.53	2.01	ns
S(F)B	20	14,928.91	-	-
S(F)C	10	42,615.89	-	-
S(F)BC	20	21,800.20	-	-
TOTAL	71			

TABLE C-34. "BANK EFFECTS ANALYSES" SOURCE TABLE, "FACTORED" OFF-TRACK DEVIATION (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	124,517.70	8.37	< 0.05
S(F)	10	14,870.20	-	-
B (Wind Ratio)	2	233,631.70	26.48	< 0.001
C (Wind Side)	1	9,706.80	0.91	ns
FB	2	45,620.03	5.17	< 0.05
FC	1	13,746.70	1.29	ns
BC	2	1,311.72	0.25	ns
FBC	2	9,407.52	1.79	ns
S(F)B	20	8,823.61	-	-
S(F)C	10	10,616.77	-	-
S(F)BC	20	5,247.43	-	-
TOTAL	71			

TABLE C-[illegible] [illegible]
CONSISTENCY [illegible]

Source of Variance	df	Mean Squares	F	p
F (Bank Effects)	1	5,442.72	3.96	ns
S(F)	10	1,374.96	-	-
B (Wind Ratio)	2	2,244.50	4.27	< 0.05
C (Wind Side)	1	304.22	0.51	ns
FB	2	1,097.39	2.07	ns
FC	1	1.39	0.002	ns
BC	2	17.55	0.06	ns
FBC	2	361.56	1.16	ns
S(F)B	20	525.84	-	-
S(F)C	10	596.47	-	-
S(F)BC	20	312.12	-	-
TOTAL	71			

TABLE C-36. "BANK EFFECTS ANALYSES" SOURCE TABLE, BOUNDARY PENETRATIONS (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	3.95	5.99	< 0.05
S(F)	10	0.66	-	-
B (Wind Ratio)	2	1.02	2.91	ns
C (Wind Side)	1	0.03	0.03	ns
FB	2	0.07	0.20	ns
FC	1	0.38	0.41	ns
BC	2	0.95	2.28	ns
FBC	2	1.86	4.48	< 0.05
S(F)B	20	0.35	-	-
S(F)C	10	0.92	-	-
S(F)BC	20	0.41	-	-
TOTAL	71			

TABLE C-37. "BANK EFFECTS ANALYSES" SOURCE TABLE, SHIP SPEED (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	63.96	8.95	< 0.05
S(F)	10	7.14	-	-
B (Wind Ratio)	2	240.70	36.40	< 0.001
C (Wind Side)	1	3.58	3.42	ns
FB	2	9.04	1.37	ns
FC	1	1.82	1.74	ns
BC	2	1.28	0.41	ns
FBC	2	4.87	1.58	ns
S(F)B	20	6.61	-	-
S(F)C	10	1.05	-	-
S(F)BC	20	3.08	-	-
TOTAL	71			

TABLE C-38. "BANK EFFECTS ANALYSES" SOURCE TABLE, RUDDER ANGLE (LEGS 1-5)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	396.12	0.88	-
S(F)	10	451.66	-	-
B (Wind Ratio)	2	17,508.85	95.48	< 0.001
C (Wind Side)	1	188.84	3.30	ns
FB	2	911.98	4.97	< 0.05
FC	1	202.02	3.53	ns
BC	2	49.37	0.77	ns
FBC	2	142.93	2.22	ns
S(F)B	20	183.37	-	-
S(F)C	10	57.22	-	-
S(F)BC	20	64.42	-	-
TOTAL	71			

TABLE C-39. "BANK EFFECTS ANALYSES" SOURCE TABLE, ZERO RUDDER CROSSINGS (LEGS 1-5 PLUS TURN)

Source of Variance	df	Mean Squares	F	P
F (Bank Effects)	1	0.03	0.14	ns
S(F)	10	0.21	-	-
B (Wind Ratio)	2	0.04	1.20	ns
C (Wind Side)	1	0.12	3.16	ns
FB	2	0.002	0.05	ns
FC	1	0.0008	0.02	ns
BC	2	0.09	3.58	ns
FBC	2	0.005	0.02	ns
S(F)B	20	0.03	-	-
S(F)C	10	0.04	-	-
S(F)BC	20	0.03	-	-
TOTAL	71			

TABLE C-40. RELATIONSHIP AMONG MEANS FOR BANK EFFECTS (F)

Performance Measure	Bank Effects	No Bank Effects	Main Effect p Value
Absolute Magnitude Off-Track Deviation (feet)	80.76	98.60	ns
"Factored" Off-Track Deviation (feet)	22.00	39.00	<0.05
Consistency (feet)	79.81	97.19	ns
Boundary Penetration (frequency)	0.14	0.56	<0.05
Ship Speed (kt)	5.90	5.50	<0.05
Rudder Angle (degrees)	20.00	21.00	ns
Zero Rudder Crossings (frequency)	12.00	10.58	ns

TABLE C-41. RELATIONSHIP AMONG MEANS FOR BANK EFFECTS (F) BY WIND RATIO (B) FOR "FACTORED" OFF-TRACK DEVIATION (FEET)

		Bank Effects (1)	No-Bank Effects (2)	Interaction p Value	Bank Effects Comparisons (F) 1-2
	8:1 (3)	10	16	0.05	ns
	10:1 (4)	23	30		ns
	13:1 (5)	31	70		**
Wind Ratio Comparisons (B)	3-4	ns	ns		
	3-5	*	**		
	4-5	ns	**		

* $p < 0.05$ ** $p < 0.01$

TABLE C-42. RELATIONSHIP AMONG MEANS FOR BANK EFFECTS (F) BY WIND RATIO (B) FOR RUDDER ANGLE

		Bank Effects (1)	No-Bank Effects (2)	Interaction p Value	Bank Effects Comparisons (F) 1-2
	8:1 (3)	15	14	0.05	ns
	10:1 (4)	22	22		ns
	13:1 (5)	23	27		**
Wind Ratio Comparisons (B)	3-4	**	**		
	3-5	**	**		
	4-5	ns	**		

** $p < 0.01$

TABLE C-43. RELATIONSHIP AMONG MEANS FOR BANK EFFECTS (F) BY WIND RATIO (B) BY SIDE (C) FOR BOUNDARY PENETRATIONS

		Bank Effects (1)	No-Bank Effects (2)	Interaction p Value	Bank Effects Comparisons (F) 1-2
STARBOARD	8:1 (3)	0.00	0.50	0.05	ns
	10:1 (4)	0.17	0.17		ns
	13:1 (5)	0.00	1.17		**
Wind Ratio Comparison (B)	3-4	ns	ns		
	3-5	ns	ns		
	4-5	ns	ns		
PORT	8:1 (6)	0.00	0.00		ns
	10:1 (7)	0.17	1.00		*
	13:1 (8)	0.50	0.50		ns
Wind Ratio Comparisons (B)	6-7	ns	*		
	6-8	ns	ns		
	7-8	ns	ns		
Wind Side Comparisons (C)	3-6	ns	ns		
	4-7	ns	*		
	5-8	ns	ns		

* $p < 0.05$ ** $p < 0.01$

TABLE C-44. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	148,854.70	47.86	< 0.001
B (Wind Ratio)	2	12,117.62	7.64	< 0.01
C (Wind Side)	1	24,820.69	7.64	< 0.01
D (Channel Width)	1	40,215.66	24.45	< 0.001
AB	4	4,327.67	2.73	< 0.05
AC	2	395.28	0.16	ns
AD	2	43,781.84	26.62	< 0.001
BC	2	87.85	0.12	ns
BD	2	11,528.55	12.60	< 0.001
CD	1	1,089.03	0.62	ns
ABC	4	2,083.80	2.95	< 0.05
ABD	4	12,509.31	13.67	< 0.001
ACD	2	3,731.86	2.14	ns
BCD	2	368.18	0.50	ns
ABCD	4	329.84	0.45	ns
S(A) Error 1	15	3,110.42	-	-
S(A)B Error 2	30	1,586.59	-	-
S(A)C Error 3	15	2,417.15	-	-
S(A)D Error 4	15	1,644.66	-	-
S(A)BC Error 5	30	707.09	-	-
S(A)BD Error 6	30	915.30	-	-
S(A)CD Error 7	15	1,744.81	-	-
S(A)BCD Error 8	30	738.27	-	-
TOTAL	215			

TABLE C-45. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, "FACTORED" OFF-TRACK DEVIATION

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	415,733.10	129.37	< 0.001
B (Wind Ratio)	2	44,492.19	8.34	< 0.01
C (Wind Side)	1	23,627.09	8.29	< 0.001
D (Channel Width)	1	88,083.87	31.03	< 0.001
AB	4	32,842.11	6.16	< 0.001
AC	2	12,535.11	4.40	< 0.05
AD	2	65,924.00	23.23	< 0.001
BC	2	3,720.74	3.57	< 0.05
BD	2	26,316.84	8.26	< 0.01
CD	1	4,869.41	1.15	ns
ABC	4	5,271.06	5.05	< 0.05
ABD	4	25,581.34	8.03	< 0.001
ACD	2	714.65	0.17	ns
BCD	2	2,004.75	0.46	ns
ABCD	4	1,137.68	0.26	ns
S(A) Error 1	15	3,215.98	-	-
S(A)B Error 2	30	5,335.15	-	-
S(A)C Error 3	15	2,850.89	-	-
S(A)D Error 4	15	2,838.48	-	-
S(A)BC Error 5	30	1,043.15	-	-
S(A)BD Error 6	30	3,186.33	-	-
S(A)CD Error 7	15	4,248.17	-	-
S(A)BCD Error 8	30	4,333.56	-	-
TOTAL	215			

TABLE C-47. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, BOUNDARY PENETRATIONS

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	11.70	51.96	< 0.001
B (Wind Ratio)	2	0.94	2.20	ns
C (Wind Side)	1	0.52	3.36	ns
D (Channel Width)	1	0.11	1.42	ns
AB	4	0.94	2.20	ns
AC	2	0.52	3.36	ns
AD	2	0.11	1.42	ns
BC	2	0.13	2.71	ns
BD	2	0.73	9.69	< 0.001
CD	1	0.18	1.27	ns
ABC	4	0.13	2.71	ns
ABD	4	0.73	9.69	< 0.001
ACD	2	0.18	1.27	ns
BCD	2	0.06	1.22	ns
ABCD	4	0.07	1.22	ns
S(A) Error 1	15	0.23	-	-
S(A)B Error 2	30	0.43	-	-
S(A)C Error 3	15	0.15	-	-
S(A)D Error 4	15	0.08	-	-
S(A)BC Error 5	30	0.05	-	-
S(A)BD Error 6	30	0.07	-	-
S(A)CD Error 7	15	0.14	-	-
S(A)BCD Error 8	30	0.05	-	-
TOTAL	215			

TABLE C-48. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, SHIP SPEED

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	277.99	65.58	< 0.001
B (Wind Ratio)	2	19.82	29.79	< 0.001
C (Wind Side)	1	2.95	1.99	ns
D (Channel Width)	1	228.31	119.45	< 0.001
AB	4	3.46	5.20	< 0.01
AC	2	1.26	0.85	ns
AD	2	188.44	61.96	< 0.001
BC	2	4.44	2.61	ns
BD	2	6.57	8.73	< 0.01
CD	1	1.38	0.85	ns
ABC	4	2.77	1.63	ns
ABD	4	1.72	2.29	ns
ACD	2	0.86	0.05	ns
BCD	2	1.63	1.76	ns
ABCD	4	2.35	2.54	ns
S(A) Error 1	15	4.24	-	-
S(A)B Error 2	30	0.67	-	-
S(A)C Error 3	15	1.48	-	-
S(A)D Error 4	15	1.91	-	-
S(A)BC Error 5	30	1.70	-	-
S(A)BD Error 6	30	0.75	-	-
S(A)CD Error 7	15	1.63	-	-
S(A)BCD Error 8	30	0.92	-	-
TOTAL	215			

TABLE C-49. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, RUDDER ANGLE

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	1,184.40	32.46	< 0.001
B (Wind Ratio)	2	811.45	37.98	< 0.001
C (Wind Side)	1	118.31	6.66	< 0.05
D (Channel Width)	1	76.72	3.58	ns
AB	4	406.16	19.00	< 0.001
AC	2	32.80	1.85	ns
AD	2	20.11	0.94	ns
BC	2	12.32	1.48	ns
BD	2	2.83	0.17	ns
CD	1	79.44	4.78	< 0.05
ABC	4	6.08	0.73	ns
ABD	4	12.87	0.76	ns
ACD	2	38.90	2.34	ns
BCD	2	3.15	0.33	ns
ABCD	4	3.86	0.40	ns
S(A) Error 1	15	36.49	-	-
S(A)B Error 2	30	21.37	-	-
S(A)C Error 3	15	17.76	-	-
S(A)D Error 4	15	21.46	-	-
S(A)BC Error 5	30	8.31	-	-
S(A)BD Error 6	30	17.01	-	-
S(A)CD Error 7	15	16.63	-	-
S(A)BCD Error 8	30	9.66	-	-
TOTAL	215			

TABLE C-50. "CHANNEL WIDTH ANALYSES" SOURCE TABLE, ZERO RUDDER CROSSINGS

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	33.30	6.85	< 0.01
B (Wind Ratio)	2	1.34	1.10	ns
C (Wind Side)	1	1.57	1.73	ns
D (Channel Width)	1	0.17	0.18	ns
AB	4	0.21	0.30	ns
AC	2	6.49	7.14	< 0.01
AD	2	1.35	1.44	ns
BC	2	0.86	0.99	ns
BD	2	1.47	1.83	ns
CD	1	0.21	0.15	ns
ABC	4	0.32	0.37	ns
ABD	4	4.46	5.58	< 0.01
ACD	2	3.16	2.27	ns
BCD	2	1.29	2.04	ns
ABCD	4	1.69	2.68	ns
S(A) Error 1	15	4.86	-	-
S(A)B Error 2	30	1.22	-	-
S(A)C Error 3	15	0.91	-	-
S(A)D Error 4	15	0.94	-	-
S(A)BC Error 5	30	0.87	-	-
S(A)BD Error 6	30	0.80	-	-
S(A)CD Error 7	15	1.39	-	-
S(A)BCD Error 8	30	0.63	-	-
TOTAL	215			

TABLE C-51. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY PERFORMANCE MEASURES

Performance Measure	800'	600'	Main Effect p Value
Absolute Magnitude Off-Track Deviation (Feet)	94.32	67.03	0.001
"Factored" Off-Track Deviation (Feet)	74.07	33.68	0.001
Consistency (Feet)	58.14	36.33	0.001
Boundary Penetration (Frequency)	0.19	0.16	
Ship Speed (Kt)	5.50	7.60	0.001
Rudder Angle (Degrees)	18.60	17.41	ns
Zero Rudder Crossings (Frequency)	2.78	2.81	ns

TABLE C-52. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY SHIP TYPE (A) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	LNG (3)	175.19	90.98	0.001	**
	80K (4)	50.47	53.02		ns
	30K (5)	57.30	57.09		ns
Ship Comparisons (A)	3-4	**	**		
	3-5	**	**		
	4-5	ns	ns		

** $p < 0.01$

TABLE C-53. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY WIND RATIO (B) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	8:1 (3)	69.00	66.30	0.001	ns
	10:1 (4)	93.75	66.97		**
	13:1 (5)	120.22	67.83		**
Wind Ratio Comparisons (B)	3-4	**	ns		
	3-5	**	ns		
	4-5	ns	ns		

** $p < 0.01$

TABLE C-54. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY CHANNEL WIDTH (D) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800'	8:1 (4)	110.86	52.21	43.92	0.001	**	**	ns
	10:1 (5)	172.91	51.59	56.70		**	**	ns
	13:1 (6)	241.82	47.62	71.26		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
600'	8:1 (7)	100.45	47.56	50.89		**	**	ns
	10:1 (8)	95.64	51.02	56.83		**	**	ns
	13:1 (9)	76.84	56.69	69.37		ns	ns	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Channel Width Comparisons (D)	4-7	ns	ns	ns				
	5-8	**	ns	ns				
	6-9	**	ns	ns				

** $p < 0.01$

TABLE C-55. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY SHIP TYPE (A) FOR "FACTORED" OFF-TRACK DEVIATION

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	LNG (3)	190.61	86.57	0.001	**
	80K (4)	8.21	7.52		ns
	30K (5)	17.40	6.97		ns
Ship Comparisons (A)	3-4	**	**		
	3-5	**	**		
	4-5	ns	ns		

** $p < 0.01$

TABLE C-56. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY WIND RATIO (B) FOR "FACTORED" OFF-TRACK DEVIATION

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	8:1 (3)	31.70	28.50	0.01	ns
	10:1 (4)	71.00	32.80		*
	13:1 (5)	119.50	39.90		**
Wind Comparisons (A)	3-4	*	ns		
	3-5	**	ns		
	4-5	**	ns		

* $p < 0.05$ ** $p < 0.01$

TABLE C-57. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), WIND RATIO (B), BY CHANNEL WIDTH (D) FOR "FACTORED" OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800'	8:1 (4)	77.93	6.88	10.30	0.001	*	**	ns
	10:1 (5)	186.72	10.04	16.31		**	**	ns
	13:1 (6)	325.17	7.71	25.59		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
600'	8:1 (7)	81.06	1.53	2.98		**	**	ns
	10:1 (8)	77.31	13.71	6.82		**	**	ns
	13:1 (9)	101.33	7.31	11.11		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Channel Width Comparisons (D)	9-7	ns	ns	ns				
	5-8	**	ns	ns				
	6-9	**	ns	ns				

* p < 0.05 ** p < 0.01

TABLE C-58. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY SHIP TYPE (A)

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800' (4)		105.60	32.58	36.75	0.001	**	**	ns
600' (5)		54.14	26.03	28.83		**	**	ns
Channel Width Comparisons (D)	4-5	**	ns	ns				

** $p < 0.01$

TABLE C-59. RELATIONSHIP AMONG MEANS FOR CONSISTENCY FOR CHANNEL WIDTH (D), BY SHIP TYPE (A), BY WIND RATIO (B)

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800'	8:1 (4)	67.42	30.58	34.33	0.01	**	**	ns
	10:1 (5)	103.00	33.82	31.75		**	**	ns
	13:1 (6)	144.83	33.33	44.17		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
600'	8:1 (7)	46.17	16.42	20.83		**	**	ns
	10:1 (8)	51.16	31.58	28.83		*	*	ns
	13:1 (9)	65.08	30.08	36.83		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Channel Width Comparisons (D)	4-7	*	ns	ns				
	5-8	**	ns	ns				
	6-9	**	ns	ns				

$* p < 0.05$ $** p < 0.01$

TABLE C-60. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY SHIP TYPE (A) FOR SHIP SPEED

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	LNG (4)	6.29	11.28	0.001	**
	80K (5)	5.16	6.10		*
	30K (6)	5.06	5.3		ns
Ship Comparisons (A)	4-5	**	**		
	4-6	**	**		
	5-6	ns	ns		

$* p < 0.05$ $** p < 0.01$

TABLE C-61. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY WIND RATIO (B) FOR SHIP SPEED

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
	8:1 (3)	5.34	6.82	0.01	**
	10:1 (4)	5.40	7.41		**
	13:1 (5)	5.77	8.45		**
Wind Ratio Comparisons (B)	3-4	ns	*		
	3-5	ns	**		
	4-5	ns	**		

* $p < 0.05$ ** $p < 0.01$

TABLE C-62. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY SIDE (C) FOR RUDDER ANGLE

	800' (1)	600' (2)	Interaction p Value	Channel Width Comparisons (D) 1-2
Starboard (3)	18.40	16.07	0.05	**
Port (4)	18.74	18.76		ns
Side Comparison (C) 3-4	ns	**		

** $p < 0.01$

TABLE C-63. RELATIONSHIP AMONG MEANS FOR ZERO RUDDER CROSSINGS FOR CHANNEL WIDTH (D), BY SHIP TYPE (A), BY WIND RATIO (B)

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800'	8:1 (4)	2.58	0.92	1.08	0.01	**	*	ns
	10:1 (5)	2.08	1.25	0.17		ns	**	*
	13:1 (6)	2.75	0.67	1.25		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	*				
	4-6	ns	ns	ns				
	5-6	ns	ns	*				
600'	8:1 (7)	2.25	1.42	0.33		ns	**	*
	10:1 (8)	2.92	0.75	0.92		**	**	ns
	13:1 (9)	2.33	2.00	0.83		ns	**	**
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	*	ns				
Channel Width Comparisons (D)	4-7	ns	ns	*				
	5-8	ns	ns	*				
	6-9	ns	**	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-64. RELATIONSHIP AMONG MEANS FOR CHANNEL WIDTH (D) BY WIND RATIO (B) FOR BOUNDARY PENETRATIONS

		800' (1)	600' (2)	Interaction p Value	Channel Width Comparison (D) 1-2
	8:1 (3)	0.06	0.14	0.01	ns
	10:1 (4)	0.14	0.17		ns
	13:1 (5)	0.36	0.17		**
Wind Ratio Comparison (B)	3-4	ns	ns		
	3-5	**	ns		
	4-5	**	ns		

** $p < 0.01$

TABLE C-65. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY CHANNEL WIDTH (D) FOR BOUNDARY PENETRATIONS

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
800'	8:1 (4)	0.17	0	0	0.001	ns	ns	ns
	10:1 (5)	0.42	0	0		**	**	ns
	13:1 (6)	1.08	0	0		**	**	ns
Wind Ratio Comparisons (B)	4-5	*	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
600'	8:1 (7)	0.42	0	0		**	**	ns
	10:1 (8)	0.50	0	0		**	**	ns
	13:1 (9)	0.50	0	0		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Channel Width Comparisons (D)	4-7	*	ns	ns				
	5-8	ns	ns	ns				
	6-9	**	ns	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-66. "RUDDER EFFECT ANALYSES" SOURCE TABLE ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	275,721.20	34.28	< 0.001
B (Wind Ratio)	2	22,305.37	9.24	< 0.001
C (Wind Side)	1	120,742.80	29.38	< 0.001
R (Rudder Effect)	1	110,092.90	16.51	< 0.001
AB	4	6,835.05	2.83	ns
AC	2	8,224.25	2.00	ns
AR	2	5,621.88	0.84	ns
BC	2	2,440.19	0.78	ns
BR	2	7,408.78	6.96	< 0.01
CR	1	24,628.50	6.65	< 0.05
ABC	4	4,434.16	1.42	ns
ABR	4	13,592.16	12.77	< 0.001
ACR	2	4,039.69	1.09	ns
BCR	2	1,611.00	1.14	ns
ABCR	4	2,067.59	1.46	ns
S(A) Error 1	15	8,042.64	-	-
S(A)B Error 2	30	2,414.48	-	-
S(A)C Error 3	15	4,109.89	-	-
S(A)R Error 4	15	6,666.56	-	-
S(A)BC Error 5	30	3,122.73	-	-
S(A)BR Error 6	30	1,064.44	-	-
S(A)CR Error 7	15	3,703.96	-	-
S(A)BCR Error 8	30	1,418.79	-	-
TOTAL	215			

TABLE C-67. "RUDDER EFFECT ANALYSES" SOURCE TABLE
"FACTORED" OFF-TRACK DEVIATION

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	367,471.20	34.38	< 0.001
B (Wind Ratio)	2	164,382.90	54.06	< 0.001
C (Wind Side)	1	20,519.41	4.88	< 0.05
R (Rudder Effect)	1	677.88	0.23	ns
AB	4	37,057.95	12.19	< 0.001
AC	2	13,405.51	3.19	ns
AR	2	94,659.62	32.07	< 0.001
BC	2	6,409.26	1.93	ns
BR	2	1,044.69	0.24	ns
CR	1	6,438.92	1.13	ns
ABC	4	5,583.75	1.68	ns
ABR	4	28,771.61	6.62	< 0.001
ACR	2	1,099.31	0.19	ns
BCR	2	1,297.82	0.49	ns
ABCR	4	3,856.46	1.45	ns
S(A) Error 1	15	10,689.00	-	-
S(A)B Error 2	30	3,040.87	-	-
S(A)C Error 3	15	4,206.61	-	-
S(A)R Error 4	15	2,951.89	-	-
S(A)BC Error 5	30	3,318.50	-	-
S(A)BR Error 6	30	4,345.87	-	-
S(A)CR Error 7	15	5,715.52	-	-
S(A)BCR Error 8	30	2,662.75	-	-
TOTAL	215			

TABLE C-68. "RUDDER EFFECT ANALYSES" SOURCE TABLE CONSISTENCY

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	32,776.25	20.12	< 0.001
B (Wind Ratio)	2	22,306.80	51.76	< 0.001
C (Wind Side)	1	230.23	0.47	ns
R (Rudder Effect)	1	892.23	2.17	ns
AB	4	2,097.98	4.87	< 0.01
AC	2	16.61	0.03	ns
AR	2	27,999.00	68.16	< 0.001
BC	2	276.23	0.57	ns
BR	2	605.69	0.72	ns
CR	1	6,475.04	10.26	< 0.01
ABC	4	759.10	1.55	ns
ABR	4	3,738.62	4.47	< 0.01
ACR	2	493.10	0.60	ns
BCR	2	9.73	0.01	ns
ABCR	4	681.30	0.87	ns
S(A) Error 1	15	1,629.00	-	-
S(A)B Error 2	30	430.94	-	-
S(A)C Error 3	15	489.29	-	-
S(A)R Error 4	15	410.78	-	-
S(A)BC Error 5	30	486.91	-	-
S(A)BR Error 6	30	836.27	-	-
S(A)CR Error 7	15	826.20	-	-
S(A)BCR Error 8	30	781.69	-	-
TOTAL	215			

TABLE C-69. "RUDDER EFFECT ANALYSES" SOURCE TABLE BOUNDARY PENETRATIONS

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	14.37	60.50	< 0.001
B (Wind Ratio)	2	1.81	9.48	< 0.001
C (Wind Side)	1	0.67	2.98	ns
R (Rudder Effect)	1	0.67	2.19	ns
AB	4	0.73	3.82	< 0.05
AC	2	0.21	0.95	ns
AR	2	0.09	0.28	ns
BC	2	0.12	0.92	ns
BR	2	0.24	1.25	ns
CR	1	0.28	1.32	ns
ABC	4	0.45	3.48	< 0.05
ABR	4	0.97	5.15	< 0.01
ACR	2	0.03	0.14	ns
BCR	2	0.06	0.54	ns
ABCR	4	0.34	2.93	< 0.05
S(A) Error 1	15	0.24	-	-
S(A)B Error 2	30	0.19	-	-
S(A)C Error 3	15	0.23	-	-
S(A)R Error 4	15	0.31	-	-
S(A)BC Error 5	30	0.13	-	-
S(A)BR Error 6	30	0.19	-	-
S(A)CR Error 7	15	0.21	-	-
S(A)BCR Error 8	30	0.12	-	-
TOTAL	215			

TABLE C-70. "RUDDER EFFECT ANALYSES" SOURCE TABLE SHIP SPEED

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	100.16	17.61	< 0.001
B (Wind Ratio)	2	34.21	35.02	< 0.001
C (Wind Side)	1	3.96	6.01	< 0.05
R (Rudder Effect)	1	242.56	101.57	< 0.001
AB	4	0.92	0.94	ns
AC	2	3.18	4.83	< 0.05
AR	2	19.16	8.02	< 0.01
BC	2	4.10	3.85	< 0.05
BR	2	15.37	18.09	< 0.001
CR	1	2.09	3.28	ns
ABC	4	3.33	3.13	< 0.05
ABR	4	0.29	0.34	ns
ACR	2	0.75	1.17	ns
BCR	2	1.38	2.69	ns
ABCR	4	2.28	4.44	< 0.01
S(A) Error 1	15	5.69	-	-
S(A)B Error 2	30	0.98	-	-
S(A)C Error 3	15	0.66	-	-
S(A)R Error 4	15	2.39	-	-
S(A)BC Error 5	30	1.07	-	-
S(A)BR Error 6	30	0.85	-	-
S(A)CR Error 7	15	0.64	-	-
S(A)BCR Error 8	30	0.51	-	-
TOTAL	215			

TABLE C-71. "RUDDER EFFECT ANALYSES" SOURCE TABLE RUDDER ANGLE

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	1,770.49	30.39	< 0.001
B (Wind Ratio)	2	556.59	42.63	< 0.001
C (Wind Side)	1	124.74	21.53	< 0.001
R (Rudder Effect)	1	1,287.50	35.05	< 0.001
AB	4	178.66	13.68	< 0.001
AC	2	38.44	6.64	< 0.05
AR	2	32.91	0.90	ns
BC	2	5.61	0.61	ns
BR	2	43.14	4.09	< 0.05
CR	1	84.73	9.83	< 0.01
ABC	4	3.83	0.41	ns
ABR	4	89.85	8.52	< 0.001
ACR	2	29.99	3.48	ns
BCR	2	2.32	0.29	ns
ABCR	4	4.31	0.54	ns
S(A) Error 1	15	58.25	-	-
S(A)B Error 2	30	13.06	-	-
S(A)C Error 3	15	5.79	-	-
S(A)R Error 4	15	36.73	-	-
S(A)BC Error 5	30	9.26	-	-
S(A)BR Error 6	30	10.54	-	-
S(A)CR Error 7	15	8.62	-	-
S(A)BCR Error 8	30	7.95	-	-
TOTAL	215			

TABLE C-72. "RUDDER EFFECT ANALYSES" SOURCE TABLE ZERO RUDDER CROSSINGS

Source of Variance	df	Mean Squares	F	P
A (Ship Type)	2	17.55	3.35	ns
B (Wind Ratio)	2	7.10	4.59	< 0.05
C (Wind Side)	1	0.46	0.29	ns
R (Rudder Effect)	1	0.39	0.19	ns
AB	4	1.46	0.94	ns
AC	2	2.82	1.74	ns
AR	2	4.18	2.04	ns
BC	2	0.37	0.31	ns
BR	2	3.27	3.14	ns
CR	1	2.18	1.96	ns
ABC	4	0.33	0.28	ns
ABR	4	2.62	2.72	< 0.05
ACR	2	0.85	0.77	ns
BCR	2	4.36	3.55	< 0.05
ABCR	4	1.15	0.93	ns
S(A) Error 1	15	5.24	-	-
S(A)B Error 2	30	1.54	-	-
S(A)C Error 3	15	1.62	-	-
S(A)R Error 4	15	2.05	-	-
S(A)BC Error 5	30	1.18	-	-
S(A)BR Error 6	30	1.04	-	-
S(A)CR Error 7	15	1.11	-	-
S(A)BCR Error 8	30	1.23	-	-
TOTAL	215			

TABLE C-73. RELATIONSHIP AMONG MEANS FOR RUDDER EFFECT (LEG 1, LEG 4) BY PERFORMANCE MEASURE

Performance Measure	Leg 1	Leg 4	Main Effect p Value
Absolute Magnitude Off-Track Deviation (Feet)	94.32	139.47	< 0.001
"Factored" Off- Track Deviation (Feet)	74.07	77.62	ns
Consistency (Feet)	58.14	54.07	ns
Boundary Penetration (Frequency)	1.26	1.37	ns
Ship Speed (Kt)	5.50	7.62	< 0.001
Rudder Angle (Degrees)	18.60	13.72	< 0.001
Zero Rudder Crossings (Frequency)	2.38	2.47	ns

TABLE C-74. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
	Leg 1 (4)	69.00	93.75	120.22	0.01	**	**	**
	Leg 4 (5)	125.41	151.06	141.95		**	ns	ns
Rudder Effect Comparisons (R)	4-5	**	**	**				

** $p < 0.01$

TABLE C-75. RELATIONSHIP AMONG MEANS FOR WIND SIDE (C) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		Starboard (1)	Port (2)	Interaction p Value	Wind Side Comparisons (C) 1-2
	Leg 1 (3)	81.36	107.29	0.05	*
	Leg 4 (4)	105.15	173.79		**
Rudder Effect Comparisons (R)	3-4	ns	**		

* $p < 0.05$ ** $p < 0.01$

TABLE C-76. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Type Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	110.86	52.21	43.92	0.001	**	**	ns
	10:1 (5)	172.91	51.59	56.74		**	**	ns
	13:1 (6)	241.82	47.62	71.23		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	189.79	93.02	93.41		**	**	ns
	10:1 (8)	230.38	108.71	114.10		**	**	ns
	13:1 (9)	182.35	98.83	144.67		**	**	**
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	ns	ns	**				
	8-9	**	ns	*				
Channel Width Comparisons (D)	4-7	**	**	**				
	5-8	**	**	**				
	6-9	**	**	**				

* p @ 0.05 ** p @ 0.01

TABLE C-77. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR "FACTORED" OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	Leg 1 (3)	196.61	8.21	17.40	0.001	**	**	ns
	Leg 4 (4)	117.93	39.13	75.79		**	**	*
Rudder Effect Comparisons (R)	3-4	**	*	**				

** p < 0.01
* p < 0.05

TABLE C-78. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR "FACTORED" OFF-TRACK DEVIATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	77.93	6.88	10.30	0.001	*	*	ns
	10:1 (5)	186.72	10.04	16.31		**	**	ns
	13:1 (6)	325.17	7.71	25.59		**	**	ns
Wind Ratio Comparisons (B)	4-5	**	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	58.68	12.58	12.67		ns	ns	ns
	10:1 (8)	123.83	40.40	57.52		*	*	ns
	13:1 (9)	171.28	64.41	157.18		**	ns	**
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	**	ns	**				
	8-9	ns	ns	**				
Rudder Effect Comparisons (R)	4-7	ns	ns	ns				
	5-8	*	ns	ns				
	6-9	**	*	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-79. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR CONSISTENCY

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	Leg 1 (3)	105.08	32.58	36.75	0.001	**	**	ns
	Leg 4 (4)	55.64	47.89	58.69		ns	ns	ns
Rudder Effect Comparison (R)	3-4	**	**	**				

** $p < 0.01$

TABLE C-80. RELATIONSHIP AMONG MEANS FOR WIND SIDE (C) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR CONSISTENCY

		Starboard (1)	Port (2)	Interaction p Value	Wind Side Comparisons (C) 1-2
	Leg 1 (3)	52.91	63.37	0.05	ns
	Leg 4 (4)	46.78	61.37		*
Rudder Effect Comparison (R)	3-4	ns	**		

* $p < 0.05$ ** $p < 0.01$

TABLE C-81. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR CONSISTENCY

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	67.42	30.58	34.33	0.01	*	**	ns
	10:1 (5)	103.00	33.83	31.75		**	**	ns
	13:1 (6)	144.83	33.33	44.17		**	**	ns
Wind Ratio Comparisons (B)	4-5	*	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	39.92	30.17	30.00		ns	ns	ns
	10:1 (8)	58.92	50.50	55.92		ns	ns	ns
	13:1 (9)	71.08	63.00	87.17		ns	ns	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	*	**	**				
	8-9	ns	ns	*				
Rudder Effect Comparisons (R)	4-7	*	ns	ns				
	5-8	**	ns	*				
	6-9	**	*	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-82. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR BOUNDARY PENETRATION

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	0.17	0.00	0.00	0.01	ns	ns	ns
	10:1 (5)	0.42	0.00	0.00		**	**	ns
	13:1 (6)	1.08	0.00	0.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	0.58	0.00	0.00		**	**	ns
	10:1 (8)	0.67	0.00	0.17		**	**	ns
	13:1 (9)	0.67	0.08	0.25		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Rudder Effect Comparisons (R)	4-7	**	ns	ns				
	5-8	ns	ns	ns				
	6-9	**	ns	ns				

** $p < 0.01$

TABLE C-83. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR BOUNDARY PENETRATION FOR STARBOARD WIND

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	0.17	0.00	0.00	0.05	ns	ns	ns
	10:1 (5)	0.33	0.00	0.00		ns	ns	ns
	13:1 (6)	1.00	0.00	0.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	0.50	0.00	0.00		**	**	ns
	10:1 (8)	0.33	0.00	0.33		ns	ns	ns
	13:1 (9)	0.67	0.00	0.00		**	**	ns
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	ns	ns	ns				
	8-9	ns	ns	ns				
Rudder Effect Comparisons (R)	4-7	*	ns	ns				
	5-8	ns	ns	ns				
	6-9	*	ns	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-84. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR BOUNDARY PENETRATION FOR PORT WIND

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	0.17	0.00	0.00	0.05	ns	ns	ns
	10:1 (5)	0.50	0.00	0.00		**	**	ns
	13:1 (6)	1.17	0.00	0.00		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	**	ns	ns				
	5-6	**	ns	ns				
LEG 4	8:1 (7)	0.67	0.00	0.00		**	**	ns
	10:1 (8)	1.00	0.00	0.00		**	**	ns
	13:1 (9)	0.67	0.17	0.50		**	ns	ns
Wind Ratio Comparisons (B)	7-8	*	ns	ns				
	7-9	ns	ns	**				
	8-9	*	ns	**				
Rudder Effect Comparisons (R)	4-7	**	ns	ns				
	5-8	**	ns	ns				
	6-9	**	ns	**				

* p @ 0.05 ** p @ 0.01

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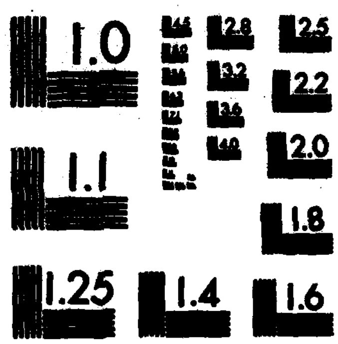

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TABLE C-85. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY RUDDER EFFECT (R) BY WIND SIDE (C) FOR BOUNDARY PENETRATIONS

		Wind Side Comparisons (C)		
		LNG	80K	30K
	8:1	ns	ns	ns
Leg 1	10:1	ns	ns	ns
	13:1	ns	ns	ns
	8:1	ns	ns	ns
Leg 4	10:1	**	ns	ns
	13:1	ns	ns	**

** $p < .01$

TABLE C-86. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR SHIP SPEED

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
	Leg 1 (4)	6.29	5.16	5.06	0.01	**	*	ns
	Leg 4 (5)	9.55	6.41	6.91		**	**	ns
Rudder Effect Comparisons (R)	4-5	**	**	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-87. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR SHIP SPEED

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
	Leg 1 (4)	5.34	5.40	5.77	0.001	ns	ns	ns
	Leg 4 (5)	6.68	7.28	8.91		**	**	**
Rudder Effect Comparisons (R)	4-5	**	**	**				

** $p < 0.01$

TABLE C-88. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR SHIP SPEED FOR STARBOARD WIND

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	5.69	4.88	5.01	0.01	ns	ns	ns
	10:1 (5)	6.08	4.97	5.13		*	*	ns
	13:1 (6)	6.62	5.60	5.21		*	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	ns	ns	ns				
	5-6	ns	ns	ns				
LEG 4	8:1 (7)	6.58	5.52	5.94		*	ns	ns
	10:1 (8)	9.10	6.09	6.53		**	**	ns
	13:1 (9)	11.18	7.40	8.16		**	**	ns
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	**	**	**				
	8-9	**	**	**				
Rudder Effect Comparisons (R)	4-7	*	ns	*				
	5-8	**	*	**				
	6-9	**	**	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-89. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR SHIP SPEED FOR PORT WIND

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	6.40	5.10	4.98	0.01	**	**	ns
	10:1 (5)	6.12	5.04	5.07		*	*	ns
	13:1 (6)	6.84	5.35	4.97		**	**	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	ns	ns	ns				
	5-6	ns	ns	ns				
LEG 4	8:1 (7)	10.43	5.67	5.95		**	**	ns
	10:1 (8)	8.86	6.23	6.86		**	**	ns
	13:1 (9)	11.13	7.53	8.05		**	**	ns
Wind Ratio Comparisons (B)	7-8	**	ns	ns				
	7-9	ns	**	**				
	8-9	**	**	**				
Rudder Effect Comparisons (R)	4-7	**	ns	*				
	5-8	**	**	**				
	6-9	**	**	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-90. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY RUDDER EFFECT (R) BY WIND SIDE (C) FOR SHIP SPEED

		Wind Scale Comparison (C)		
		LNG	80K	30K
	8:1	ns	ns	ns
Leg 1	10:1	ns	ns	ns
	13:1	ns	ns	ns
	8:1	**	ns	ns
Leg 4	10:1	ns	ns	ns
	13:1	ns	ns	ns

* $p < .01$

TABLE C-91. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B) BY RUDDER EFFECT (R) (LEGS 1 and 4) FOR RUDDER ANGLE

	8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
Leg 1 (4)	15.04	18.63	22.14	0.05	**	**	**
Leg 4 (5)	11.64	13.87	15.66		*	**	*
Rudder Effect Comparisons (R) 4-5	**	**	**				

$* p < 0.05$ $** p < 0.01$

TABLE C-92. RELATIONSHIP AMONG MEANS FOR WIND SIDE (C) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR RUDDER ANGLE

		Starboard (1)	Port (2)	Interaction p Value	Wind Side Comparisons (C) 1-2
	Leg 1 (3)	18.47	18.74	0.01	ns
	Leg 4 (4)	12.34	15.11		**
Rudder Effect Comparisons (R)	3-4	**	**		

** $p < 0.01$

TABLE C-93. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A) BY WIND RATIO (B) BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR RUDDER ANGLE

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	21.59	15.73	7.80	0.001	**	**	**
	10:1 (5)	20.41	23.70	11.78		*	**	**
	13:1 (6)	19.10	25.78	21.55		**	ns	**
Wind Ratio Comparisons (B)	4-5	ns	**	*				
	4-6	ns	**	**				
	5-6	ns	ns	**				
LEG 4	8:1 (7)	14.91	14.80	5.21		ns	**	**
	10:1 (8)	14.91	19.42	7.28		**	**	**
	13:1 (9)	17.35	19.99	9.62		ns	**	**
Wind Ratio Comparisons (B)	7-8	ns	**	ns				
	7-9	ns	**	**				
	5-6	ns	ns	ns				
Rudder Effect Comparisons (R)	4-7	**	ns	ns				
	5-8	**	**	**				
	6-9	ns	**	**				

* $p < 0.05$ ** $p < 0.01$

TABLE C-94. RELATIONSHIP AMONG MEANS FOR SHIP TYPE (A), BY WIND RATIO (B), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR ZERO RUDDER CROSSINGS

		LNG (1)	80K (2)	30K (3)	Interaction p Value	Ship Comparisons (A) 1-2	1-3	2-3
LEG 1	8:1 (4)	2.58	0.92	1.08	0.05	*	*	ns
	10:1 (5)	2.08	1.25	0.17		ns	**	*
	13:1 (6)	2.75	0.67	1.33		**	*	ns
Wind Ratio Comparisons (B)	4-5	ns	ns	ns				
	4-6	ns	ns	ns				
	5-6	ns	ns	*				
LEG 4	8:1 (7)	1.67	1.83	0.50		ns	*	*
	10:1 (8)	1.50	1.50	1.42		ns	ns	[illegible]
	13:1 (9)	2.83	1.92	2.08		ns	ns	[illegible]
Wind Ratio Comparisons (B)	7-8	ns	ns	ns				
	7-9	*	ns	**				
	8-9	*	ns	ns				
Rudder Effect Comparisons (R)	4-7	ns	ns	*				
	5-8	ns	ns	*				
	6-9	ns	*	ns				

* $p < 0.05$ ** $p < 0.01$

TABLE C-95. RELATIONSHIP AMONG MEANS FOR WIND RATIO (B), BY WIND SIDE (C), BY RUDDER EFFECT (R) (LEGS 1 AND 4) FOR ZERO RUDDER CROSSINGS

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons (B) 1-2	1-3	2-3
LEG 1	Starboard (4)	1.50	1.44	1.50	0.05	ns	ns	ns
	Port (5)	1.56	0.89	1.67				
Wind Side Comparison (C)	4-5	ns	ns	ns		ns	ns	ns
LEG 4	Starboard (6)	1.11	0.78	2.39		ns	**	**
	Port (7)	1.56	2.17	2.17				
Wind Side Comparison (C)	6-7	ns	*	ns		ns	ns	ns
Rudder Effect Comparisons (R)	4-6	ns	ns	**				
	5-7	ns	*	ns				

** $p < 0.01$
* $p < 0.05$

TABLE C-96. "PILOT EXPERIENCE GROUP ANALYSES" SOURCE TABLE, ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

Source of Variance	df	Mean Squares	F	P
E (Experience Group)	1	152,068.60	0.60	ns
S(E)	10	252,953.00	-	-
B (Wind Ratio)	2	37,402.31	1.01	ns
C (Wind Side)	1	321,562.30	10.35	0.01
EB	2	19,923.97	0.54	ns
EC	1	69,325.19	2.23	ns
BC	2	976.44	0.06	ns
EBC	2	75,846.06	4.98	0.05
S(E)B	20	37,212.75	-	-
S(E)C	10	31,059.68	-	-
S(E)BC	20	15,220.70	-	-
TOTAL	71			

TABLE C-97. "PILOT EXPERIENCE GROUP ANALYSIS" SOURCE TABLE, CONSISTENCY

Source of Variance	df	Mean Squares	F	P
E (Experience Group)	1	2,222.22	0.25	ns
S(E)	10	8,751.13	-	-
B (Wind Ratio)	2	2,736.22	4.19	0.05
C (Wind Side)	1	968.00	2.03	ns
EB	2	1,683.39	2.59	ns
EC	1	1,352.00	2.83	ns
BC	2	173.17	0.57	ns
EBC	2	21.50	0.07	ns
S(E)B	20	652.95	-	-
S(E)C	10	476.91	-	-
S(E)BC	20	294.78	-	-
TOTAL	71			

TABLE C-9[illegible]. "PILOT EXPERIENCE GROUP ANALYSIS [illegible]," BOUNDARY PENETRATIONS

Source of Variance	df	Mean Squares	F	p
E (Experience Group)	1	24.30	0.67	ns
S(E)	10	36.37	-	-
B (Wind Ratio)	2	2.04	0.62	ns
C (Wind Side)	1	0.22	0.07	ns
EB	2	6.79	2.07	ns
EC	1	2.00	0.59	ns
BC	2	3.18	1.61	ns
EBC	2	0.04	0.02	ns
S(E)B	20	3.28	-	-
S(E)C	10	3.38	-	-
S(E)BC	20	1.98	-	-
TOTAL	71			

TABLE C-9?. PILOT [illegible]

Source of Variance	df	Mean Square	F	p
E (Experience Group)	1	[illegible]	[illegible]	[illegible]
S(E)	10	[illegible]		
B (Wind Ratio)	2	340.31	26.91	0.001
C (Wind Side)	1	51.51	4.52	ns
EB	2	7.26	0.57	ns
EC	1	28.02	2.46	ns
BC	2	21.22	3.50	0.05
EBC	2	1.50	0.25	ns
S(E)B	20	12.65	-	-
S(E)C	10	11.38	-	-
S(E)BC	20	6.06	-	-
TOTAL	71			

TABLE C-[illegible]. [illegible]

Performance Measure	[illegible] Experience Group 1	Pilot Experience Group 2	Main Effect p-Value
Absolute Magnitude Off-Track Deviation (Feet)	113.94	95.15	ns
Consistency (Feet)	110.00	98.89	ns
Boundary Penetration (Frequency)	3.17	2.00	ns
Ship Speed (Kt)	7.05	6.30	ns

TABLE C-101. RELATIONSHIP AMONG MEANS FOR PILOT EXPERIENCE GROUP (E) BY WIND RATIO ([illegible]) BY WIND SIDE (C) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION

		8:1 (1)	10:1 (2)	13:1 (3)	Interaction p Value	Wind Ratio Comparisons ([illegible]) 1-2	1-3	2-3
GROUP 1	Starboard (4)	77.00	105.00	99.00	0.05	ns	ns	ns
	Port (5)	144.00	129.00	126.00		ns	ns	ns
Wind Side Comparisons (C)	4-5	**	ns	ns				
GROUP 2	Starboard (6)	84.00	87.00	93.00		ns	ns	ns
	Port (7)	75.00	118.00	114.00		**	*	ns
Wind Side Comparisons (C)	6-7	ns	*	ns				
Experience Comparisons (E)	4-6	ns	ns	ns				
	5-7	**	ns	ns				

** $p < 0.01$

* $p < 0.05$

TABLE C-102. CONFIDENCE INTERVALS ([illegible]) FOR ABSOLUTE MAGNITUDE OFF-TRACK DEVIATION AND CONSISTENCY

Ship Type and Wind Ratio		Absolute Magnitude Off-Track Deviation (feet)	Consistency (feet)
LNG	8:1	$103.25 \leq \mu_o \leq 152.21$	$111.60 \leq \mu_o \leq 138.74$
		$35.30 \leq \sigma_o \leq 73.20$	$19.57 \leq \sigma_o \leq 40.58$
	10:1	$133.77 \leq \mu_o \leq 182.13$	$137.80 \leq \mu_o \leq 168.70$
		$34.87 \leq \sigma_o \leq 72.32$	$22.28 \leq \sigma_o \leq 46.21$
	13:1	$147.34 \leq \mu_o \leq 176.80$	$167.09 \leq \mu_o \leq 184.41$
		$21.24 \leq \sigma_o \leq 44.05$	$12.49 \leq \sigma_o \leq 25.90$
80K	8:1	$57.66 \leq \mu_o \leq 98.24$	$66.52 \leq \mu_o \leq 81.32$
		$29.27 \leq \sigma_o \leq 60.69$	$10.68 \leq \sigma_o \leq 22.14$
	10:1	$65.14 \leq \mu_o \leq 103.62$	$68.62 \leq \mu_o \leq 94.54$
		$27.75 \leq \sigma_o \leq 57.54$	$18.69 \leq \sigma_o \leq 38.77$
	13:1	$65.97 \leq \mu_o \leq 94.59$	$71.17 \leq \mu_o \leq 93.33$
		$20.64 \leq \sigma_o \leq 42.81$	$15.98 \leq \sigma_o \leq 33.14$
30K	8:1	$49.90 \leq \mu_o \leq 96.06$	$79.94 \leq \mu_o \leq 95.90$
		$33.28 \leq \sigma_o \leq 69.02$	$11.50 \leq \sigma_o \leq 23.85$
	10:1	$51.76 \leq \mu_o \leq 108.80$	$85.07 \leq \mu_o \leq 108.93$
		$41.13 \leq \sigma_o \leq 85.30$	$17.20 \leq \sigma_o \leq 35.66$
	13:1	$85.63 \leq \mu_o \leq 148.01$	$95.10 \leq \mu_o \leq 120.90$
		$44.98 \leq \sigma_o \leq 93.28$	$18.60 \leq \sigma_o \leq 38.58$

APPENDIX D

TEST SUBJECT PROCEDURAL INFORMATION

CAORF Orientation

Welcome aboard the SS CAORF. We trust that your participation in the CAORF research program will be a stimulating and rewarding one.

The purpose of this manuscript is to provide you with an orientation as to what CAORF is, including it objectives and capabilities. CAORF (Computer Aided Operations Research Facility) is the most sophisticated and versatile ship maneuvering simulator in the world today. It was developed by the U.S. Maritime Administration and is managed by the National Maritime Research Center.

A realistic shipboard environment is achieved in the CAORF simulator by means of a full-scale wheelhouse with a complement of actual bridge hardware that can be found on most large contemporary merchant vessels. The wheelhouse is 20 feet wide with a depth of 14 feet. The flexible design of the bridge provides the capability to vary the equipment suite and physical arrangement, as desired.

The existing wheelhouse instrumentation consists of:

- o Two relative motion/true motion radar sets with the simulator capability of generating and displaying up to 40 moving target ships, and features normally found in the open sea, harbors, and docking areas, such as navigational aids and shoreline.
- o A computer-aided collision avoidance system.
- o Gyro pilot steering control stand which includes the helm with steering mode control, heading indicator, rate of turn indicator, rudder order and rudder angle indicators.
- o Propulsion console consisting of combined engine order telegraph/throttle control, propulsion plant operating mode control, and RPM indicator.
- o Bow and stern thruster controls, thruster output indicators and status lights.
- o Speed log and ship's clock.
- o Rate of turn indicator.
- o Communications equipment including sound-powered telephone, ship's intercom system, single-side-band HF radio, VHF radio and ship's whistle.
- o Wind speed and direction indicator.
- o Loran radio navigation equipment.

One of the unique and more extraordinary features of the CAORF simulator is the computer-generated visual imagery projected using television techniques which simulates the scene of the outside world as seen through the wheelhouse windows. Around the bridge is a 60-foot diameter cylindrical projection screen onto which the external situation is displayed covering a 240-degree field of view in relative bearing and 24 degrees in elevation. Detailed representations in full color can be provided of other ships, coastlines, buoys, bridges, buildings, piers, and other significant elements of the visual environment. The scene also includes "own ship's fore-body" which is superimposed on the centerline of the screen. The visual scene changes in real time in accurate response to own and other ship maneuvering motions. Other unique characteristics include the capability to (1) simulate restricted visibility conditions by altering the color intensity of an object in the visual scene as a function of the distance of the object from own ship such that the color of the object approaches the color of fog or haze; (2) control the scene illumination level so that either day or nighttime scenes may be simulated; (3) vary the correspondence of the generated scene to the watchkeeper's eye height above the waterline for the particular own ship being simulated; (4) change the data base to simulate any port in the world; and (5) change the data base to simulate many different vessels.

The conduct of experiments using the CAORF simulator is directed toward the achievement of the Maritime Administration's research goals, which are threefold:

- To [illegible] the [illegible] of the [illegible] [illegible] [illegible] [illegible] [illegible] [illegible] systems.

- To recognize high risk areas and implement procedures and equipment to reduce these risks, thereby increasing productivity and cutting costs.

- To reduce the cost of operations by developing new and safer procedures and equipment to minimize accidents and concurrent loss of life and damage to the environment.

Five major CAORF research programs have been planned which are directly tied to these goals and will be implemented over the next several years. They are in the areas of collision avoidance, ship control navigation, bridge system design, and harbor and restricted waterway research, and training and certification research. The objectives of these programs are to reduce the incidence of marine casualties and increase the capability of the watchkeeper to avoid collisions, to derive operational criteria and standards for the Maritime industry, and to develop merchant vessel and port design guidelines. It is with your cooperation and participation in the upcoming CAORF experiment that we hope to continue accomplishing these goals.

EXPERIMENT RESPONSIBILITIES AND [illegible] CHECK LIST FOR [illegible]

1) Test subject will be greeted by the Test Subject Coordinator and will fill out necessary forms in the lounge area including a Test Subject Experience - Run Sheet form, Figure D-1.

2) General familiarization regarding CAORF and current experiment by CAORF Research staff.

3) Bridge familiarization by Control Station staff.

4) Maneuvering Training by mate.

5) Brief subject on the channel using harbor information sheet and chart by CAORF Research staff.

   Explain unlimited visibility conditions and emphasize the five-knot speed requirements for the runs.

   Advise subject that he is to issue only rudder commands to the helm, no course commands, no steady commands.

   Prior to a run on a particular ship the channel depth and the height of the banks as well as the shoal area should be explained to the subject.

   30,000 DWT tanker and LNG Carrier
   Depth 45' Banks 36'

   80,000 DWT tanker
   Depth 50' Banks 40'

   Advise the subject that he will encounter no traffic in the channel.

6) Verbalization training by CAORF Research staff.

   Subject should be advised of the verbal report requirements of the study. Instruct the subject that our interest lays in determining what sources of information he is using and what criteria are used in leading to a particular command. For this purpose he is to comment on these factors after each command.

7) Check that the proper vessel characteristics booklet is on bridge by mate.

8) Base line run (Run 1) - mate on bridge.

9) Completion of initial Desired Track Sheet by CAORF Research staff. NOTE: Comments regarding DTS should be tape recorded - tape number and counter reading inserted on Test Subject Experience Run Sheet.

   Obtain optimal/intended trackline from the subject using scaled diagram and tape record verbal comments. This should be done prior to the second experiment run as well as subsequent runs (for changes). A concerted effort should be made to encourage the subject to provide information here.

10) [illegible] mate. For data collection purposes the subject [illegible] be fitted with the wireless microphone.

11) Mate to note helm and speed orders on data sheets (Figure D-2) during all runs. Change of Desired Track Sheet at conclusion of each run, to be noted.

12) Run (3) immediately after DTS change.

13) Continue through Run (7).

14) Final debriefing of subject. Use check list for debriefing. Remarks should be tape recorded during all debriefings with tape # and counter reading inserted on Test Subject Experience Run Sheet.

15) The Control Station operators should be aware of the following

- [illegible]
- [illegible]
- [illegible]
- [illegible] is in the [illegible] mode.
- Bow [illegible] inoperative.
- [illegible] should be [illegible].
- Video tape recorder should be set up.
- Gyro repeater is set prior to each run.
- The mate will have the responsibility during each run to record helm orders and engine orders and to comment when speed gets higher than six knots.
- For each experiment, run a Vessel Characteristics chart for the specific ship should be placed on the bridge.
- Wind noises properly set for wind conditions.

[illegible]

[illegible]

1. Subject ID # ____________

2. Date ________________

3. Experiment Subject # ____________ 80,000 DWT tanker
   30,000 DWT tanker
   LNG 125,000 m^3 carrier

4. Type of Experience ______________________________________
   ____
   ____

5. Years of Experience __________

6. Prior CAORF Experience __________Yes __________No
   If Yes: ____
   ____
   ____

7. Check off for initial optimal path ____________________
   Tape # ________________ Counter ________________

8.

Run #	Condition	Additional Changes to DTS
1	1	
2	______	
3	______	
4	______	
5	______	
6	______	

9. Final Debriefing _______ Tape # _______ Counter _______

Figure D-1 Ship Characteristic Experiment Test Subject Experience - Run Sheet

ENGINE AND RUDDER ORDERS (SHIP # ________)

DATA SHEET

SUBJECT I.D. # ____________________ MATE ____________________

RUN # ____________________ HELMSMAN ____________________

PLAYBACK TAPE # ____________________ DATE ____________________

BRIDGE TIME	ENGINE ORDERS	RUDDER ORDERS

Figure D-2 Engine and Rudder Orders Data Sheet