GRAVINA ACCESS PROJECT

Monte Carlo Navigation Simulation
Technical Memorandum

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DOT&PF Project 67698
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The U.S. Coast Guard Office of Bridge Administration in Juneau requested that modern simulation methods be applied to determine the horizontal clearance for any bridge planned across Tongass Narrows. PIANC recommends that horizontal clearances be estimated using fast-time Monte Carlo maneuvering simulation techniques during preliminary design, and that the final project design be verified using full-mission ship maneuvering simulations with the participation of marine pilots and ship masters. A Monte Carlo fast-time maneuvering simulation study has been performed of large cruise ships and Alaska ferries transiting Tongass Narrows under the alternative bridge sites of the Gravina Access Project (GAP). This study estimates the probability distributions and statistics for 26,639 cruise ship transits and 45,550 Alaska ferry transits during a 50-year exposure period. Monte Carlo random variables include steady wind speed and direction, wind gusts, current, initial position and heading. The maneuvering characteristics of the cruise ships and ferries have been individually calibrated to available data. All vessels are under the control of a trackline autopilot intended to represent the abilities of a good marine pilot and quartermaster (helmsman).

This Monte Carlo maneuvering simulation study does not include simulation of the extreme avoidance maneuvers and actions (other than commanding maximum helm angles) that might be ordered and attempted once the master or marine pilot recognizes that an accident is imminent. Possible extreme avoidance actions include the following or combinations of the following: crash stops, twin-screw maneuvers (i.e., differential thrust), use of the bow thruster and deploying one or both anchors. Their efficacy is completely dependent on how soon an operator recognizes that an accident is imminent and the timing and choice of subsequent action. Thus these extreme avoidance maneuvers and actions belong entirely to the domain of human factors. Accordingly, the best way to evaluate their effectiveness is in a full-mission simulator where the behavior of the expert mariner can be tested and studied in a realistic stimulus context.

Probability distributions and statistics developed by this Monte Carlo maneuvering simulation study provide a good basis for evaluating the probable safety and economic consequences of any selected or postulated horizontal clearance. However, there is no generally recognized and accepted standard for the probability of ship allisions or groundings. This Monte Carlo study uses the risk associated with current operations in Tongass Narrows as a metric for the risks associated with proposed new bridges. The following table shows passage risk normalized by that associated with large cruise ships transiting the north branch of Tongass Narrows at its narrowest point in the vicinity of Charcoal Point. This table shows that the risk associated with the East Channel passage between Idaho and California Rocks is 8.66 times more hazardous than the passage near Charcoal Point, and transiting West Channel is 10.72 times more hazardous (or 24% more hazardous than East Channel). A bridge located at C3(a)/C4 with an effective horizontal clearance of 550 feet presents a passage hazard 3.97 times greater than the existing natural passage near Charcoal Point, but this is less than half of the hazard currently accepted in the transit of East Channel. A bridge located at C3(a)/C4 with an effective horizontal clearance of 650 feet would present a hazard only 1.44 times greater than that associated with the existing passage near Charcoal Point.

COMPARATIVE RISK OF POTENTIAL GROUNDINGS/ALLISIONS OF LARGE CRUISE SHIPS OPERATING IN TONGASS NARROWS

Natural Channel or Bridge Alternative	Width (feet)	Normalized Risk Factor Relative to Natural Channel near Charcoal Point
Charcoal Point	687	1.00
East Channel	477	8.66
West Channel	476	10.72
C3(a) or C4	500	6.73
	550	3.97
	600	2.37
	650	1.44
	687	1.00
	700	0.88

Gusting wind has been identified as the principal cause of the rare large off-track excursions; when such excursions occur, they are exacerbated by bank suction effects. The ameliorating effect of imposing wind speed limits on large cruise ship transits under bridges C3(a) or C4 was investigated. For a bridge with a 550 foot horizontal clearance a limiting wind speed of 11.8 knots would result in a probability of allision similar to that associated with the 687 foot natural channel near Charcoal Point in the absence of wind speed limitations (i.e., the current natural risk). If the horizontal clearance were to be increased to 650 feet the corresponding wind speed limit could be increased to 17.9 knots.

This Monte Carlo study confirms the need for pier protection unless the piers are located outside the grounding line for large cruise ships. The probability distributions developed by this Monte Carlo study (suitably modified to account for extreme avoidance actions) are suitable for first principles based design of energy absorbing and/or barrier type pier protection structures.

1—Introduction

The Alaska Department of Transportation and Public Facilities (DOT&PF) is investigating ways to improve access between the City of Ketchikan (on Revillagigedo Island) and Gravina Island as part of the Gravina Access Project. Initial estimates of the navigation channel width (between bridge piers) were developed using the PIANC (International Navigation Association) concept design method. Based on the principal dimensions of the *Carnival Conquest*-class cruise ship as the design vessel, that method suggested horizontal clearances ranging from a minimum of 326 feet to 609 feet, depending on varying assumptions regarding intrinsic vessel maneuverability, water depth, wind speed, aids to navigation and visibility. Based on these estimates a concept design horizontal clearance of 550 feet was selected for bridges with sufficient vertical clearance to permit passage of large cruise ships. Similar estimates ranging from 196 feet to 434 feet were developed for Alaska Marine Highway System ferries, resulting in selection of a 500 foot horizontal clearance for concept designs of bridges with vertical clearance sufficient for Alaska ferries but not large cruise ships.

The U.S. Coast Guard, Office of Bridge Administration in Juneau requested that modern simulation methods be applied to determine the horizontal clearance for any bridge planned across Tongass Narrows. PIANC recommends that horizontal clearances be estimated using fast-time Monte Carlo maneuvering simulator techniques during preliminary design and that the final project design (should a bridge be selected as the preferred alternative) be verified using full-mission ship maneuvering simulations with marine pilots and cruise ship masters participating. This report addresses the fast-time Monte Carlo maneuvering simulations for several bridge alignments that remain under consideration as project alternatives.

Marine vessel transits were simulated at the bridge alignments of five project alternatives: C3(a), C3(b), C4, D, and F3. For Alternatives C3(a) and C4 (with a vertical clearance of 200 feet), 49,804 transits by large cruise ships were simulated; for Alternatives C3(b) and D (with a vertical clearance of 120 feet), 59,982 transits by Alaska Marine Highway System (AMHS) large ferries were simulated. The greatest directly sampled horizontal clearance at each bridge alignment was 1,222 feet for Alternatives C3(a) and C4, 502 feet for Alternative C3(b), and 664 feet for Alternative D.

Based on the sample probability distributions obtained from these simulations, the horizontal clearances required for a 50-year service life were estimated, predicated on 26,639 transits by large cruise ships and 45,550 transits by AMHS ferries. Summarized statistics for horizontal clearances are given in Table 1.1.

TABLE 1.1
MAXIMUM HORIZONTAL CLEARANCE STATISTICS FOR 50-YEAR SERVICE LIFE

Bridge Alternative	*Vertical Clearance (feet)*	*Design Class of Vessel*	*Most Probable Clearance (feet)*	*Probability of Exceeding Most Probable Clearance*	*Horizontal Clearance (feet) with Exceedance Probability of 0.9999*	*50% Confidence Extreme Clearance (feet)*
C3(a), C4	200	Large cruise ships	1,096	0.64	847	1,143
F3	200	Large cruise ships	1,125	0.64	875	1,172
C3(b)	120	AMHS ferries	364	0.64	296	377
D	120	AMHS ferries	587	0.70	393	653

These statistics represent horizontal clearances exceeded by one ship in 50 years. Additional statistics for horizontal clearances exceeded by two, three, four, and five ships over a 50-year period are given in Table 4.10 (for Alternatives C3[a] and C4), Table 5.6 (for Alternative C3[b]), and Table 5.7 (for Alternative D).

The autopilot parameters necessary to ensure good performance in Tongass Narrows confirm that the professional marine pilots are applying a high level of skill when piloting large cruise ships through Tongass Narrows. It was observed that the gusting wind was most responsible for the rare large off-track performance. Once a vessel was forced off-track by the wind, the off-track course was further exacerbated by bank suction effects. These Monte Carlo simulations were the emergency maneuvering actions that may be anticipated by the marine pilots to avoid an actual grounding or impact with bridge piers. Those actions might include crash stop maneuvers, application of bow thrusters, and/or dropping of one or both anchors. It is assumed that the marine pilots and ship masters would have the bow thrusters on standby and the anchors rigged for emergency deployment before transiting Tongass Narrows, especially on a windy day. Thus, the rare off-track behavior that dominates the horizontal clearance requirements, identified by this Monte Carlo study, may not represent actual groundings or impacts with bridge piers, but merely the potential.

The majority of ship transits are confined within a narrow corridor around the intended trackline. To illustrate this, Table 1.2 provides the horizontal clearances at everyday probability levels.

TABLE 1.2
EVERYDAY HORIZONTAL CLEARANCE STATISTICS AT COMMON PROBABILITY LEVELS

Bridge Alternative	*Vertical Clearance (feet)*	*Design Class of Vessel*	*0.9 (1 in 10)*	*0.99 (1 in 100)*	*0.999 (1 in 1000)*	*0.9999 (1 in 10,000)*
C3(a), C4	200	Large Cruise Ships	299	506	716	986
F3	200	Large Cruise Ships	310	526	743	1,013
C3(b)	120	AMHS Ferries	124	184	244	318
D	120	AMHS Ferries	124	185	287	451

For Alternatives C3(a) and C4 (large cruise ships), there are real, measurable, nonzero probabilities of allision with a bridge pier over the 50-year service life, unless the bridge piers are located outside the natural channel, i.e., located so that the ship will go aground first. The probability of a large cruise ship excursion to the limits of the natural channel in way of C3(a)/C4 (≈ 1,169 feet) over a 50-year period is approximately 43%. Consequently, unless the bridge piers are located outside the natural channel, pier protection is important.

The width of Tongass Narrows decreases as one proceeds from bridge site alternatives C3(a) and C4 to the vicinity of Charcoal Point opposite the Ketchikan shipyard. In this area the natural channel (between 5 fathom contours) is approximately 687 feet. This can be used to calibrate the probabilities for allisions with bridge piers at bridge site alternatives C3(a) and C4. Main channel horizontal clearances between bridge piers that exceed 687 feet will not introduce a greater hazard than that afforded by the natural channel in the vicinity of Charcoal Point. Main channel horizontal clearances between bridge piers less than 687 feet will introduce increases to the hazard of navigating the north branch of Tongass Narrows.

Bridge alternative F3 would have the effect of forcing large cruise ships to navigate West Channel. Currently large cruise ships prefer to use East Channel, so alternative F3 would force a change in cruise ship operations. AMHS ferries currently use West Channel so alternative F3 would not force a change of navigating practice on those vessels. The natural channel in West Channel is only about 476 feet wide. This corresponds to a probability for potential groundings of about 1 in every 60 large cruise ship transits of West Channel.

This study did not consider strong evasive action by ship masters or marine pilots. One effect of such evasive action should be to reduce excursions crossing the plane of the bridge at large off-track distances—because of a combination of those vessels that either stopped short of the plane (due to crash stop attempts), and those that successfully sheared back towards channel center (due to the action of the bow thrusters). A second effect should be, for those ships that do cross the plane of the bridge at large off-track distances, to reduce the speed at which any allision with bridge piers occurs (thereby reducing impact forces and energy).

2—PIANC Recommendations

The International Navigation Association (PIANC)[1] has headquarters in Brussels, Belgium. PIANC is an organization concerned with technical aspects of navigation and port infrastructure, and with the associated safety, economic, and environmental matters. PIANC was founded in 1885 and is sponsored by 40 national governments, including the United States, which joined in 1902.

The National Commission, composed of 11 members, is the central governing body of the U.S. Section of PIANC. The chairman is the Assistant Secretary of the Army (Civil Works); the Director of Civil Works for the U.S. Army Corps of Engineers serves as President; and the secretary is employed by the U.S. Army Corps of Engineers, Institute for Water Resources.

The U.S. Section has established technical committees to carry out PIANC's work. There are four committees: Environment; Shallow-Draft Waterways and Ports; Deep-Draft Waterways and Ports; and Sport and Recreation Navigation. These committees complement the structure of the international organization.

2.1 Concept Design Method

Reference 1, "Approach Channels – A Guide for Design," was developed by a joint working group of PIANC and IAPH (International Association of Ports and Harbors), in cooperation with IMPA (International Maritime Pilots Association) and IALA (International Association of Lighthouse Authorities).

Chapter 5 of Reference 1 describes a concept design method for channels. The method is based on a design ship (or ships) and determines, through an accumulation of factors, the minimum recommended channel width as a multiple of the design ship beam. In addition to the intrinsic maneuverability of the design ship(s) (good, moderate, or poor), the considered factors are:

- Vessel speed (knots): fast, moderate, or slow
- Prevailing cross wind (knots)
- Prevailing cross current (knots)
- Prevailing longitudinal current (knots)
- Significant wave height and wave length (meters)
- Aids to navigation:
  - Excellent with shore traffic control
  - Good
  - Moderate with infrequent poor visibility
  - Moderate with frequent poor visibility
- Bottom surface:
  - Smooth and soft
  - Smooth or sloping and hard
  - Rough and hard
- Depth of waterway relative to design ship draft
- Cargo hazard level: low, medium, or high
- Additional width for passing distance in two-way traffic
- Additional width for bank clearance

[1] Formerly the Permanent International Association of Navigation Congresses (PIANC).

PIANC's concept design method has been applied to Tongass Narrows using the *Carnival Conquest* class of cruise ship (this class includes *Carnival Conquest*, *Carnival Glory*, and *Carnival Victory*) as the design ship. The principal dimensions of the ships are given in Table 2.1. The results are summarized in Table 2.2.

TABLE 2.1
DIMENSIONS OF CRUISE SHIPS IN DESIGN SHIP CLASS

Parameter	*Dimension*
Length	894.0 feet
Beam	141.7 feet
Draft	27.2 feet
Speed *	7.0 knots

** Speed in Tongass Narrows is restricted by federal regulation to 7 knots.*

TABLE 2.2
MINIMUM AND MAXIMUM CHANNEL WIDTHS OF TONGASS NARROWS
Estimated Using PIANC Concept Design Method (One-Way, Light-Density Traffic Only)

Aids to Navigation	*Wind Speed (knots)*	*Water Depth (ft)*	*Intrinsic Vessel Maneuverability at Various Channel Widths (in feet)*		
			Good	*Moderate*	*Poor*
Good	10.15	40	411	439	482
		41	326	354	397
	33	40	482	510	553
Moderate with Frequent Poor Visibility	10.15	40	468	496	538
		41	383	411	453
	33	40	538	567	609
Minimum Channel Width			326	354	397
Maximum Channel Width			538	567	609

Design ship is Carnival Conquest *class cruise ship.*

In the calculation of the estimated minimum channel widths shown in Table 2.2, the following assumptions were made in all cases:

- (1) The cross current is 0.5 knots;
- (2) The longitudinal current is 3.0 knots;
- (3) The cargo hazard is low; and
- (4) The bank configuration is steep and hard with a rough and hard bottom surface.

According to the PIANC concept design method, under the most favorable of assumptions and circumstances, the minimum recommended channel width could be as little as 326 feet, while under the least favorable of assumptions and circumstances, it might be as large as 609 feet.

2.2 Preliminary Design Method

The overall channel design logic set forth in Reference 1 is illustrated by the logic diagram in Figure 2.1.

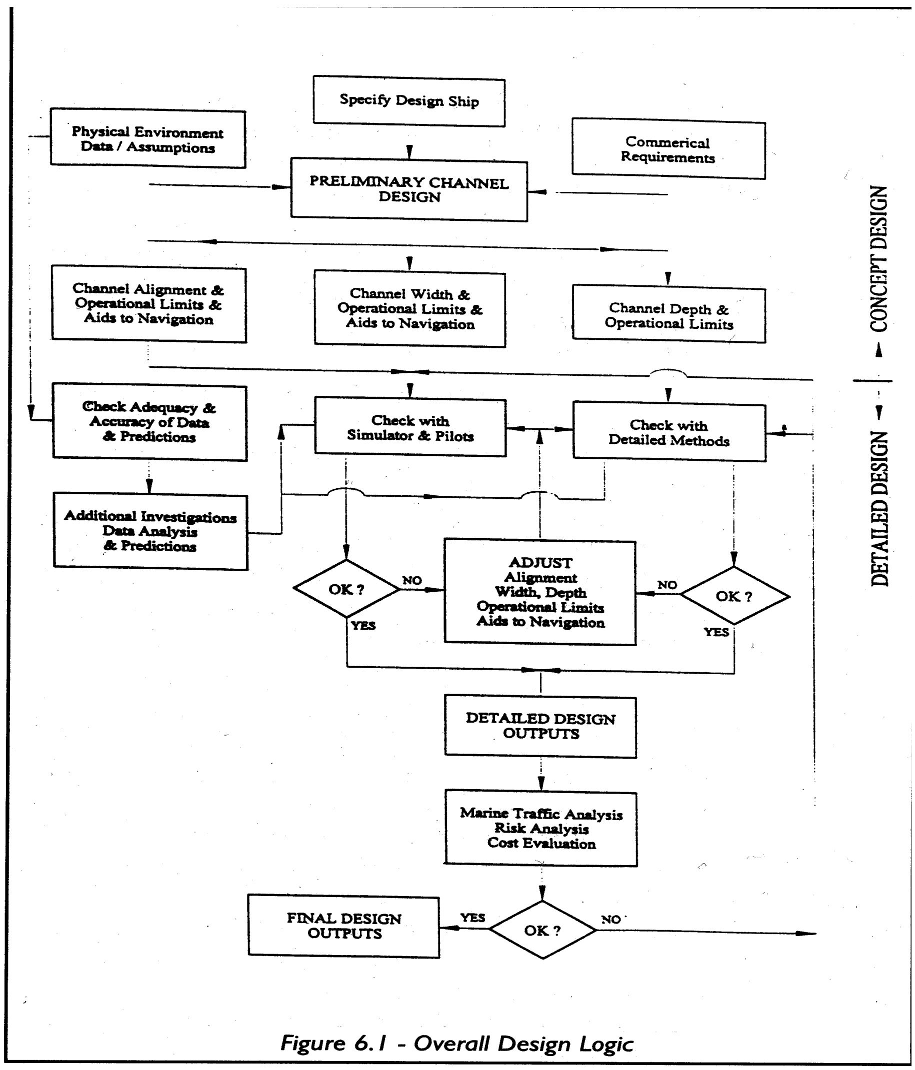

FIGURE 2.1
CHANNEL DESIGN LOGIC (FIGURE 6.1 FROM REFERENCE 1)

In Reference 1, PIANC does not specifically describe a method for the preliminary design stage. Chapter 5 of Reference 1 states that the concept design methods described in Chapter 5 may be applied: "*. . . to enable initial decisions (usually based on economic considerations)*" between "*. . . one or more concepts of width, depth and alignment.*" Chapter 5 goes on to state that the concept design method "*. . . will be satisfactory for the preliminary design of most channels but it is accepted that some occasions will arise when such a technique will be inappropriate and the more elaborate methods of Detailed Design will have to be employed, even for preliminary design.*" [emphasis added]

Fast-Time vs. Real-Time Simulations. *Chapter 6 of Reference 1 describes detailed design methods for channels. Two methods are described, the first using real-time simulation methods and the second using fast-time simulation methods. Both methods are described in Subchapter 6.4 of Reference 1, "Channel Width," and further applications of simulators are described in Chapter 7, "Marine Risk and Safety of Operation," and Chapter 8, "Methodology Overview: The Marine Impact Assessment." Figure 2.2, copied from Reference 1, illustrates the logic and roles of real-time and fast-time simulations in the design.*

Fast-time simulation is appropriate to a preliminary design for which alternative bridge alignments must be evaluated. The advantage of fast-time simulation is the substantially lower cost per run compared with real-time simulation, which makes fast-time simulation more economical in the preliminary evaluation of multiple sites. The disadvantage is that the assessment with fast-time simulation is less realistic, particularly regarding human factors.

Simulations for This Study. The preliminary design method of this report is Monte Carlo fast-time simulations. In this technique, maneuvering models of one or more suitable vessels are engaged in multiple fast-time simulator runs through the channel associated with a bridge alignment to be evaluated. The channel model should include in adequate detail:

- Local current
- Water depth (which affects vessel squat and maneuvering characteristics)
- The location and nature of banks (which gives rise to the "bank effects" that plague those maneuvering vessels in restricted channels)

Vessels operate under the command of programmed autopilots that may include random features introduced to mimic human operators. Conditions for runs are drawn from underlying probability distributions for direction of travel (northbound or southbound), tidal stage and associated current, and wind (including possibly the spatial and temporal gustiness associated with unsteady wind, initial off-track error, initial heading error, and initial yaw rate).

A run begins some distance (e.g., one mile) before the passage under the bridge alignment and continues a short distance beyond it. When passing the plane of the bridge, the closest points of approach to the bank, both on the left and on the right, are recorded as state variables for the run. Runs are repeated hundreds of times to obtain sample probability distributions for the closest point of approach to each bank, as illustrated in Figure 2.3.

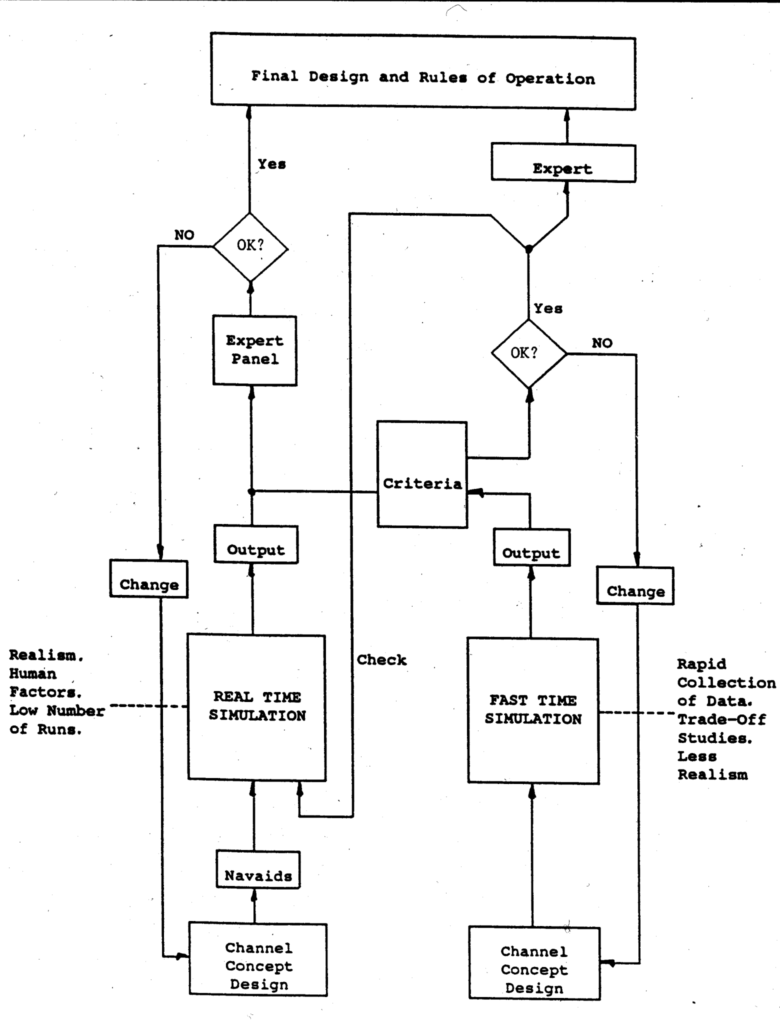

Figure 6.8 - Use of Real and Fast Time Simulation

FIGURE 2.2
USE OF REAL- AND FAST-TIME SIMULATION
(FIGURE 6.8 FROM REFERENCE 1)

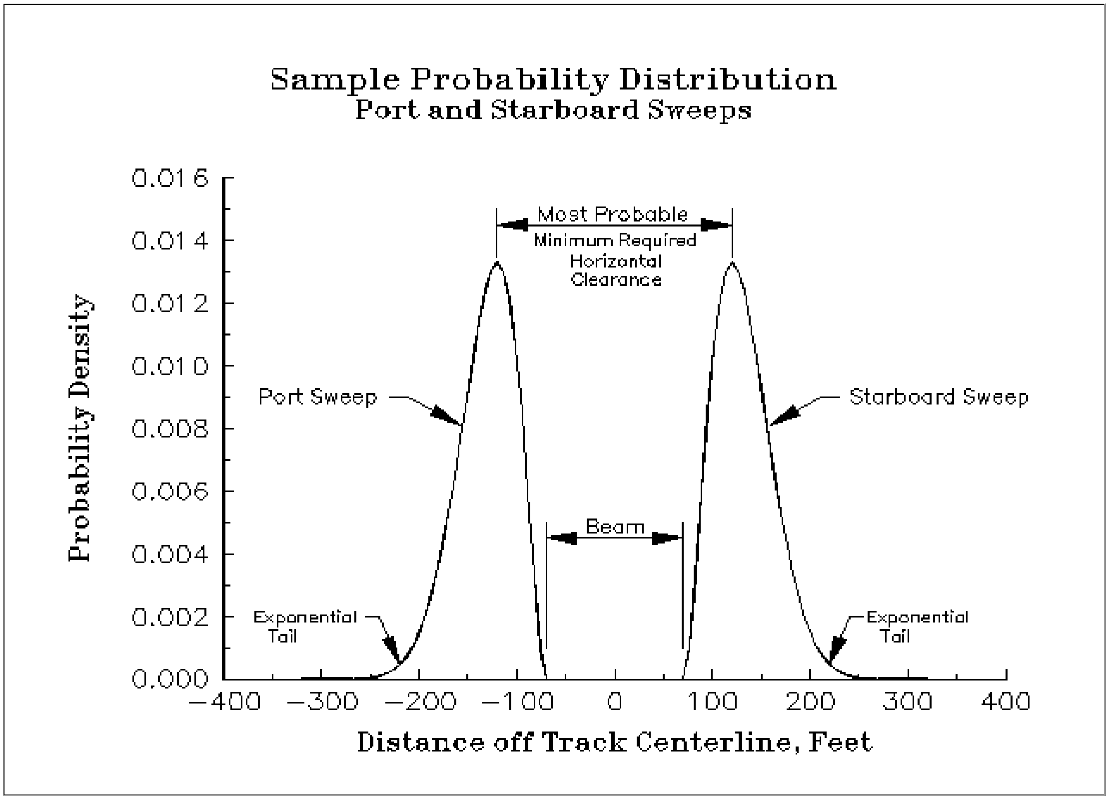

FIGURE 2.3
SAMPLE PROBABILITY DISTRIBUTIONS FOR CLOSEST POINT OF APPROACH TO EACH BANK

2.3 Final Design Method

Full-mission, real-time simulation methods are appropriate for final design once the potential bridge alignments have been winnowed down to one alternative. This is because full-mission, real-time simulations best evaluate human factors and because such techniques are the only methods that can garner the confidence of marine pilots. Thus full-mission, real-time simulations contribute substantially to the acceptance of a project by marine pilots, and in turn is expected to contribute to acceptability by the U.S. Coast Guard.

Full-mission simulators not only include the hydrographic, hydrodynamic, and current models common with the fast-time simulator, but also display visual projections of above-water features (topography, buildings, aids to navigation, etc.) viewed by the marine pilots operating the simulated vessel(s). Weather phenomena such as fog can be simulated, and the simulated time of day can be adjusted for daytime, dusk, or night-time. The pilots operate the simulated vessel from a realistic mockup of a navigation bridge. The mockup includes engine, rudder, and bow thruster controls; radar; fathometer; compasses; global positioning system (GPS), and radio. Visual and radar images of other ship traffic can also be generated. A partial list of measures and observations that may be obtained from a real-time full-mission simulator is provided in Table 2.3.

Because a full-mission simulator necessarily operates in real-time, which for ships is slow, and because of the substantial facilities and marine pilots' time necessary to make use of full-mission real-time simulation methods, these methods are usually regarded as prohibitively expensive for all but the final design process. For a bridge, that final design process would presumably include variations on bridge pier spacing in addition to runs with different current, wind, visibility, and marine traffic conditions.

At least two different Ketchikan marine pilots should be engaged to participate in the simulator exercises. This helps compensate for differences in both skill and luck of the pilots in their ability to successfully perform the simulation exercises. Also, there are two competing marine pilots' associations in Ketchikan, so using at least one pilot from each association would be prudent and politic.

An important application of real-time full-mission simulators is to gain insight into the human performance of cruise ship masters and marine pilots in emergency situations that require extreme avoidance measures such as crash stops, differential twin-screw maneuvers, and/or deployment of anchors. Measures of interest from such situations include recognition time, time from recognition until emergency orders are given, and the appropriateness and effectiveness of the emergency measures ordered.

Fast-time simulations can complement and enhance the value of the full-mission real-time simulation exercises. Fast-time simulation work performed in advance can help in the intelligent selection of exercises for the full-mission simulator. And measures of human performance that can be obtained from the full-mission simulator can subsequently be used to improve the ability of the fast-time simulator autopilot to mimic realistic human performance. Thus, additional fast-time simulations are sometimes commissioned following completion of the full-mission real-time simulation program, to obtain final sample probability distributions from which to estimate the probability of allision.

TABLE 2.3
PERFORMANCE MEASURES AND OBSERVATIONS
OBTAINABLE FROM A REAL-TIME FULL-MISSION SIMULATOR *

(1)	Vessel Speed (restricted to 7 knots in Tongass Narrows)	Too fast? OK ? Too slow?
(2)	Rudder Activity	Mean, maximum, and variance Frequency
(3)	Engine Movements	Frequency Number
(4)	Assessment of Ship's Line and Position Maintenance	Were you able to keep to the vessel's intended track (on your own side of the channel in a two-way channel)? With ease? With some difficulty? Hardly at all? Were you able to assess your position, both geographically and with relation to other traffic by day / by night? in poor visibility? with ease and quickly? with some difficulty? with considerable difficulty? Off track deviations: mean, maximum, and variance Heading deviations: mean, maximum, and variance Swept track at bridge: maximum port and starboard sweeps
(5)	Aids to Navigation	Buoy/light position and spacing: OK? Range lights: OK?
(6)	Aborts	Last point for safe abort? Point of no return: OK?
(7)	Visibility	Minimum needed to maintain design speed?
(8)	Control and Safety	Did you feel "in control" throughout? If not, why? Did you feel the channel (bridge width) to be safe? If not, why?

** Partial list, based in part on Figure 6.9 of Reference 1*

3—Fast-Time Monte Carlo Simulations

Monte Carlo maneuvering simulations as set forth in Table 3.1 were carried out for large cruise ships for Alternatives C3(a) and C4, and for AMHS ferries for Alternatives C3(b) and D.

TABLE 3.1
SUMMARY OF MONTE CARLO MANEUVERING SIMULATIONS

Class of Vessel and Bridge Alternatives	*Direction of Travel*	*Number of Distinct Vessels*	*Number of Transits Simulated*	*Number of Independent Climate Realizations*
Large Cruise Ships—Alternatives C3(a) and C4	Northbound	8	7,944	993
	Southbound	14	41,860	2,990
	Total		49,804	
AMHS Ferries—Alternatives C3(b) and D	Northbound	6	29,988	4,998
	Southbound	6	29,994	4,999
	Total		59,982	

Project Alternatives. The project alternatives crossing Tongass Narrows to provide access to Gravina Island are shown in Figure 3.1. The alignments of the four bridge alternatives used for the navigation simulations are shown in blue (Alternatives C3(a) and C3(b)), green (Alternative C4), and red (Alternative D). Alternatives C3(a) and C4 have identical bridge alignments across the Tongass Narrows marine navigation channel. The alignment of a fifth bridge alternative, F3, is shown in yellow.

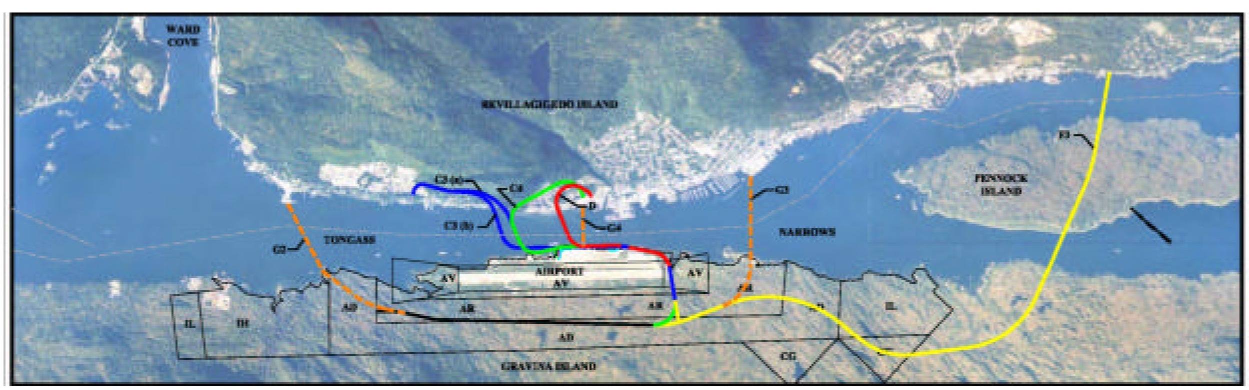

FIGURE 3.1
GRAVINA ACCESS PROJECT ALTERNATIVES

Table 3.2 presents the design vertical clearance and approximate natural channel width for all bridge alternatives. Of particular interest is the 687 foot width of the natural channel in the vicinity of Charcoal Point, the 477 foot width of the East Channel between Idaho Rock and California Rock, and the 476 foot width of West Channel associated with Alternative F3.

TABLE 3.2
GRAVINA ACCESS PROJECT BRIDGE ALTERNATIVES

Bridge Alternative	*Design Vertical Clearance (feet)*	*Approximate Natural Channel Width (Feet)*	*Class of Design Vessel*
C3(a)	200	1,169	Large Cruise Ships
C3(b)	120	1,316	AMHS Ferries
C4	200	1,169	Large Cruise Ships
D	120	1,251	AMHS Ferries
F3	200	476	Large Cruise Ships
Tongass Narrows (natural channel) in the vicinity of Charcoal Point		687	Large Cruise Ships
East Channel (natural channel between Idaho Rock and California Rock)		477	Large Cruise Ships (current practice)
West Channel (natural channel)		476	Large Cruise Ships (if alternative F3 is implemented)

The approximate natural channel width is between 5- fathom (30-foot) depth contours.
Channel widths are estimated perpendicular to vessel trackline.

Natural channel widths are measured perpendicular to the vessel trackline between 5-fathom (30-foot) depth contours. The 30-foot depth contours were selected as the nominal grounding line for large cruise ships in consideration of the following:

- The average draft of large cruise ships expected to call at Ketchikan is 25.9 feet
- The maximum draft of large cruise ships expected to call at Ketchikan is 28.9 feet
- Squat (including trim effects) at 7 knots may be on the order of 1.1 feet
- Extreme low water in Tongass Narrows is –5.0 feet

Alternatives C3(a) and C4. Alternatives C3(a) and C4 are the two bridge alternatives with vertical clearance suitable for large cruise ships. For this report, the horizontal clearance requirements for these two alternatives were evaluated for large cruise ships.

Alternatives C3(b) and D. The 120-foot vertical clearance of Alternatives C3(b) and D is suitable for such AMHS ferries and small cruise ships, but unsuitable for large cruise ships. For this report, horizontal clearance requirements for these alternatives were evaluated using large conventional AMHS ferries (e.g., *Columbia, Kennicott, Matanuska, Taku,* and *Aurora*).

Alternative F. Alternative F3 comprises a bridge across East Channel with a vertical clearance of 60 feet and a bridge across West Channel, with a vertical clearance suitable for large cruise ships. This 60-foot vertical clearance bridge is suitable for passage by local small craft up to (and including) the smallest U.S. Coast Guard cutter stationed at Ketchikan (the *Naushon*). The 60-foot bridge is not suitable for cruise ships, AMHS ferries, Inter-Island Ferry Authority ferries, or the larger U.S. Coast Guard cutters. Monte Carlo simulations have been carried out for large cruise ship transits of West Channel assuming that the high bridge over West Channel would not have piers in inside the navigation channel defined by the 30 fathom depth contours.

3.1 Tracklines

Cruise ship tracklines through Tongass Narrows were provided by Capt. Robert G. Winter of the Southeastern Alaska Pilots Association. Figure 3.2 shows the northbound trackline through Tongass Narrows, and Figure 3.3 shows the southbound trackline. The northbound and southbound tracklines are congruent, but the waypoints (WPs) are numbered in opposite directions (i.e., WP 1 is WP 10 for the other). Tables 3.3 and 3.4 provide the specific coordinates of waypoints, distances between waypoints, and course headings.

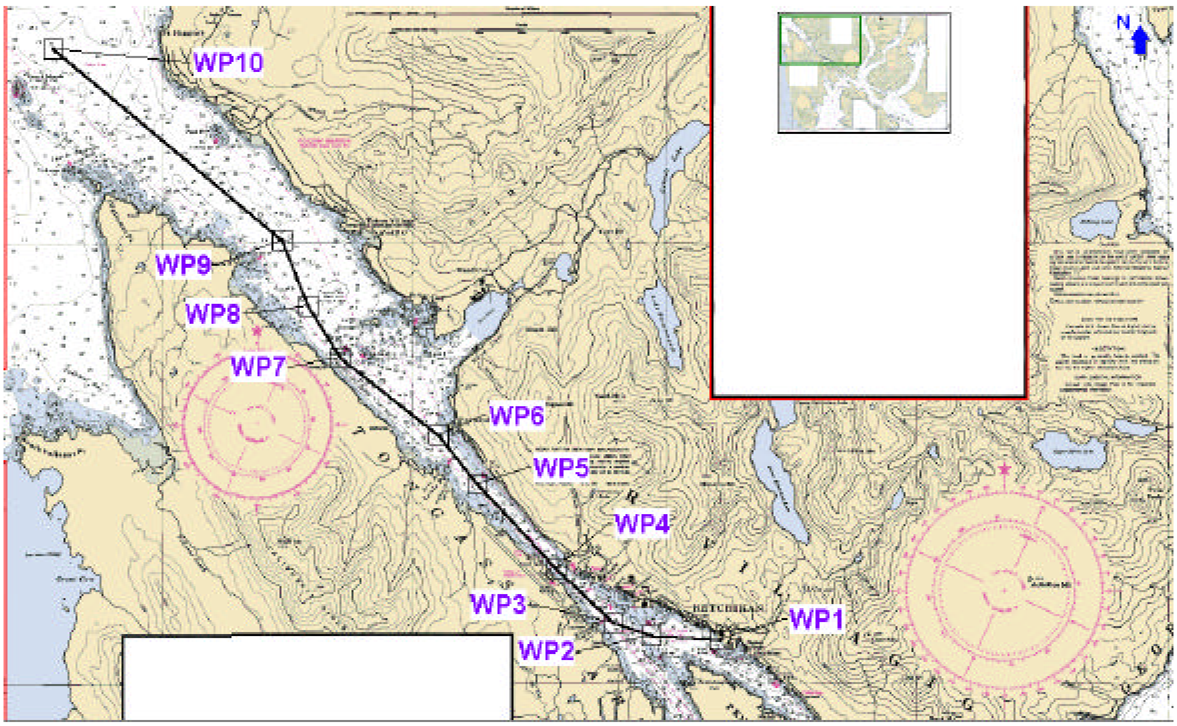

FIGURE 3.2
NORTHBOUND TRACKLINE THROUGH TONGASS NARROWS FROM KETCHIKAN TO GUARD ISLAND

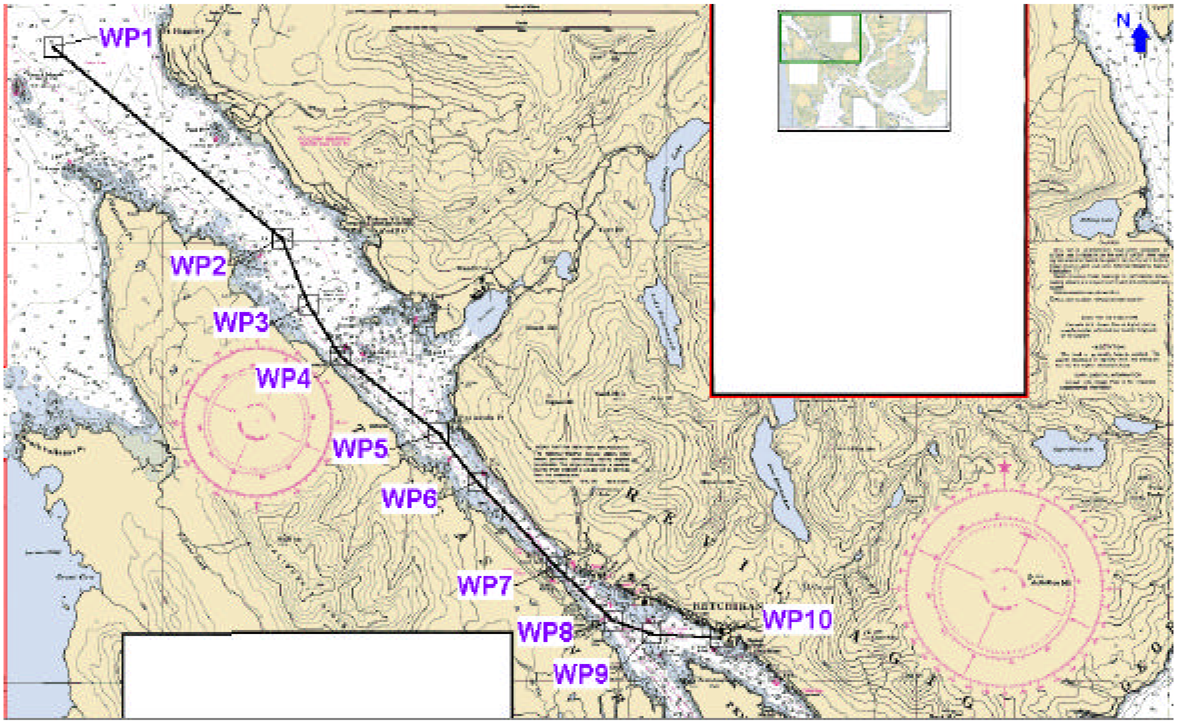

FIGURE 3.3
SOUTHBOUND TRACKLINE THROUGH TONGASS NARROWS
FROM GUARD ISLAND TO KETCHIKAN

TABLE 3.3
NORTHBOUND TRACKLINE WAYPOINTS
FROM KETCHIKAN TO GUARD ISLAND

Way-point	*Lat (N)*	*Long (W)*	*Next WP Distance*	*Next WP Bearing (True)*	*Next WP Bearing (Mag.)*
1	55° 20.498'	131° 38.916'	0.77 nm	274°	250°
2	55° 20.550'	131° 40.271'	0.45 nm	288°	264°
3	55° 020.688'	131° 41.020'	0.90 nm	314°	291°
4	55° 21.318'	131° 42.154'	1.31 nm	317°	293°
5	55° 22.274'	131° 43.728'	0.70 nm	322°	298°
6	55° 22.826'	131° 44.500'	1.41 nm	308°	285°
7	55° 23.705'	131° 46.452'	0.68 nm	328°	304°
8	55° 24.282'	131° 47.087'	0.81 nm	338°	314°
9	55° 25.031'	131° 47.617'	3.37 nm	310°	287°
10	55° 27.208'	131° 52.142'			

TABLE 3.4
SOUTHBOUND TRACKLINE WAYPOINTS
FROM GUARD ISLAND TO KETCHIKAN

Way-point	*Lat (N)*	*Long (W)*	*Next WP Distance*	*Next WP Bearing (True)*	*Next WP Bearing (Mag.)*
1	55° 27.208'	131° 52.142'	3.37 nm	130°	107°
2	55° 25.031'	131° 47.617'	0.81 nm	158°	134°
3	55° 24.282'	131° 47.087'	0.68 nm	148°	124°
4	55° 23.705'	131° 46.452'	1.41 nm	128°	105°
5	55° 22.826'	131° 44.500'	0.70 nm	142°	118°
6	55° 22.274'	131° 43.728'	1.31 nm	137°	113°
7	55° 21.318'	131° 42.154'	0.90 nm	134°	111°
8	55° 20.688'	131° 41.020'	0.45 nm	108°	084°
9	55° 20.550'	131° 40.271'	0.77 nm	094°	070°
10	55° 20.498'	131° 38.916'			

Presumed tracklines through West Channel are shown in Figure 4.17 in the next section and presumed tracklines through East Channel are shown in Figure 4.24.

3.2 Autopilot

Two- and three-term trackline autopilots are alternatively applied in these Monte Carlo simulations to mimic the actions of a local marine pilot and quartermaster (helmsman) navigating Tongass Narrows. The autopilot attempts to follow a predetermined trackline that is defined by waypoint coordinates and headings between waypoints. The autopilot functions in two different modes.

Mode 1 is a steering mode that mimics a mechanical or human autopilot commanded to steer to maintain a particular course heading (e.g., "steer 285° true"). This is accomplished using a standard two-term autopilot function (i.e., heading error and yaw rate error):

$$d = c_1(y - y_0) + c_2(\dot{y}' - \dot{y}_0') \tag{3.1}$$

where: d is the commanded rudder angle

ψ is the actual (instantaneous) vessel heading

ψ_0 is the desired course heading

c_1 and c_2 are constants (i.e., "gains")

$$\dot{\psi}_0' = \dot{\psi}_0 \sqrt{\frac{L_{pp}}{g}}$$

where $\dot{y}_0$ is the desired yaw rate (usually zero)

L_{pp} is the length between perpendiculars of the ship

g is gravitational acceleration

$$\dot{\psi}' = \dot{\psi} \sqrt{\frac{L_{pp}}{g}}$$

where $\dot{y}$ is the actual (instantaneous) vessel yaw rate

Mode 2 is a mode that attempts not only to steer a particular course but also to simultaneously adhere to the predetermined trackline, minimizing the off-track distance. This is accomplished by using a three-term autopilot function. To better mimic the behavior of a human pilot, the commanded rudder angle, if it exceeds 10 degrees, is applied in steps of 5 degrees:

$$\delta = c_1(\psi - \psi_0) + c_2(\dot{\psi}' - \dot{\psi}_0') + c_3 \frac{\varepsilon(s)}{L_{pp}} \tag{3.2}$$

where: s is a parameter (e.g., distance along track between waypoints)

$\varepsilon(s)$ is the cross-track position error, distance measured perpendicular to the trackline

c_3 is an additional constant (i.e., "gain")

The desired position (x, y) is treated as parametric functions: $x = f(s)$ and $y = g(s)$. Cross-track position error is determined using a vector cross-product.

In principle, a dependence on a cross-track velocity term could also be included. However, it was judged that such cross-track velocities are difficult for a human pilot to observe and that the human pilot is therefore unlikely to respond to cross-track velocity. For that reason, cross-track velocity was not included in the autopilot equation.

3.2.1 Autopilot Gains

Gains were determined using trial-and-error experimentation. Gains used in these Monte Carlo simulations were (c_1, c_2, c_3) = (3, 0.2, 2).

3.2.2 Looking Ahead and Overshoot at Waypoints

The heading and off-track error are computed by the autopilot based on an anticipated ship position half a ship length directly ahead of the bow. This creates some "look ahead" that anticipates future course changes. Without this look-ahead anticipation, the autopilot causes the vessel to overshoot at waypoints. Human pilots do look ahead and anticipate changes.

3.2.3 Dead Zone for Sensitivity to Off-track Error

Human pilots are insensitive to small off-track errors. When the off-track error is small, the human pilot is, in general, content to command the quartermaster to steer a course for heading alone, resulting in a track essentially parallel to the intended track. However, when the off-track error exceeds some threshold, the human pilot will command measures to bring it back to within acceptable bounds.

Telephone discussions with a marine pilot at the Southeastern Alaska Pilots Association indicated that, for passage under a fixed bridge, a pilot would correct for any detectable off-track distance. Fixed bridges are normally provided with range marks and range lights. If the range marks were 8 inches wide and separated by 60 feet, then a misalignment equal to the width of the range mark would correspond to an off-track error of 33.75 feet at a distance of one-half nautical mile (approximately 3½ ship lengths). The detectable off-track error would become progressively smaller as the ship approached the bridge.

It may also be possible to establish range marks at the northern end of Pennock Island. These range marks would provide an excellent forward range for southbound vessels and a somewhat less useful back range for northbound vessels.

The off-track dead zone modeled in these Monte Carlo simulations is half the beam of the ship on either side of the track line.

3.2.4 Dead Zone for Sensitivity to Heading Error

Similar to the dead zone for sensitivity to off-track error, the marine pilot and quartermaster will exhibit insensitivity to small errors in heading. Below this threshold, the helmsman will not act to correct heading. The heading error dead zone used in these Monte Carlo simulations was ±1 degree.

3.2.5 Rudder Response

The rudder responds to the commands with a rudder rate of 2.33 degrees per second—corresponding to 30 seconds hard-over to hard-over, based on a maximum rudder angle of 35 degrees.

3.3 Initial Position and Heading

Initial position and heading at the beginning of each Monte Carlo trial were treated as random variables. Northbound vessels start from a random position within a 1,000-foot-diameter maneuvering area off Ketchikan terminals, with a random heading that is between 15 degrees to either side of the trackline heading. Southbound vessels start from a random position within a circular area near Waypoint 5 in Table 3.4. The diameter of this circular area is equal to the beam of the ship. The initial ship heading is random between 5 degrees to either side of the trackline heading.

3.4 Speed

According to 33 CFR § 162.240 (b):

> *No vessel, except for floatplanes during landings and take-offs and non-commercial, open skiffs of less than 20 feet in length, shall exceed a speed of seven knots in the region of Tongass Narrows bounded to the north by Tongass Narrows Buoy 9 and to the south by Tongass Narrows East Channel Regulatory Buoy at position 55°19'22.0" N 131°36'40.5" W and Tongass Narrows West Channel Regulatory Buoy at position 55°19'28.5" N 131°39'09.7" W, respectively.*

These speed restrictions effectively limit or eliminate the likelihood of overtaking traffic in the most restricted areas of Tongass Narrows.

In the simulations, northbound vessels start from within the maneuvering area off Ketchikan terminals with an initial speed of 1 knot and a commanded speed of 7 knots. The southbound vessels start from their initial position near Waypoint 5 in Table 3.4 with an initial speed of 8 knots and a commanded speed of 7 knots. The command speed is held steady at 7 knots throughout every passage.

3.5 Bank Effects

When ships navigate in narrow channels, they are subject to additional hydrodynamic forces known as "bank effects." These are forces of attraction towards the bank brought about by the accelerated fluid flow between the vessel and the bank. For large R, these forces decay roughly at the rate of 1/R, where R is the distance from the ship to the bank. For a ship navigating down the center of a channel, the attraction forces to opposing banks are equal and opposite, thereby canceling. But as the vessel moves off centerline, the forces to the near bank become stronger and there is a net force towards the near bank.

Bank effects in these fast-time Monte Carlo maneuvering simulations were modeled using the method of images (see Reference 5). The banks were located in the hydrodynamic model of Tongass Narrows at the mean lower low water (MLLW) contours on each side of the channel.

3.6 One-Way vs. Two-Way Traffic

While two-way traffic is legal in Tongass Narrows, the *de facto* practice of vessels requiring pilotage is to make courtesy passing arrangements before entering the speed restricted zone. Both marine pilots' associations active in Ketchikan, and the masters and pilots of the AMHS ferries, have described this practice of making passing arrangements and have indicated that tugs with barge tows usually participate as well. As a consequence of these practices, two-way meetings between large vessels are in actuality rare or nonexistent.

As reported in Reference 6, it is theoretically possible (projected over the next 50 years) to schedule all large cruise ship traffic calling at Ketchikan for one-way traffic in Tongass Narrows.

If two-way traffic of large vessels in Tongass Narrows were determined to be a design case, then it would be necessary to include vessel-to-vessel hydrodynamic interaction in the maneuvering simulations. Such interactions are not included in the present study.

4—Cruise Ship Simulation Results for Alternatives C3(a), C4, and F3

4.1 Large Cruise Ship Principal Dimensions

In 2001 Ketchikan received 386 port calls by large cruise ships. Of these, 282 (73%) were by southbound cruise ships and 104 (27%) were by northbound cruise ships. Principal dimensions of the eight large cruise ships modeled for northbound transits are given in Table 4.1, and for the fourteen modeled for southbound transits, in Table 4.2. These sets of ships are augmented sets wherein, in an attempt to capture the continuing trend towards larger cruise ships, some of the smaller ships in the 2001 Ketchikan cruise calendar are replaced by larger (in passenger capacity) ships of the same cruise line.

TABLE 4.1
PRINCIPAL DIMENSIONS OF NORTHBOUND CRUISE SHIPS

Ship I.D.	*% of Northbound Transits*	*LWL (feet)*	*Water Line Beam (feet)*	*Maximum Beam (feet)*	*Draft (feet)*	*Displacement (Long Tons S.W.)*	*Approximate GRT*
N-1	10.64%	858	118	158	26.25	49,050	109,000
N-2	3.19%	713	97	97	26.33	28,180	48,621
N-3	1.06%	870	105	121	26.00	45,578	91,000
N-4	9.57%	781	103	119	25.50	40,798	77,713
N-5	27.66%	773	106	132	26.58	39,372	77,441
N-6	9.57%	826	106	116	25.25	38,309	78,491
N-7	29.79%	648	101	118	25.26	31,450	55,451
N-8	8.51%	807	110	142	27.20	50,006	101,500

LWL = length at waterline; GRT = gross register tonnage @ 100 cu.ft. of enclosed volume; Long Ton = 2240 pounds

Two of the southbound cruise ships used, identified as S-11 and S-12 have air drafts greater than 200 feet. Overall, they represent about 7% of the large cruise ship calls at Ketchikan in the model. The resulting Monte Carlo database has not been analyzed to determine the influence of specific cruise ships on the results. In the absence of such an analysis it is not possible to speculate on the influence of cruise ships S-11 and S-12 on the findings of this study.

TABLE 4.2
PRINCIPAL DIMENSIONS OF SOUTHBOUND CRUISE SHIPS

Ship I.D.	*% of Northbound Transits*	*LWL (feet)*	*Water Line Beam (feet)*	*Maximum Beam (feet)*	*Draft (feet)*	*Displacement (Long Tons S.W.)*	*Approximate GRT*
S-1	3.30%	858	118	158	26.25	49,050	109,000
S-2	1.83%	713	97	97	26.33	28,180	48,621
S-3	7.33%	870	105	121	26.00	45,578	91,000
S-4	4.40%	781	103	119	25.50	40,798	77,713
S-5	7.69%	680	93	105	23.00	31,103	50,760
S-6	10.26%	773	106	132	26.58	39,372	77,441
S-7	9.89%	826	106	116	25.25	38,309	78,491
S-8	8.06%	765	106	118	26.25	38,391	78,000
S-9	3.66%	557	88	88	27.30	22,528	23,500
S-10	11.72%	648	101	118	25.26	31,450	55,451
S-11	3.66%	807	110	142	27.20	50,006	101,500
S-12	5.86%	921	117	156	28.90	63,467	142,000
S-13	7.33%	722	96	106	23.60	32,566	53,900
S-14	15.02%	704	106	124	26.58	33,344	63,000

LWL = length at water line; GRT = gross register tonnage

4.2 Ship Maneuvering Characteristics

The ease with which a vessel can be held to a desired course in open water as well as in a restricted channel is determined by the inherent controllability of the vessel and the actions of the helmsman/pilot. There are a number of definitive maneuvers that serve to characterize the controllability of a ship. These include the direct or reversed spiral, zigzag, turning circle, etc. The results of the zigzag maneuver are indicative of the ability of a ship's rudder to control the ship. The zigzag trials results for three of the ships in the present study are shown in Figures 4.1 through 4.5. These were compared with simulated results for the same three ships to ensure that the models behave reasonably.

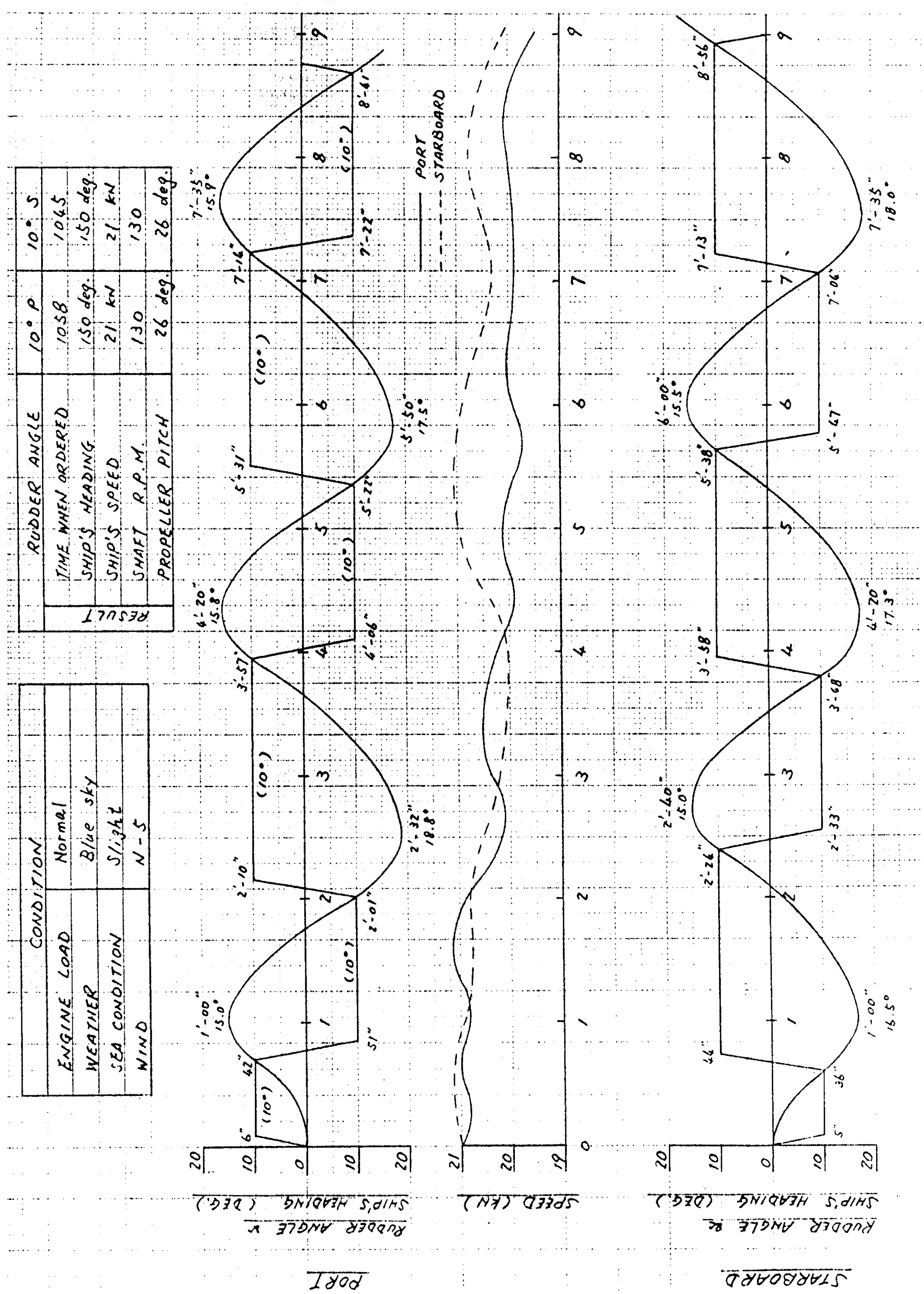

FIGURE 4.1
RESULTS OF THE 10°/10° ZIGZAG TEST FOR VESSEL A

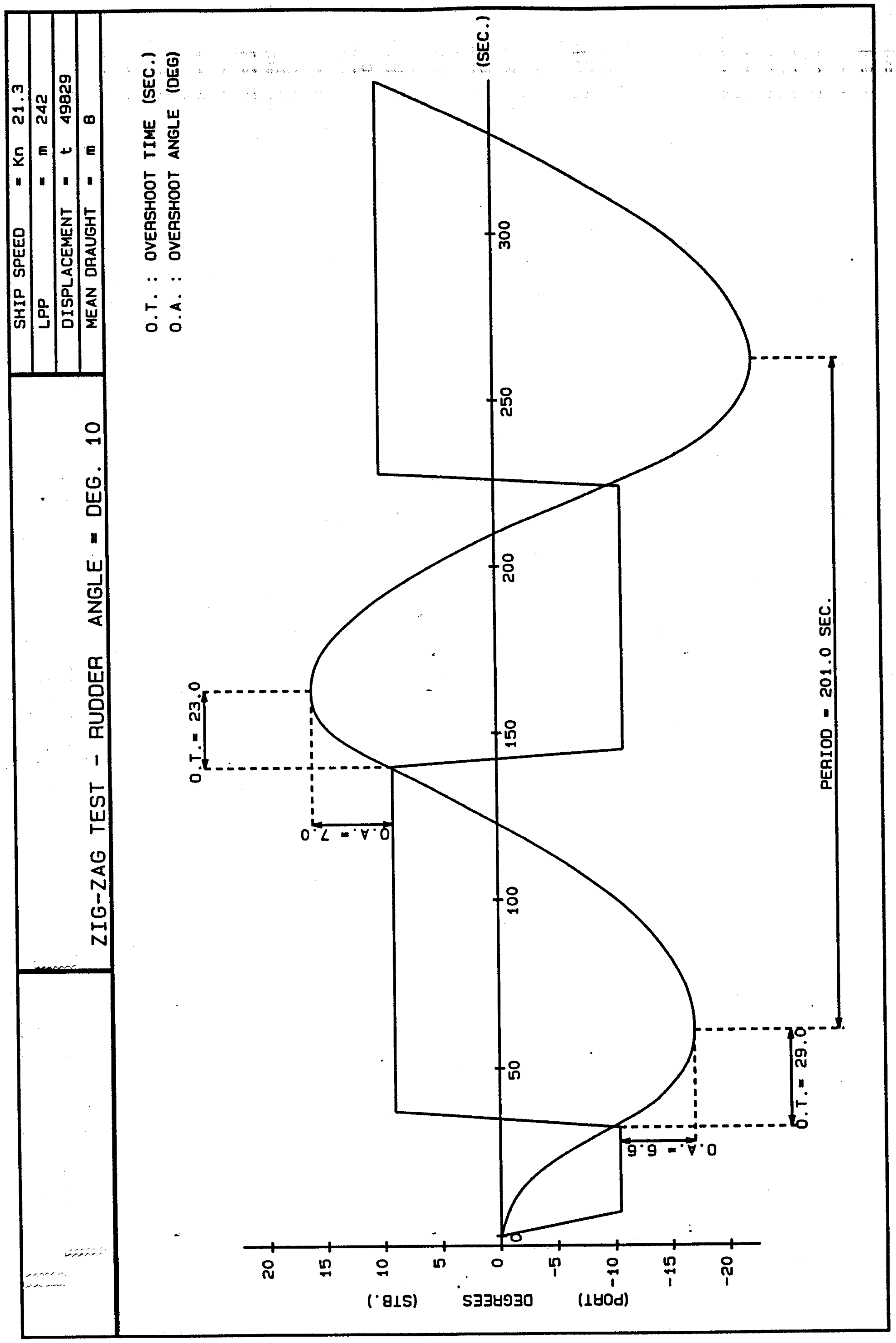

FIGURE 4.2
RESULTS OF THE 10°/10° ZIGZAG TEST FOR VESSEL B

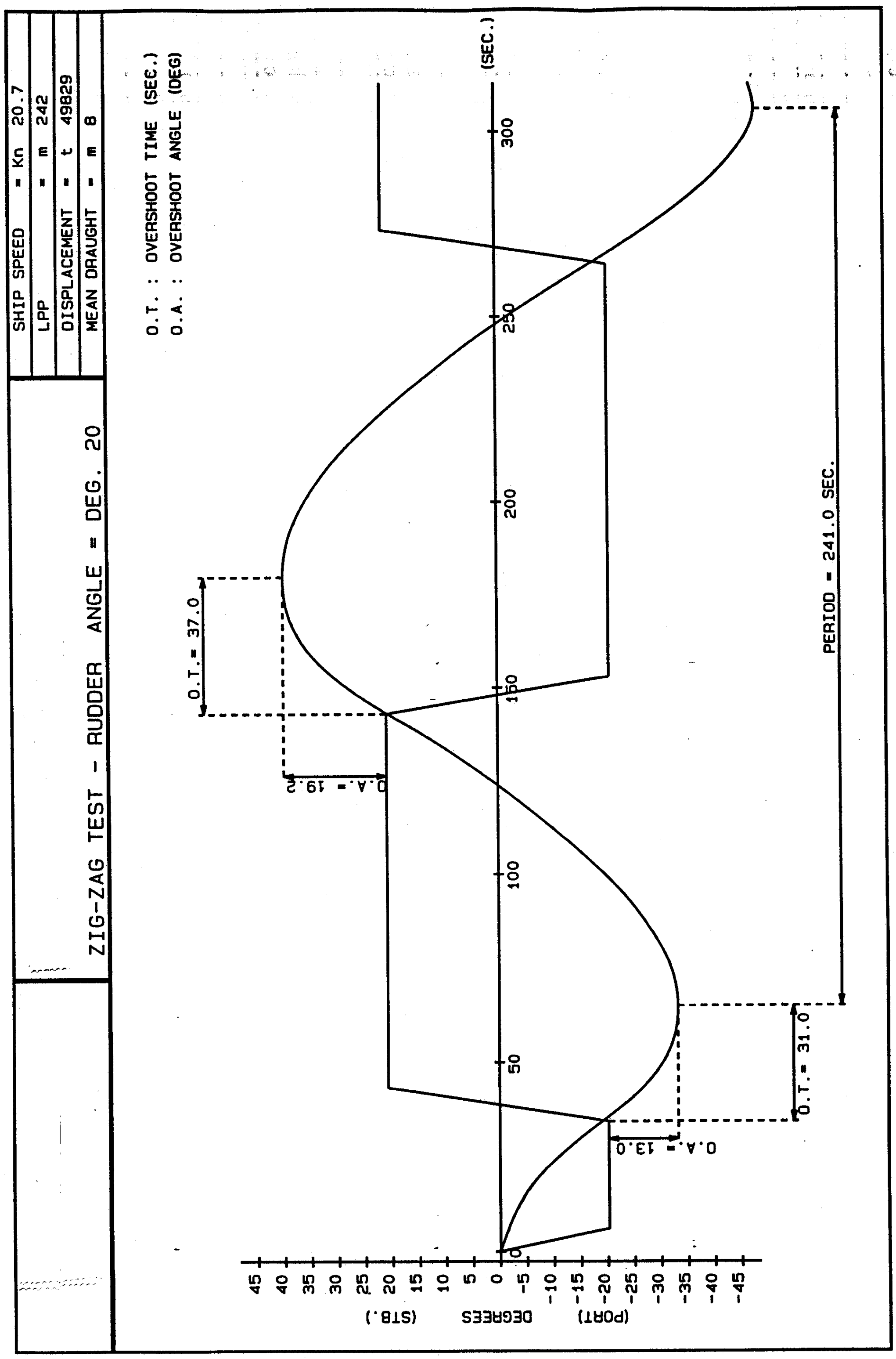

FIGURE 4.3
RESULTS OF THE 20°/20° ZIGZAG TEST FOR VESSEL B

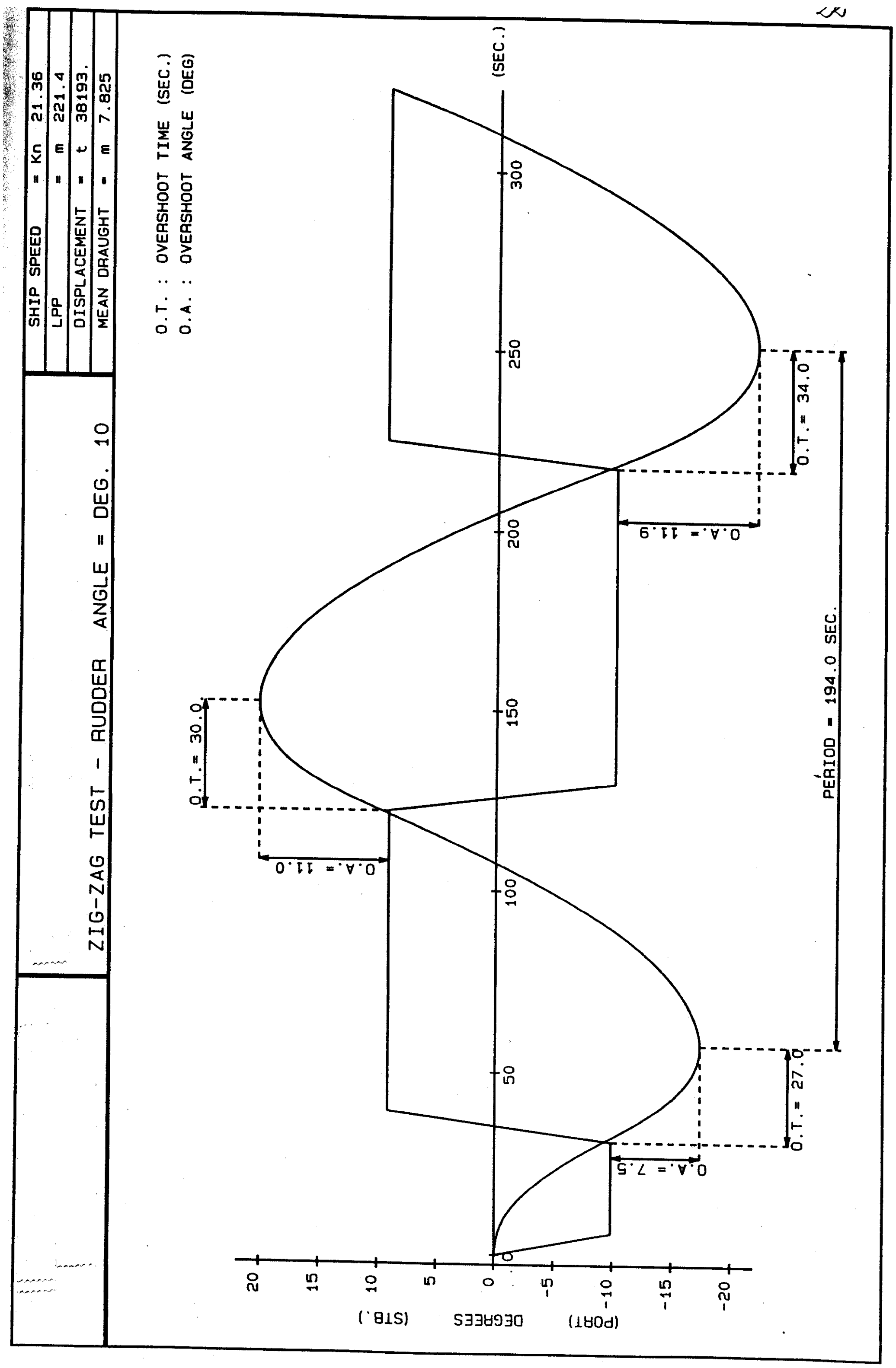

FIGURE 4.4
RESULTS OF THE 10°/10° ZIGZAG TEST FOR VESSEL C

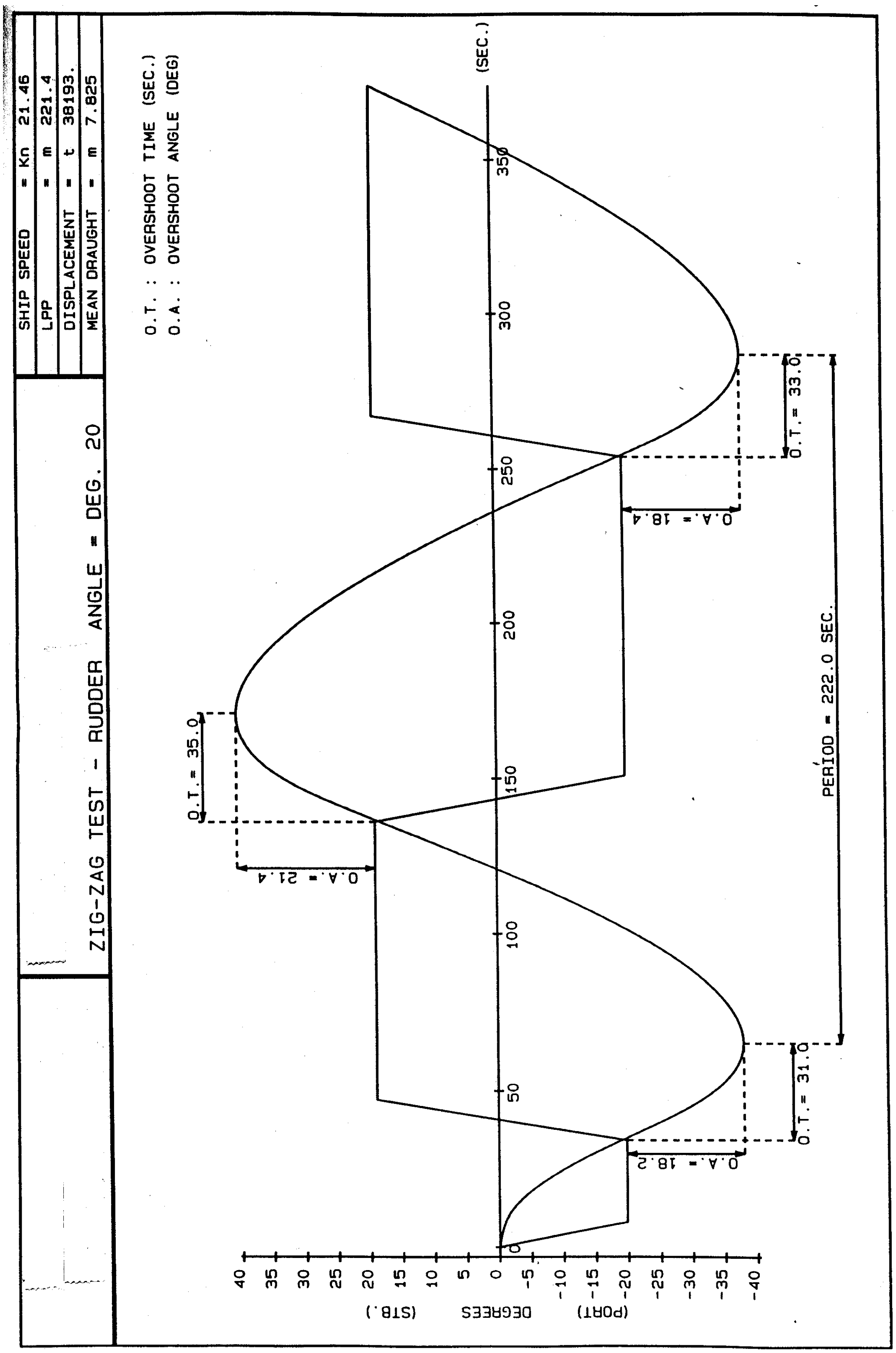

FIGURE 4.5
RESULTS OF THE 20°/20° ZIGZAG TEST FOR VESSEL C

The International Maritime Organization (IMO) adopted Resolution A.751 (18), "Interim Standards for Ship Maneuvering" at their 18th Assembly Session in 1993. These interim standards establish recommended performance as measured by the 10°/10° and 20°/20° zig-zag maneuvers, and turning circles. The salient measures predicted by the fast-time simulator for the northbound and southbound large cruise ships used in this Monte Carlo study are summarized in Tables 4.3 and 4.4.

TABLE 4.3
SUMMARY MANEUVERING CHARACTERISTICS OF NORTHBOUND CRUISE SHIPS AS SIMULATED

	10°/10° Zig-Zag		*20°/20° Zig-Zag*		
Ship I.D.	*1st Overshoot Angle*	*2nd Overshoot Angle*	*1st Overshoot Angle*	*Ratio of Tactical Diameter to Ship Length*	*Satisfies IMO Recommendations*
N-1	8°	10°	14°	4.4	YES
N-2	7°	8°	12°	4.4	YES
N-3	8°	9°	13°	4.4	YES
N-4	7°	8°	12°	4.8	YES
N-5	9°	11°	15°	4.4	YES
N-6	10°	15°	18°	3.2	YES
N-7	6°	6°	11°	4.3	YES
N-8	7°	8°	12°	4.4	YES

TABLE 4.4
SUMMARY MANEUVERING CHARACTERISTICS OF SOUTHBOUND CRUISE SHIPS AS SIMULATED

	10°/10° Zig-Zag		*20°/20° Zig-Zag*	*Turning Circles*	
Ship I.D.	*1st Overshoot Angle*	*2nd Overshoot Angle*	*1st Overshoot Angle*	*Ratio of Tactical Diameter to Ship Length*	*Satisfies IMO Recommendations*
S-1	8°	10°	14°	4.4	YES
S-2	7°	8°	12°	4.4	YES
S-3	8°	9°	13°	4.4	YES
S-4	7°	8°	12°	4.8	YES
S-5	9°	11°	15°	4.4	YES
S-6	7°	10°	13°	4.4	YES
S-7	8°	10°	15°	4.4	YES
S-8	7°	10°	14°	4.4	YES
S-9	9°	11°	15°	4.5	YES
S-10	10°	15°	18°	3.2	YES
S-11	6°	6°	11°	4.3	YES
S-12	7°	8°	12°	4.4	YES
S-13	7°	9°	13°	4.4	YES
S-14	9°	11°	17°	4.4	YES

All of the large cruise ships considered by this study satisfy the recommendations of the IMO interim standards.

4.3 Wind

The Monte Carlo procedure used to generate a pseudo-time function for unsteady wind acting over Tongass Narrows is described in the following subsections. The unsteady wind process is divided into two steps, the first to determine the mean wind speed and direction and the second to determine the magnitude and direction of gust perturbations.

4.3.1 Average Wind Parameters

Hourly vector (magnitude and direction) mean wind (one-minute average) is available from the Ketchikan Airport. These data have been analyzed and are the subject of a separate wind climatology report (Reference 2). Monthly joint probabilities of wind speed and direction were developed from the Ketchikan Airport wind data. Monthly joint probabilities for May, June, July, August, and September, corresponding to the cruise season in Alaska, were composited to obtain a joint probability distribution of wind speed and direction for the period May through September. This composite joint probability is for a 25-year period of record extending from 1974 through 1999. The composite joint probability is given in Appendix A to this report.

The procedure for generating the parameters of a random wind are to generate a random variable, ξ_1, from a uniform distribution between zero and one. This random variable is treated as a cumulative probability in order to interpolate a wind speed, U, from a table of cumulative probability of wind speed obtained from the marginal probability of wind speed which in turn is developed from the joint probability distribution given in Appendix A (Ketchikan Airport Wind Climatology [1974-1999]). Table 4.5 is the resulting cumulative probability distribution for one-minute average wind speed at the Ketchikan Airport during the period May through September. A Type-II fit of this cumulative probability distribution is shown in Figure 4.6.

TABLE 4.5
CUMULATIVE PROBABILITY, P(U),
OF WIND SPEED AT KETCHIKAN AIRPORT FOR MAY THROUGH SEPTEMBER (PERIOD OF RECORD, 1974-1999)

U (knots)	P(U)	U (knots)	P(U)
0	0	26	0.999799
2	0.000696	28	0.999907
4	0.093681	30	0.999907
6	0.272504	32	0.999923
8	0.566432	34	0.999923
10	0.710326	36	0.999923
12	0.886132	38	0.999938
14	0.955805	40	0.999938
16	0.976085	42	0.999938
18	0.989636	44	0.999954
20	0.997479	46	0.999985
22	0.997974	48	0.999985
24	0.999567	50	1.000000

Once a one-minute average wind speed, U, has been determined, then the mean direction may be obtained from a double interpolation in a table of conditional probability of wind direction, U_dir, given a wind speed, U. Table 4.6 is the table of cumulative conditional probability of wind direction given wind speed. To interpolate from this table one needs the wind speed, U, obtained using random variable ξ_1 and Table 4.5 as well as a new random variable ξ_2, also obtained from a uniform distribution between zero and one.

Following this Monte Carlo procedure, a one-minute average wind speed, U (knots), and average wind direction, U_dir (degrees true), can be generated.

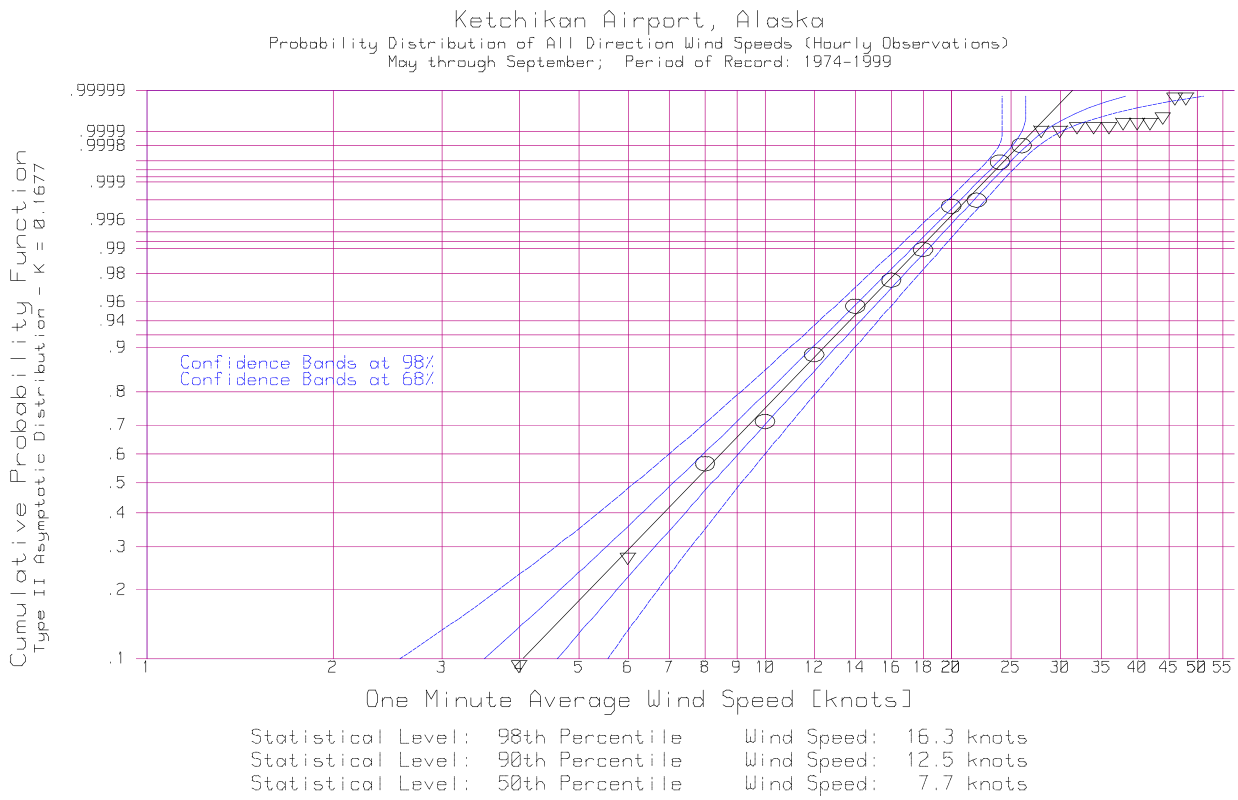

FIGURE 4.6
CUMULATIVE PROBABILITY OF ONE-MINUTE AVERAGE WIND SPEED AT KETCHIKAN AIRPORT FOR MAY THROUGH SEPTEMBER

TABLE 4.6
CUMULATIVE CONDITIONAL PROBABILITY, P(U_DIR|U), OF WIND DIRECTION (DEGREES–TRUE) GIVEN WIND SPEED AT KETCHIKAN AIRPORT FOR MAY THROUGH SEPTEMBER
(PERIOD OF RECORD, 1974-1999)

	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
0 kts	0.000000	0.083333	0.166667	0.250000	0.333333	0.416667	0.500000	0.583333	0.666667	0.750000	0.833333	0.916667	1.000000
2 kts	0.000000	0.066667	0.088889	0.133333	0.222222	0.444444	0.511111	0.600000	0.666667	0.733333	0.777778	0.844444	1.000000
4 kts	0.000000	0.013808	0.024788	0.040426	0.105473	0.306937	0.499085	0.619032	0.686741	0.736483	0.801031	0.909832	1.000000
6 kts	0.000000	0.006401	0.010640	0.019464	0.094464	0.366522	0.565657	0.660900	0.679412	0.693945	0.735381	0.874827	1.000000
8 kts	0.000000	0.004368	0.005316	0.008157	0.079101	0.381085	0.556865	0.607021	0.610231	0.612020	0.637072	0.813378	1.000000
10 kts	0.000000	0.002903	0.003440	0.004623	0.057945	0.344442	0.517738	0.550204	0.551387	0.551817	0.576435	0.757257	1.000000
12 kts	0.000000	0.002728	0.002904	0.004048	0.042323	0.354070	0.561549	0.587242	0.588297	0.589001	0.601144	0.741575	1.000000
14 kts	0.000000	0.001776	0.001776	0.002442	0.025311	0.409414	0.698490	0.716696	0.717362	0.718028	0.728020	0.814165	1.000000
16 kts	0.000000	0.000000	0.000000	0.000763	0.017544	0.446987	0.801678	0.809306	0.810069	0.810069	0.817696	0.890160	1.000000
18 kts	0.000000	0.000000	0.000000	0.001142	0.014840	0.477169	0.902968	0.912100	0.913242	0.913242	0.921233	0.957763	1.000000
20 kts	0.000000	0.000000	0.000000	0.000000	0.007890	0.532544	0.962525	0.970414	0.970414	0.970414	0.972387	0.998028	1.000000
22 kts	0.000000	0.000000	0.000000	0.000000	0.031250	0.593750	0.968750	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
24 kts	0.000000	0.000000	0.000000	0.000000	0.009709	0.563107	0.990291	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
26 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
28 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.428571	0.857143	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
30 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
32 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
34 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
36 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
38 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
40 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
42 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
44 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
46 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
48 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
50 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000
52 kts	0.000000	0.000000	0.000000	0.000000	0.133333	0.466667	0.800000	0.933333	0.933333	0.933333	0.933333	1.000000	1.000000

Row headings are wind speed (knots).
Column headings are wind direction, degrees (true).
Table entries are conditional cumulative probabilities for direction, given the wind speed.

4.3.2 Pseudo-Time Domain Gusting Wind

As shown in Figure 4.7, the hourly maximum gusts at Ketchikan are, on average, 152% of the one-minute average wind speed. The standard error of the regression fit shown in Figure 4.7 is 4.6.

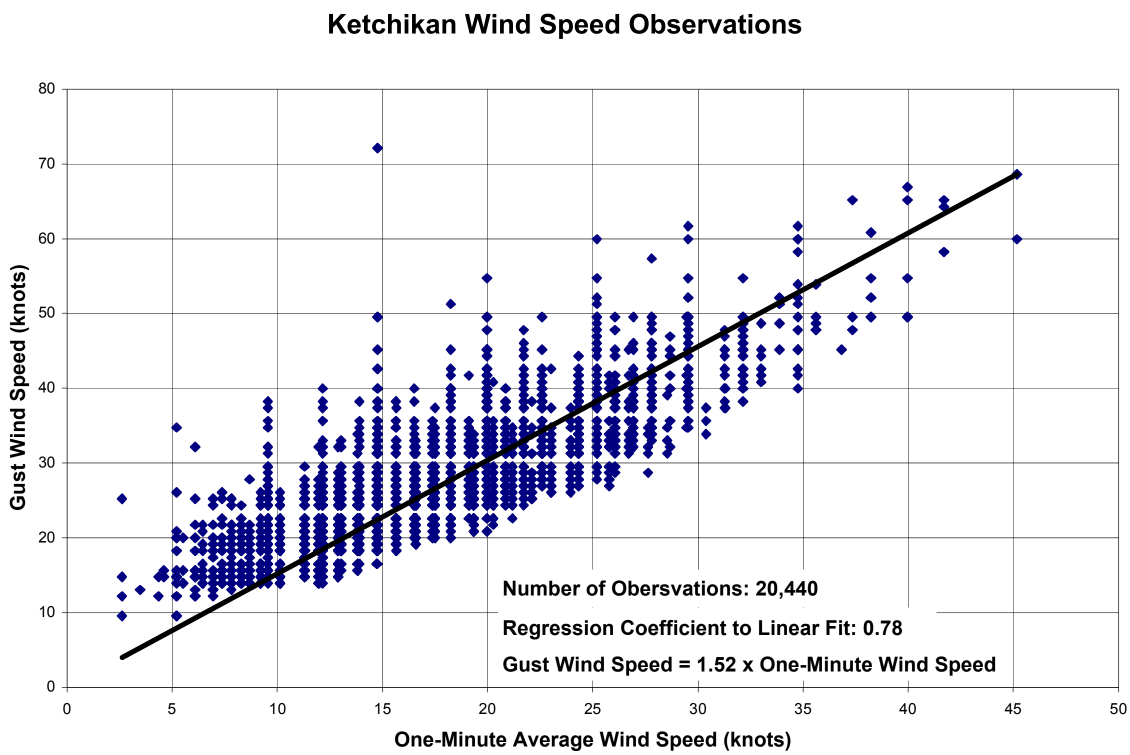

FIGURE 4.7
CORRELATION BETWEEN PEAK GUSTS AND ONE-MINUTE AVERAGE WIND SPEED AT KETCHIKAN AIRPORT

Thus, given a one-minute average wind speed, U (knots), the hourly maximum gust is estimated as:

hourly maximum gust amplitude = 0.52 U + N(0,4.6)

where: the gust amplitude is in knots

U is the one-minute average wind speed (knots)

N(0,4.6) is a Monte Carlo random sample from the Normal distribution[2] with zero mean and standard deviation of 4.6

[2] Ang and Tang, Vol. 2, (Reference 3), pp. 284-285, provide a procedure for generating normally distributed Monte Carlo sample variables.

This is the hourly maximum gust. For simulation, we need the sample population of wind gusts given a one-minute average wind speed. This is taken to be:

gust amplitude = Uniform(0, 1) $\times$ 0.52 U + N(0,4.6)

where: Uniform(0, 1) uniform distribution between 0 and 1

The duration (persistence) of each gust is modeled using a uniform distribution between 5 seconds and 60 seconds, rounded to the nearest 5 seconds.

The gust direction is also a random variable. The direction of the gust is a random variable selected from a uniform distribution extending between 0 degrees and 360 degrees. The instantaneous wind realization is the vector sum of the one-minute average wind vector and gust vector.

4.3.3 Windage Area of Large Cruise Ships

The longitudinal and lateral windage areas of the large cruise ships modeled for northbound transits are given in Table 4.7 and for cruise ships modeled for southbound transits in Table 4.8. Wind forces and moments were modeled using methods set forth for cruise ships in Reference 4.

TABLE 4.7
WINDAGE AREAS OF NORTHBOUND LARGE CRUISE SHIPS

Ship I.D.	*% of Northbound Transits*	*LWL (feet)*	*Draft (feet)*	*Longitudinal Windage Area (square feet)*	*Lateral Windage Area (square feet)*
N-1	10.64%	858	26.25	20,262	114,322
N-2	3.19%	713	26.33	11,303	69,972
N-3	1.06%	870	26.00	12,918	99,038
N-4	9.57%	781	25.50	13,994	87,196
N-5	27.66%	773	26.58	12,918	98,499
N-6	9.57%	826	25.25	13,456	97,961
N-7	29.79%	648	25.26	9,958	69,972
N-8	8.51%	807	27.20	21,221	125,518

LWL = Length at water line

TABLE 4.8
WINDAGE AREAS OF SOUTHBOUND LARGE CRUISE SHIPS

Ship I.D.	*% of Northbound Transits*	*LWL (feet)*	*Draft (feet)*	*Longitudinal Windage Area (square feet)*	*Lateral Windage Area (square feet)*
S-1	3.30%	858	26.25	20,262	114,322
S-2	1.83%	713	26.33	11,303	69,972
S-3	7.33%	870	26.00	12,918	99,038
S-4	4.40%	781	25.50	13,994	87,196
S-5	7.69%	680	23.00	11,845	83,808
S-6	10.26%	773	26.58	12,918	98,499
S-7	9.89%	826	25.25	13,456	97,961
S-8	8.06%	765	26.25	13,994	87,196
S-9	3.66%	557	27.30	8,237	54,142
S-10	11.72%	648	25.26	9,958	69,972
S-11	3.66%	807	27.20	21,221	125,518
S-12	5.86%	921	28.90	23,363	143,348
S-13	7.33%	722	23.60	11,845	83,808
S-14	15.02%	704	26.58	12,918	77,508

LWL = Length at water line

4.4 Current

Current in Tongass Narrows is primarily tidal in origin. Table 4.9 gives the cumulative probability of current velocity in Tongass Narrows for the cruise ship season (1 May 2001 through 30 September 2001). Figure 4.8 is a plot of that cumulative probability distribution. A Monte Carlo scheme is developed (similar to that used for the one-minute average wind speed) that determines the current velocity from this cumulative distribution.

TABLE 4.9
CUMULATIVE PROBABILITY, P($V_{CURRENT}$), OF CURRENT VELOCITY IN TONGASS NARROWS FOR MAY THROUGH SEPTEMBER 2001

Current Velocity (knots)	*Cumulative Probability*	*Current Velocity (knots)*	*Cumulative Probability*
-1.3	.00%	0.0	61.40%
-1.2	.16%	0.1	65.17%
-1.1	.95%	0.2	68.90%
-1.0	2.45%	0.3	73.45%
-0.9	5.35%	0.4	78.61%
-0.8	9.34%	0.5	84.41%
-0.7	14.87%	0.6	89.32%
-0.6	22.58%	0.7	93.71%
-0.5	30.61%	0.8	96.95%
-0.4	38.52%	0.9	98.76%
-0.3	45.66%	1.0	99.55%
-0.2	51.66%	1.1	99.99%
-0.1	57.15%	1.2	100.00%
0.0	61.40%	1.3	100.00%

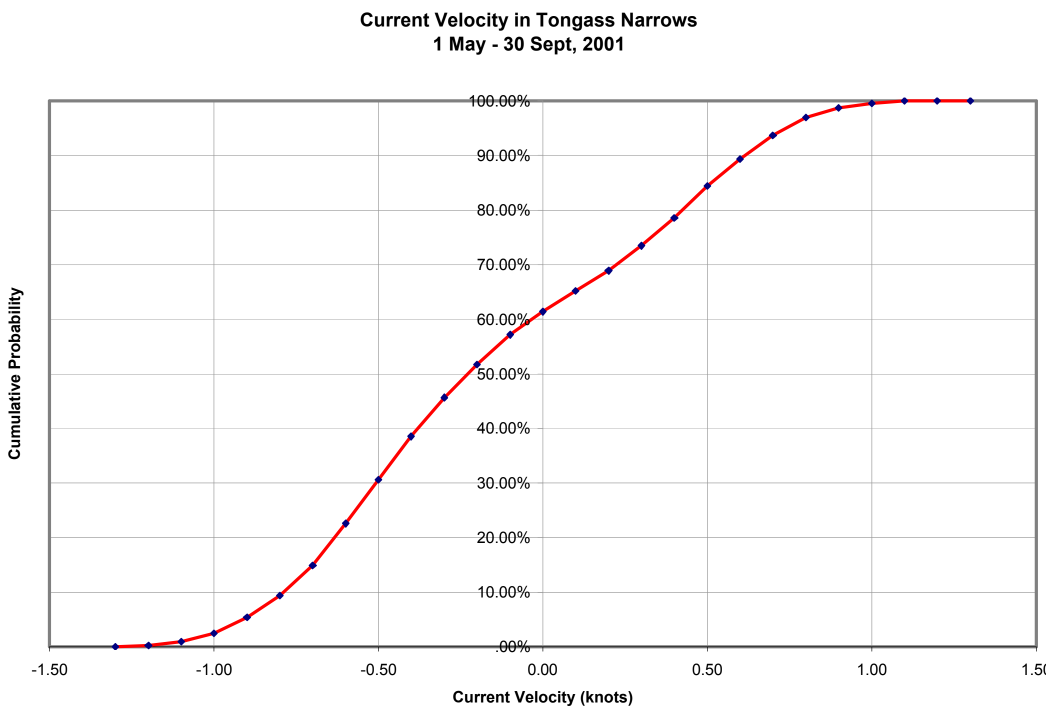

FIGURE 4.8
CUMULATIVE PROBABILITY DISTRIBUTION FOR CURRENT IN TONGASS NARROWS

4.5 Results

4.5.1 Bridge Alternatives C3(a) and C4

Figures 4.9 and 4.10 show the cumulative probability distributions of east and west bank sweeps at the bridge alignment of Alternatives C3(a) and C4 for large cruise ships headed northbound and southbound, respectively. For northbound ships, the width between sweeps is approximately 290 feet at the 0.9 probability level, and 499 feet at the 0.99 level. For southbound ships, the width between sweeps is approximately 300 feet at the 0.9 probability level, and 510 feet at the 0.99 level. A sweep is defined as the extreme extents of the intersection of the vessel footprint with the bridge alignment line. Here, it is given in terms of the distance from the east end to the extreme points measured along the bridge alignment line.

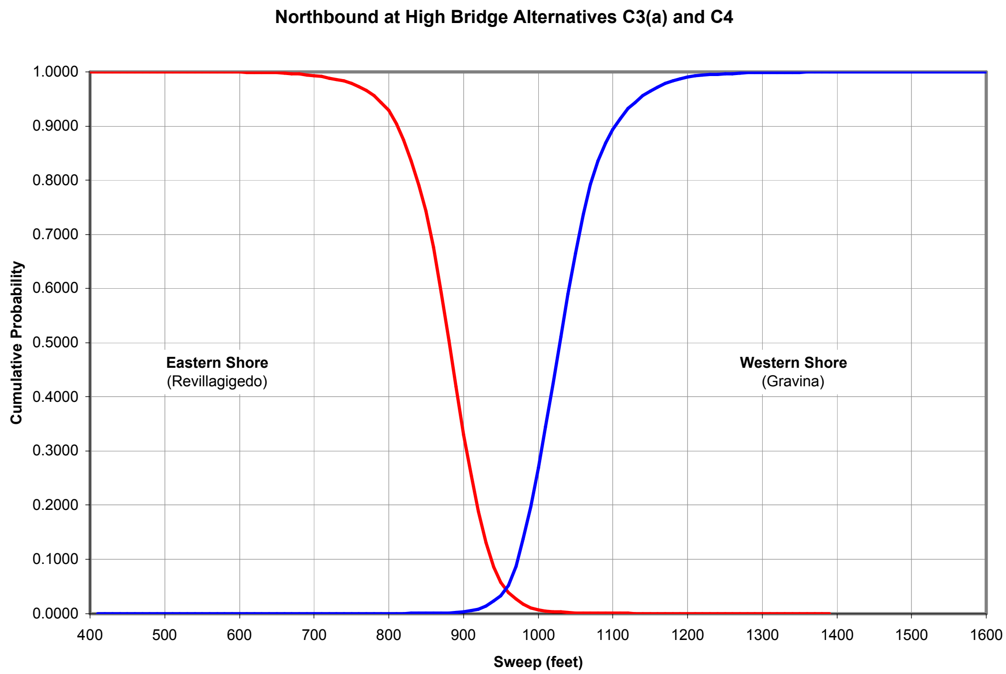

FIGURE 4.9
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR NORTHBOUND LARGE CRUISE SHIPS FOR ALTERNATIVES C3(A) AND C4

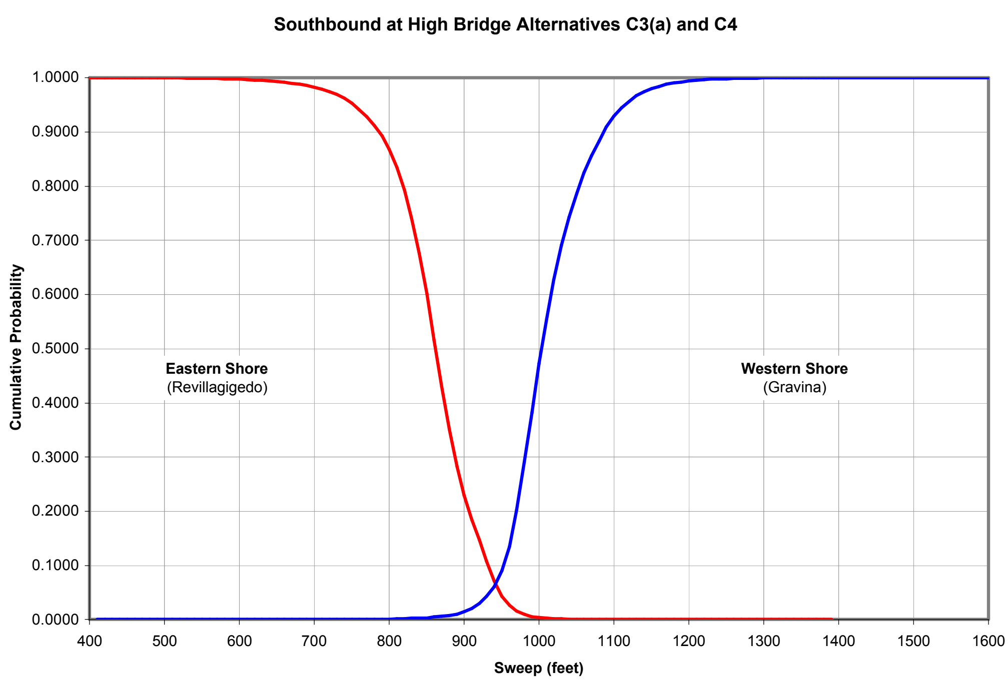

FIGURE 4.10
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR SOUTHBOUND LARGE CRUISE SHIPS FOR ALTERNATIVES C3(A) AND C4

Figure 4.11 shows the cumulative probability distributions of east and west bank sweeps for both northbound and southbound large cruise ships at the alignment of bridge Alternative C3(a) or C4. At the 0.9 probability level, the width between east and west bank sweeps is approximately 298 feet; at the 0.99 level, the width is approximately 504 feet.

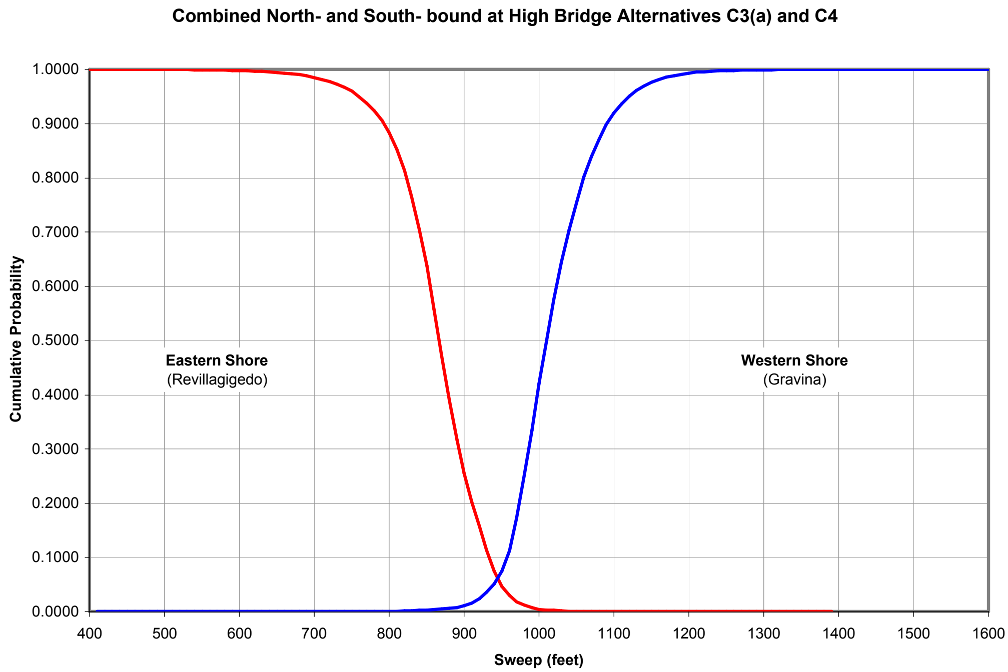

FIGURE 4.11
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS FOR ALTERNATIVES C3(A) AND C4

Figure 4.12 shows the probability density function for the horizontal clearance at bridge Alternatives C3(a) and C4. The most frequently occurring clearance is on the order of 129 feet, approximating the weighted average of the maximum beams of the cruise ships.

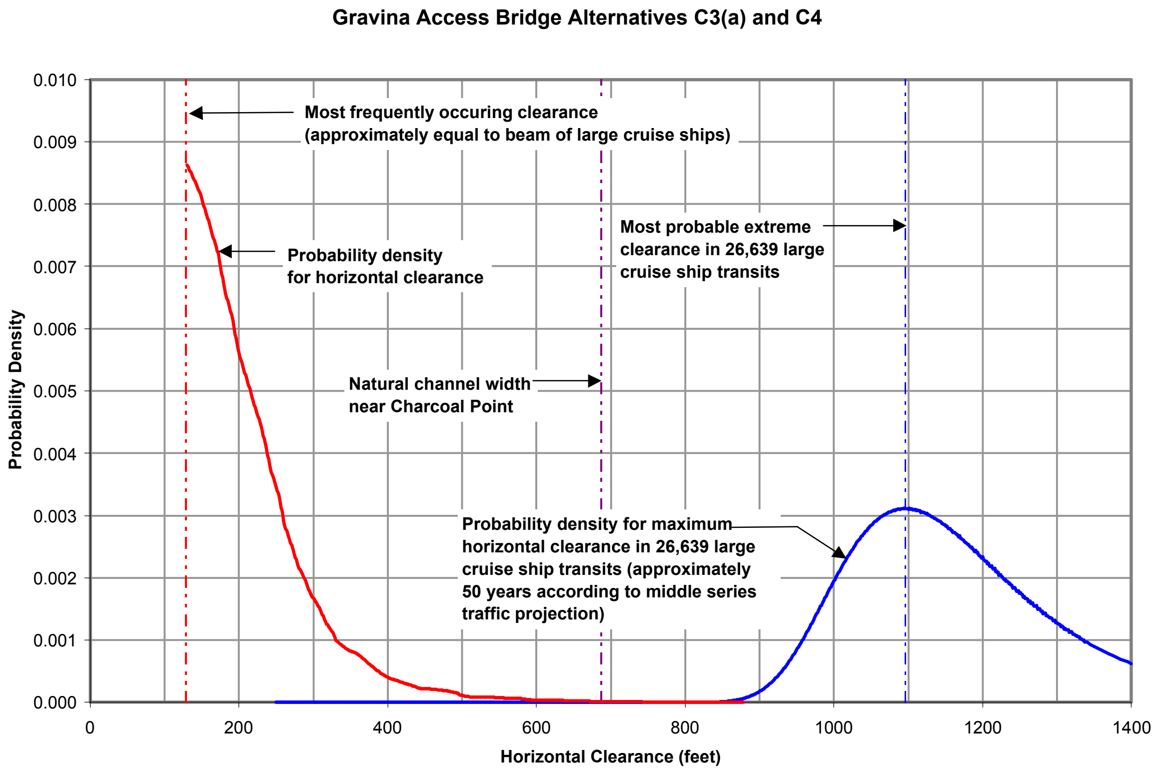

FIGURE 4.12
PROBABILITY DENSITY DISTRIBUTIONS OF HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS FOR ALTERNATIVES C3(A) AND C4

The distribution to the right in Figure 4.12 was developed using order statistics procedures applied to the cumulative and density distributions at bridge Alternatives C3(a) or C4. Order statistics provide a method whereby the cumulative density distributions of extreme values can be determined from the underlying distributions. If f(x) is the probability density and F(x) is the cumulative probability, then the cumulative probability distribution of the maximum in N independent trials is $[F(x)]^N$ and the probability density function (found by differentiation) is $N f(x) [F(x)]^{N-1}$.

The distribution given on the right in Figure 4.12 is the probability density function for the maximum horizontal clearance in 26,639 large cruise ship transits. That is the number of transits projected to occur over 50 years, according to the middle projection in Reference 6. The most probable extreme value is approximately 1,096 feet. However, the probability of exceeding this most probable value (in 50 years) is 64%. With 50% confidence in 50 years, the horizontal clearance should be 1,143 feet. A natural channel width of 1,169 feet is given in Table 3.2 for the immediate vicinity of alignments C3(a) or C4. At that horizontal clearance, the confidence is approximately 57% in 50 years. However, as shown in Figure 4.13, immediately south of C3(a) or C4 the natural channel narrows to approximately 687 feet[3] in the vicinity of Charcoal Point. As may be observed in Figure 4.12, the probability density distribution for 26,639 large

[3] Following adjustment to a measure perpendicular to the trackline: 694 ft. x cos(8°) = 687 ft.

cruise ships lies entirely to the right of 687 feet indicating a virtual certainty that at least one grounding (or event requiring extreme avoidance measures to prevent a grounding) in the natural channel near Charcoal Point may occur over the next 50 years.

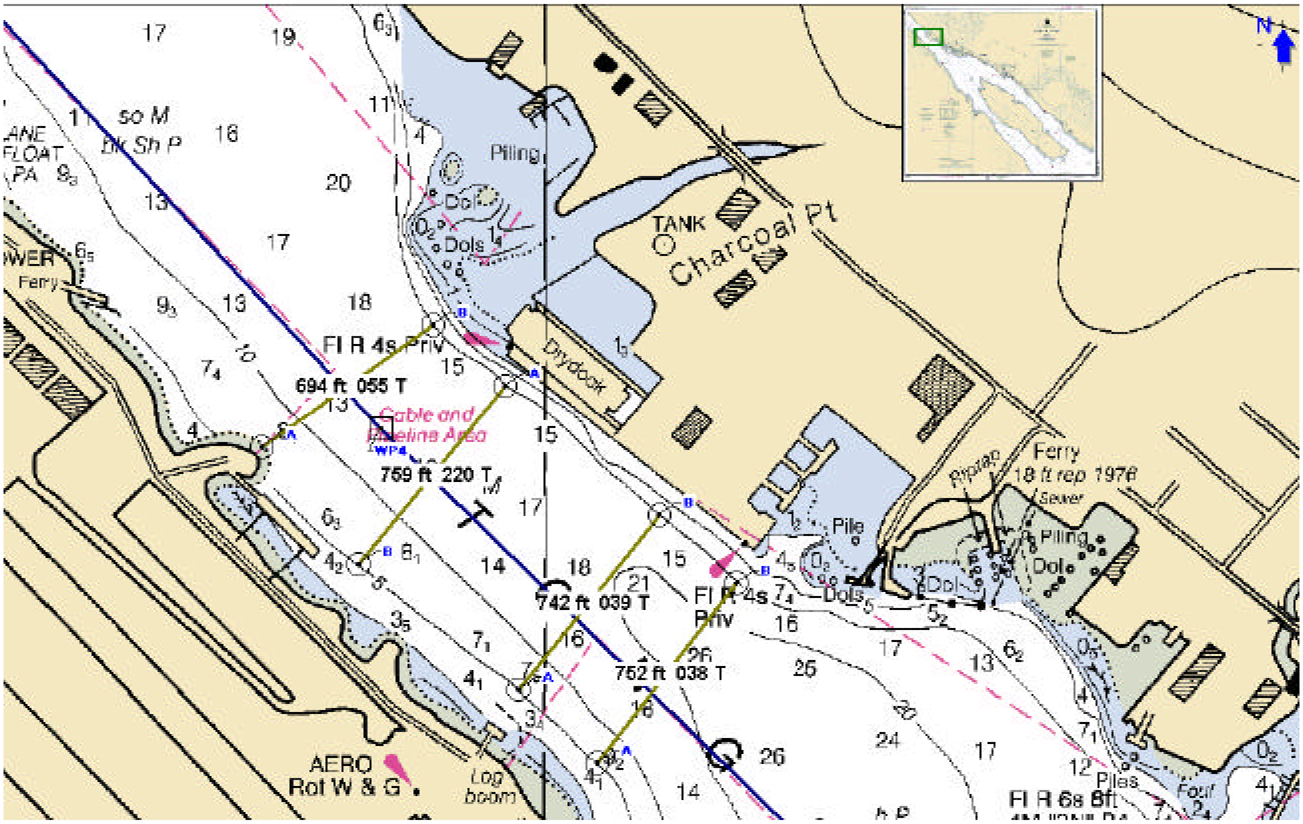

FIGURE 4.13
TRACKLINE AND NATURAL CHANNEL WIDTHS IN TONGASS NARROWS NEAR CHARCOAL POINT

Table 4.10 provides order statistics for the horizontal clearance at bridge Alternatives C3(a) and C4. Order statistics are provided for the horizontal clearance expected to be violated by N=1,2,3,4,…,15,20,25 and 50 ships over a 50-year period in which 26,639 large cruise ships transit the north branch of Tongass Narrows.

The fourth column gives the horizontal clearance that is expected to be exceeded with near certainty (probability of 0.99999). Over a 50-year period it is nearly certain that at least one ship would violate a 822-foot horizontal clearance. Likewise, it is nearly certain that at least five large cruise ships would violate a 654-foot horizontal clearance over the same period. And it is nearly certain that at least one ship per year (on average) will exceed 435-foot horizontal clearance.

TABLE 4.10
50-YEAR ORDER STATISTICS FOR HORIZONTAL CLEARANCE
FOR BRIDGE ALTERNATIVES C3(A) AND C4

Potential Number of Large Cruise Ships Allisions	*Most Probable Horizontal Clearance (feet)*	*Probability of Exceeding Most Probable Horizontal Clearance*	*Horizontal Clearance (feet) with Exceedance Probability of 0.99999*	*Average Return Period (Years)*
1	1,096	0.64	822	50.0
2	1,016	0.64	748	25.0
3	968	0.65	706	16.7
4	935	0.65	677	12.5
5	910	0.65	654	10.0
6	890	0.65	636	8.3
7	873	0.65	620	7.1
8	858	0.65	607	6.3
9	845	0.65	595	5.6
10	834	0.64	585	5.0
11	823	0.65	576	4.5
12	814	0.65	567	4.2
13	805	0.65	560	3.8
14	797	0.65	552	3.6
15	790	0.65	546	3.3
20	759	0.65	519	2.5
25	735	0.65	498	2.0
50	663	0.65	435	1.0

Order statistics for 26,639 large cruise ship transits corresponding to 50 years, according to the middle series projections of Reference 6

The final column of Table 4.10 gives the average return period between potential large cruise ship allision events. Thus, if there are five potential large cruise ship allision events in fifty years the average return period is ten years.

Figure 4.14 presents a Type II extremal probability fit of the tail of the cumulative probability distribution for large cruise ships at bridge Alternatives C3(a) and C4. Also shown are 68% and 98% confidence bands for the fit. The narrowness of the bands indicates that an excellent fit was obtained (especially in the region of horizontal clearances between 400 and 850 feet). Above about 940 feet, the confidence bands widen. The number of ship transits is indicated by the vertical scale on the right.

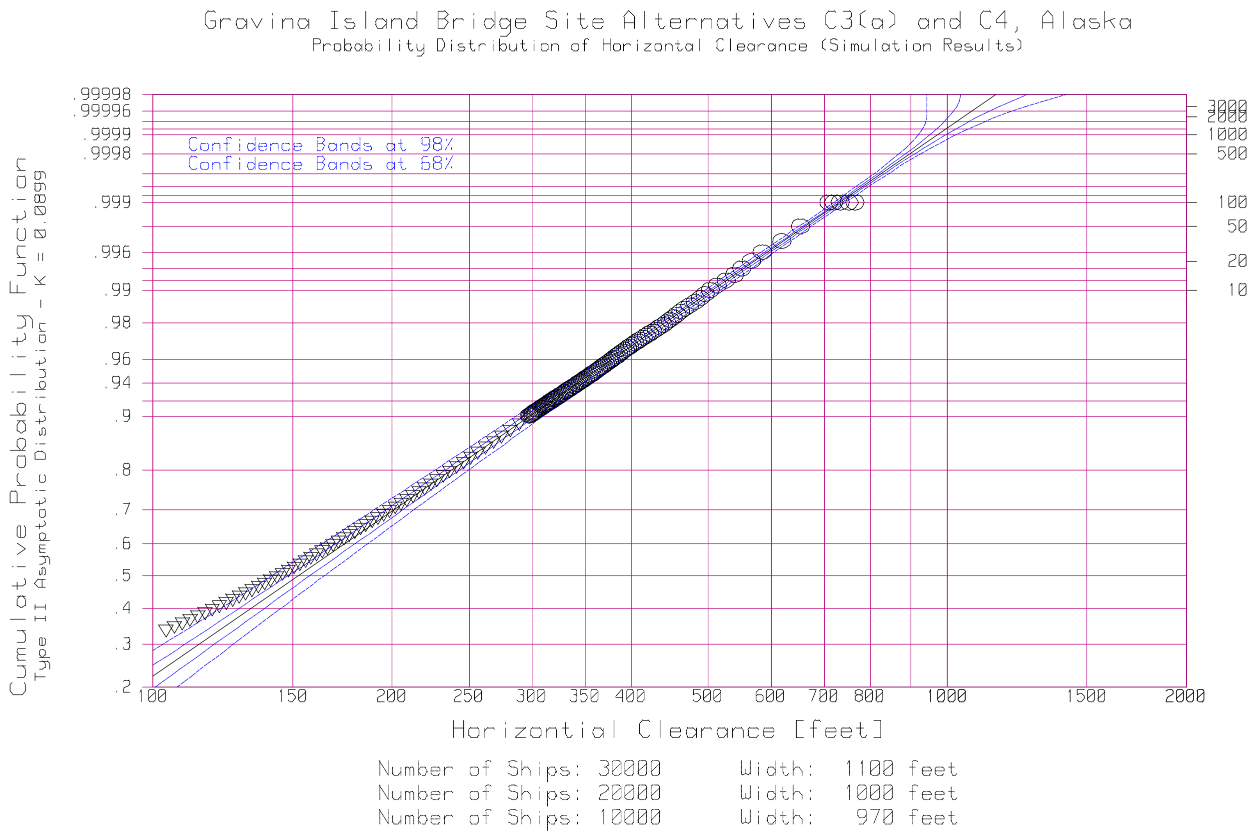

FIGURE 4.14
EXTRAPOLATION OF TYPE II EXTREMAL PROBABILITY FOR HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS FOR ALTERNATIVES C3(A) AND C4

4.5.2 Effect of Limiting Large Cruise Ship Transits Based on Wind

Gusting wind has been identified as a primary cause of the extreme off-track excursions of large cruise ships operating in Tongass Narrows. An auxiliary investigation was undertaken to ascertain the potential mitigating effects of restricting large cruise ship transits under the bridge based on one-minute average wind speed. One-minute average wind speed was selected as being statistically more reliable than measures of gusting wind behavior. Wind gust behavior is presumed to be parametrically dependent on the one-minute average wind. For the purposes of this auxiliary analysis it is presumed that large cruise ships do not transit under bridges located at C3(a) or C4 if the one-minute average wind exceeds the specified limiting wind speed. When the wind exceeds the limiting wind speed cruise ships would presumably depart to or arrive from the south through Nichols Passage.

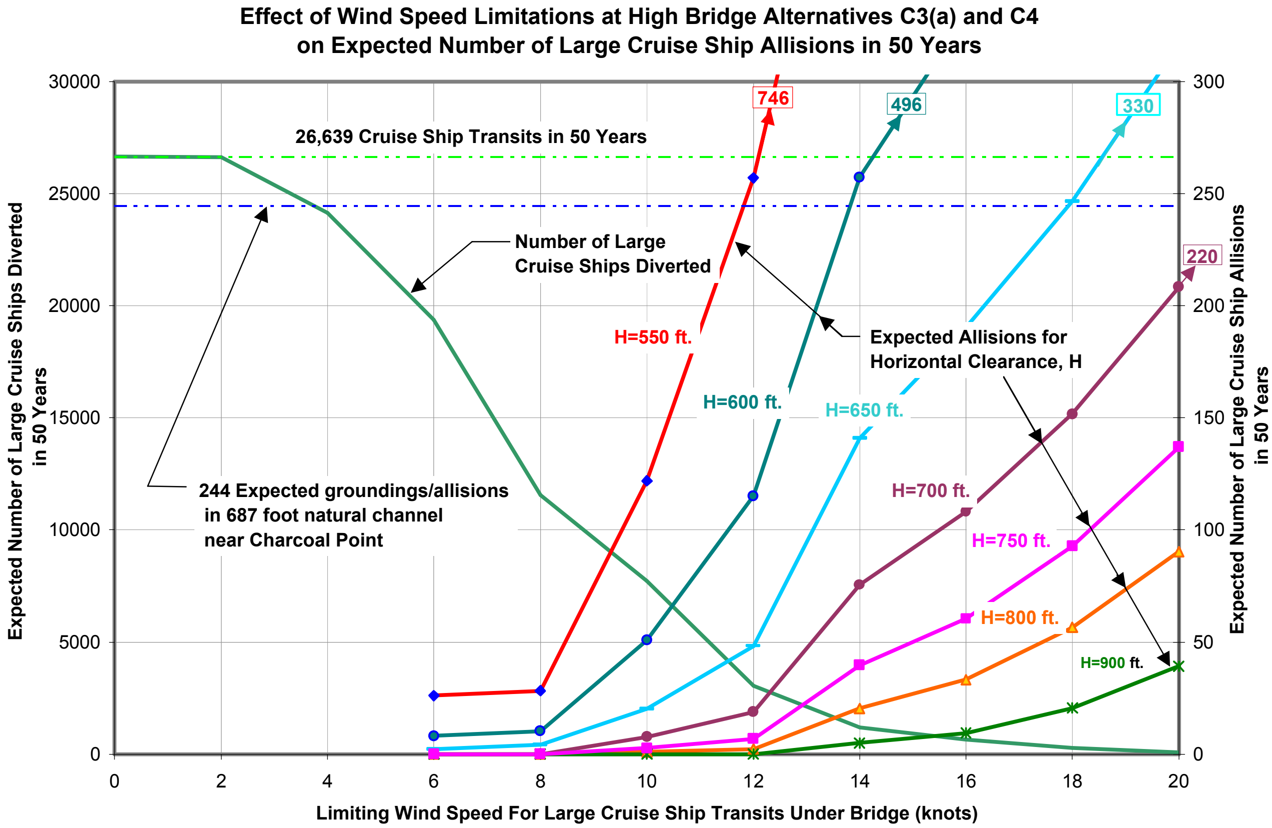

FIGURE 4.15
EFFECT OF WIND SPEED LIMITATIONS ON LARGE CRUISE SHIP TRANSITS FOR ALTERNATIVES C3(A) AND C4

Figure 4.15 shows the effect of horizontal clearance and wind speed limitations on the expected number of potential cruise ship allisions in 50 years and the number of cruise ships that are diverted through Nichols Passage as a function of limiting wind speed.

The natural channel in the vicinity of bridge alignments C3(a) and C4 is about 1340 feet and the expected number of potential groundings in fifty years approaches one in the absence of any operating restrictions based on wind speed. However, near Charcoal Point, adjacent to the Ketchikan shipyard, the natural channel width narrows to about 687 feet. Here the expected number of potential groundings in fifty years is about 244 in the absence of any restrictions based on wind speed. The most probable number of groundings in the vicinity of Charcoal Point is 20 (approximately one every 2.5 years) and the median number of potential groundings is 60 in fifty years (approximately 1.2 potential groundings per year).

It may be observed that the a limiting wind speed of 20 knots has negligible effect and that limiting wind speed thresholds below 20 knots have progressively more effect.

For a 550 foot horizontal clearance and a 11.8 knot limiting wind speed, 244 potential large cruise ship allision events are expected over a fifty year exposure period (the same as in the natural channel near Charcoal Point) and 3,357 large cruise ships (12.6%) would be diverted to the south, through Nichols Passage, as a consequence of the wind speed limitations.

Increasing the horizontal clearance reduces the expected number of potential large cruise ship allisions for any presumed limiting wind speed and conversely increases the limiting wind speed that must be imposed to adhere to any specified risk of allision. For example, a 650 foot horizontal clearance and a 17.9 knot limiting wind speed results in an expected number of potential large cruise ship allision events essentially identical to the number of potential groundings expected in the natural channel near Charcoal Point (H=687 feet) without any limitations based on wind. A 17.9 knot wind speed limitation would result in the diverting of 288 large cruise ships (1.1%) over a 50 year period.

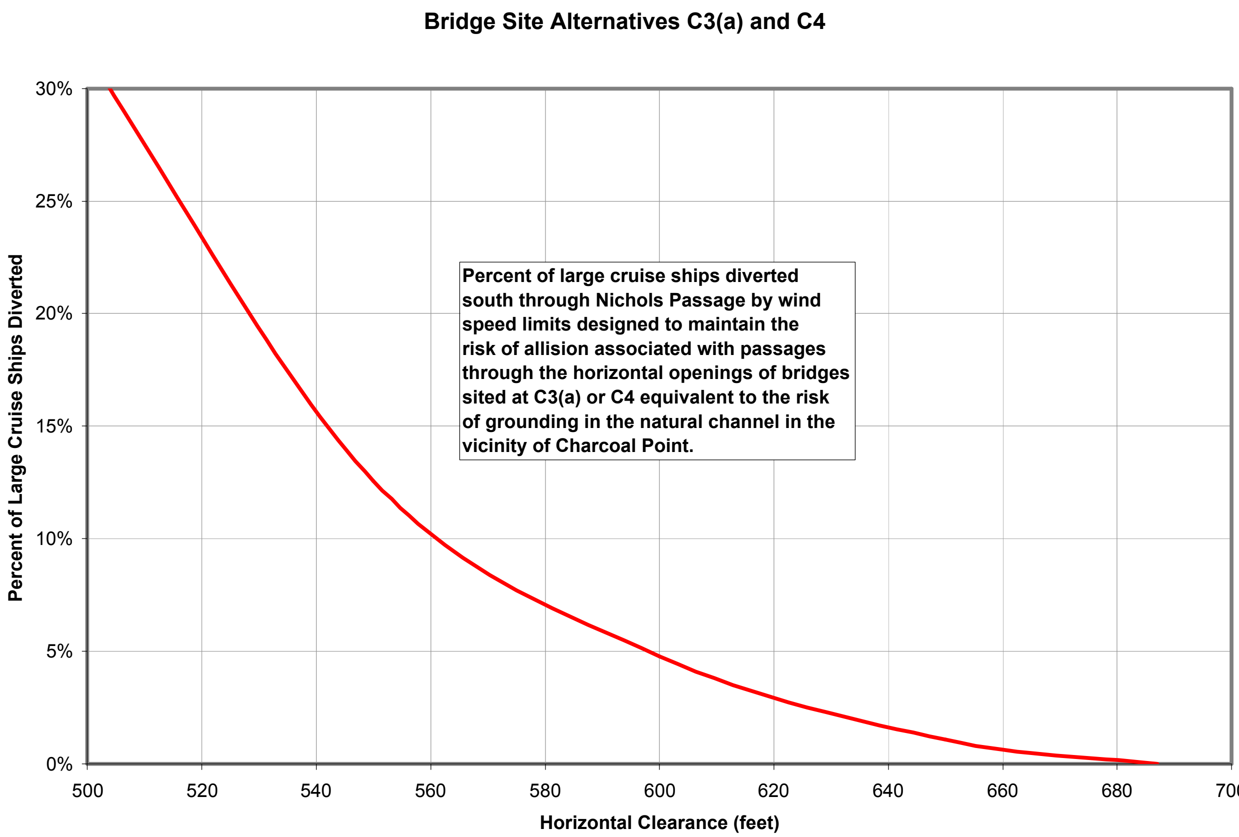

FIGURE 4.16
EFFECT OF WIND SPEED LIMITATIONS ON LARGE CRUISE SHIP TRANSITS FOR ALTERNATIVES C3(A) AND C4

These trends are summarized in Figure 4.16 that shows the percentage of large cruise ships that would be diverted south through Nichols Passage in order to maintain the risk of potential allision through a bridge at C3(a) or C4 equivalent to the current risk of potential grounding in the 687 foot natural channel in the vicinity of Charcoal Point.

One alternative to limiting large cruise ship transits under the bridge according to wind speed would be to require tethered tug escort for wind speeds above some threshold value. It is anticipated that modern escort tugs capable of rendering effective steering and braking assistance at speeds up to 7 knots would cost somewhere between $2,000 and $3,000 per transit. Such modern escort tugs are not currently available in

Ketchikan but might be attracted if sufficient business could be generated. Presumably the cruise ship operators would evaluate the cost of these escort tug services against the extra time and fuel required to sail south through Nichols Passage. Extra fuel is on the order of 3,200 gallons and average time lost is 55 minutes for large cruise ships diverted through Nichols Passage.

4.5.3 Bridge Alternative F3 – Traffic Through West Channel

Bridge alternative F3 would limit large cruise ship traffic arriving from or departing to the south to the use of West Channel between Pennock and Gravina Islands. This would be a change from the present practice where large cruise ships routinely use East Channel. AMHS ferries currently make routine use of West Channel, hence bridge alternative F3 would impose no change on their current practice. Figure 4.17 shows the presumed trackline for large cruise ships through West Channel.

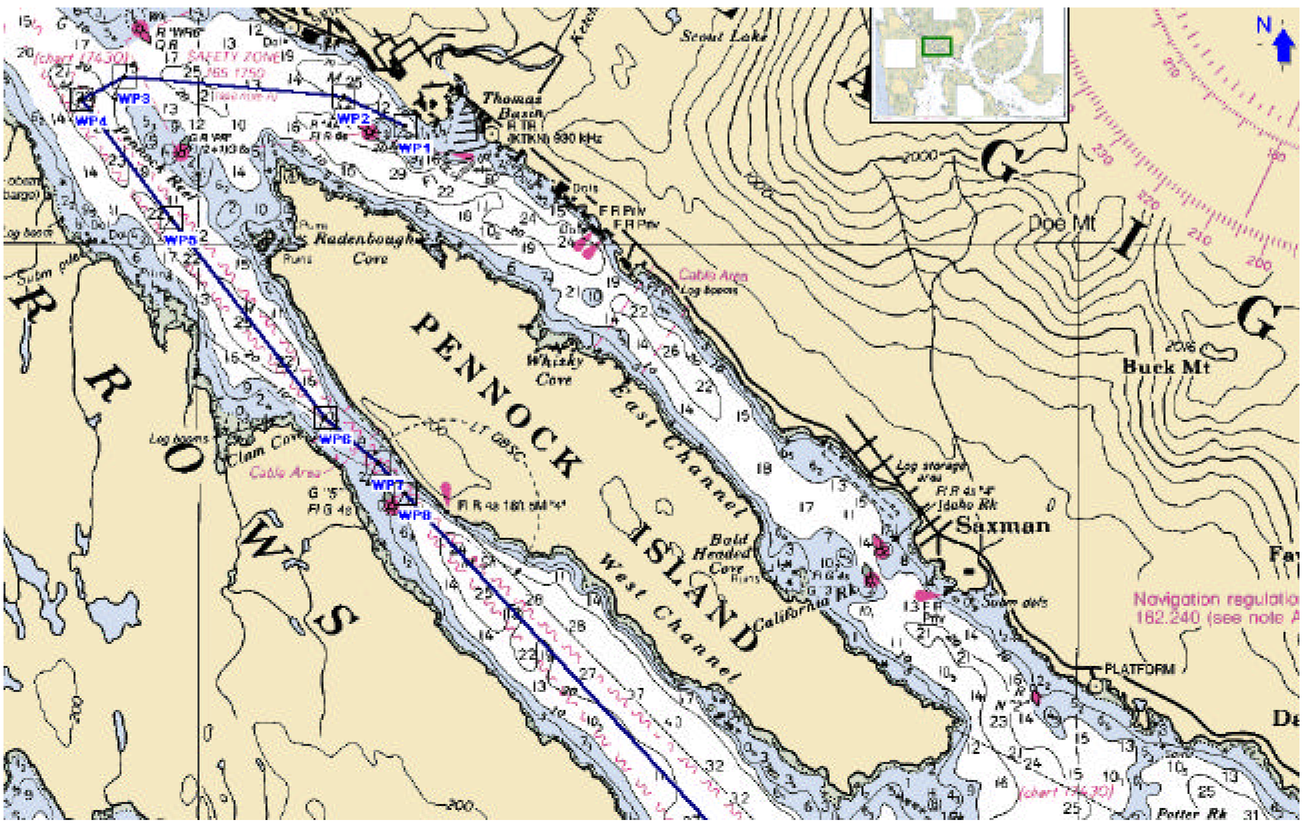

FIGURE 4.17
TRACKLINE THROUGH WEST CHANNEL

The approximate natural channel width in West Channel is 476 feet, as given in Table 3.2 and depicted in Figure 4.18. This is considerably less than the channel width (1,169 feet) available in the vicinity of bridge alternatives C3(a) and C4 and also less than the width of Tongass Narrows near Charcoal Point (687 feet).

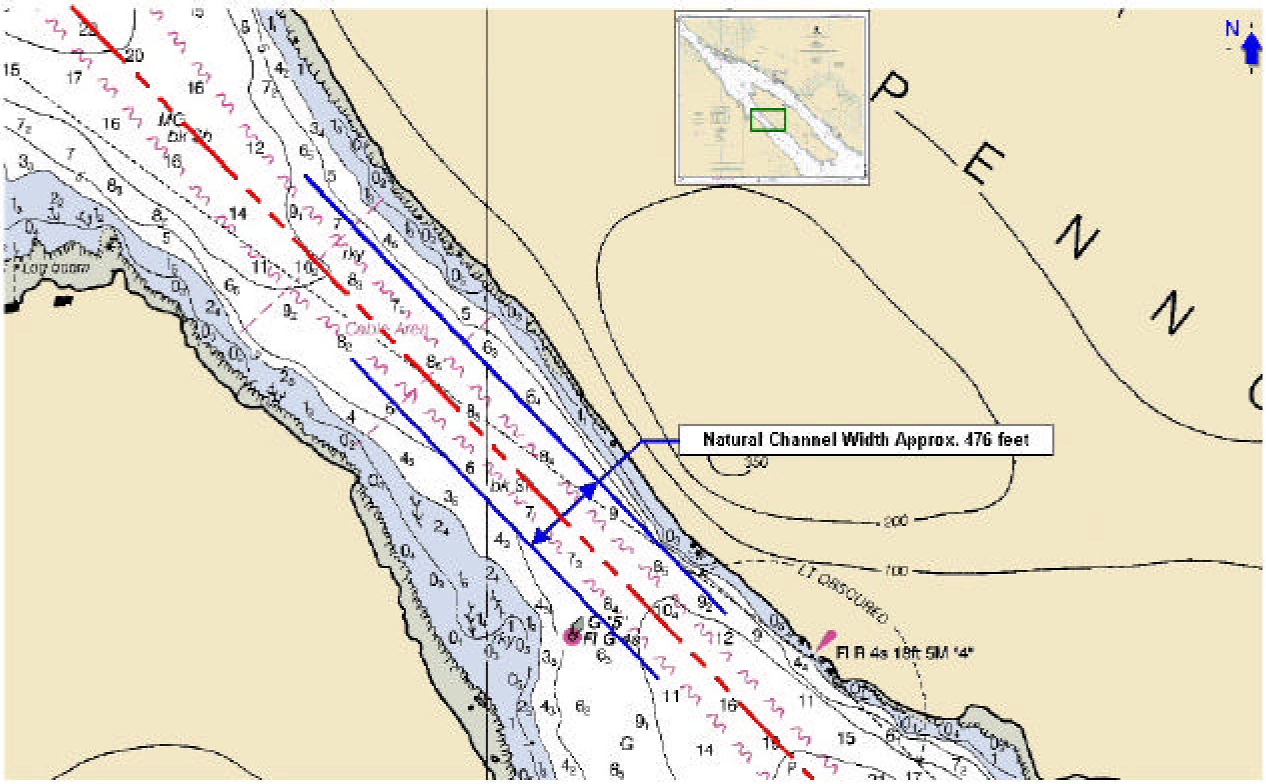

FIGURE 4.18
SHOWING THE NATURAL CHANNEL WIDTH IN WEST CHANNEL

Figures 4.19 and 4.20 show the cumulative probability distributions of east and west bank sweeps in West Channel for large cruise ships headed northbound and southbound, respectively. For northbound ships, the width between sweeps is approximately 287 feet at the 0.9 probability level, and 485 feet at the 0.99 level. For southbound ships, the width between sweeps is approximately 313 feet at the 0.9 probability level, and 530 feet at the 0.99 level. A sweep is defined as the extreme extents of the intersection of the vessel footprint with the bridge alignment line. Here, it is given in terms of the distance from the east end to the extreme points measured along the bridge alignment line.

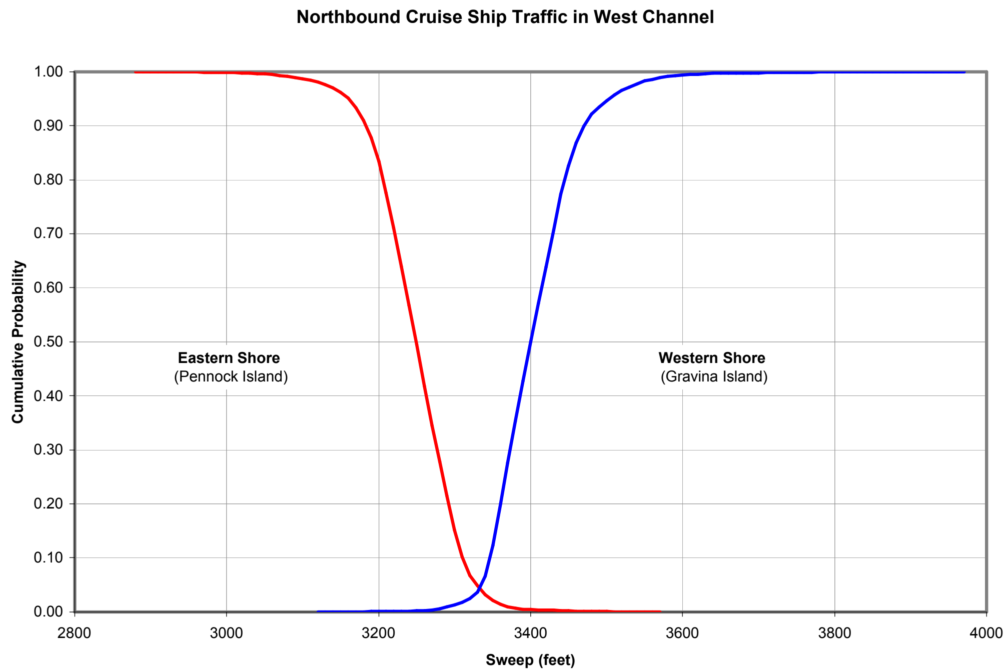

FIGURE 4.19
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR NORTHBOUND LARGE CRUISE SHIPS IN WEST CHANNEL

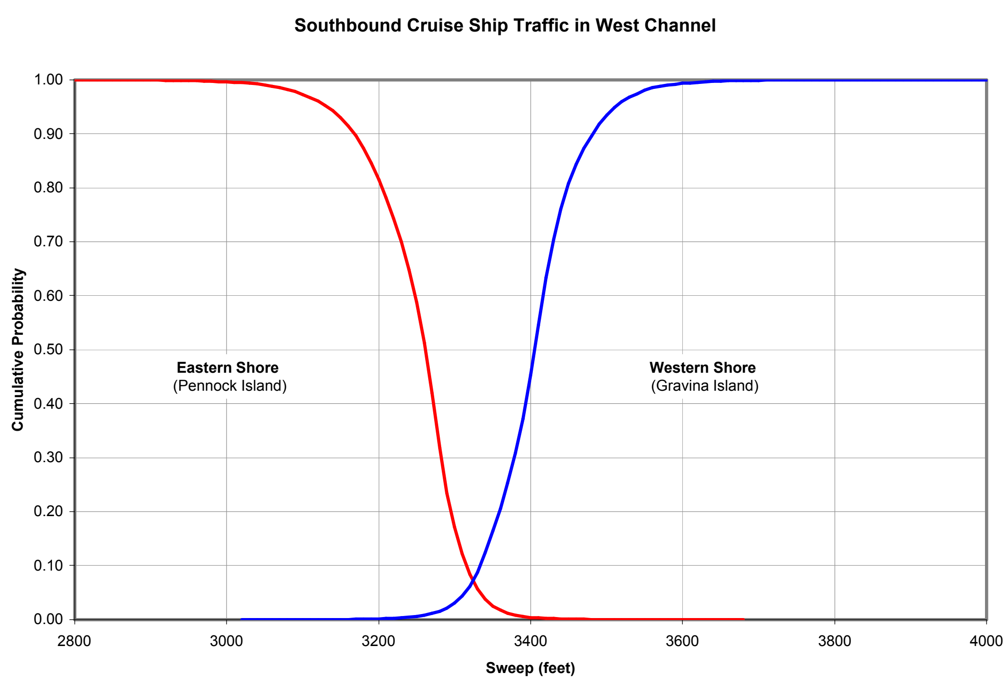

FIGURE 4.20
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR SOUTHBOUND LARGE CRUISE SHIPS IN WEST CHANNEL

Figure 4.21 shows the cumulative probability distributions of east and west bank sweeps for both northbound and southbound large cruise ships in West Channel. At the 0.9 probability level, the width between east and west bank sweeps is approximately 313 feet; at the 0.99 level, the width is approximately 526 feet.

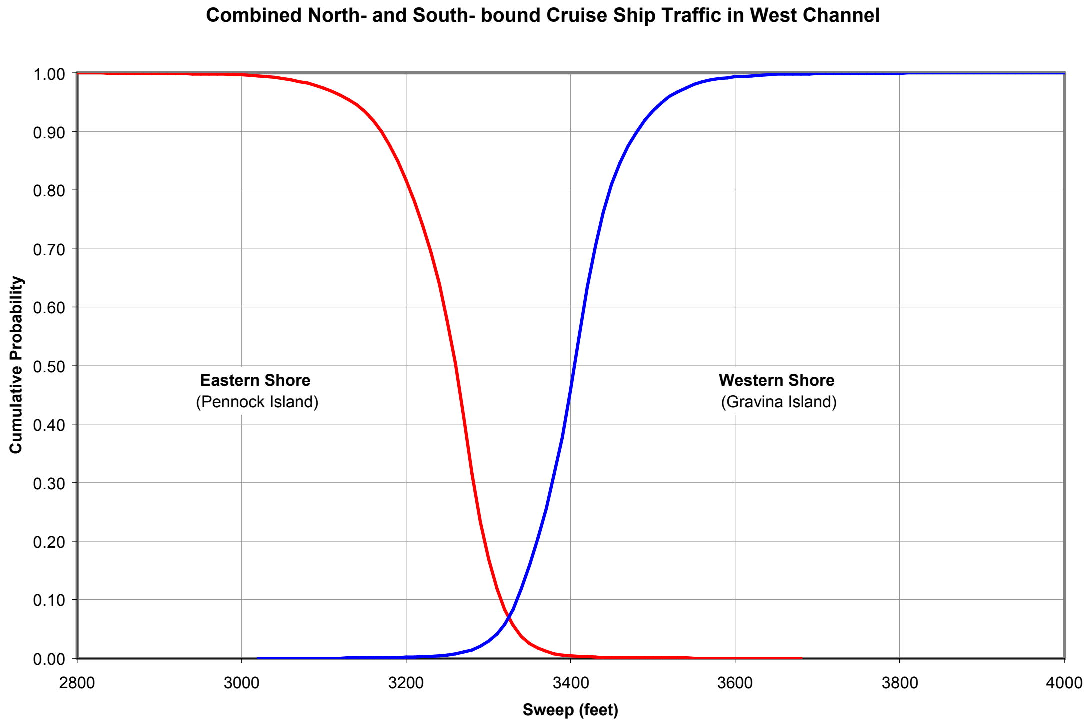

FIGURE 4.21
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN WEST CHANNEL

Figure 4.22 shows the probability density function for the horizontal clearance required by large cruise ships operating in West Channel. The most frequently occurring clearance is on the order of 132 feet, approximating the weighted average of the maximum beams of the cruise ships.

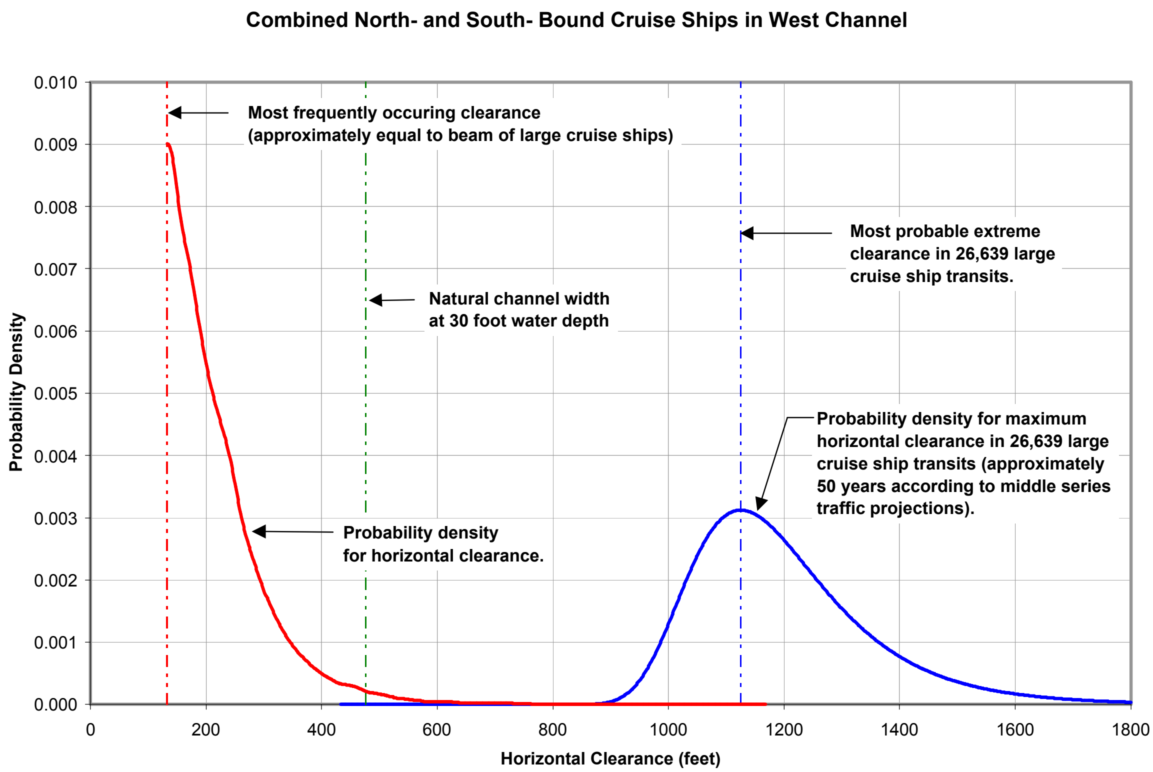

FIGURE 4.22
PROBABILITY DENSITY DISTRIBUTIONS OF HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN WEST CHANNEL

The distribution to the right in Figure 4.22 was developed using order statistics procedures applied to the cumulative and density distributions for large cruise ships operating in West Channel. The order statistics distribution given is the probability density function for the maximum horizontal clearance in 26,639 large cruise ship transits. That is the number of transits projected to occur over 50 years, according to the middle projection in Reference 6. The most probable extreme value is approximately 1,125 feet, a distance nearly double that of the available natural channel. Furthermore, the probability of exceeding this most probable value (in 50 years) is nearly 64%. With 50% confidence in 50 years, the horizontal clearance should be 1,172 feet. It is virtually certain that the 476 foot natural channel width will be exceeded in 50 years.

Table 4.11 provides statistics for the risk of large cruise ship groundings presuming that 26,639 large cruise ship transits were attempted in West Channel over 50 years without regard to the wind conditions. The most probable number of potential groundings in 50 years is 224, or approximately 4.5 large cruise ship grounding per year. The expected number of potential groundings in 50 years is 1,583, or about 32 groundings per year. Potential groundings are events that would result in an actual grounding if extreme avoidance measures (e.g., crash stops, twin screw propulsive maneuvers, use of bow thrusters, deployment of anchors, or some combination) are not implemented in a timely manner. To the extent that effective extreme avoidance measures are employed the actual groundings will be less than the potential groundings.

TABLE 4.11
50-YEAR ORDER STATISTICS FOR POTENTIAL GROUNDINGS OF LARGE CRUISE SHIPS OPERATING IN WEST CHANNEL

Most Probable Number of Groundings	*Probability of Exceeding Most Probable Number of Groundings*	*Median Number of Groundings*	*Expected Number of Groundings*	*Average Number of Groundings per Year*
224	0.866	649	1,583	32

Order statistics for 26,639 large cruise ship transits corresponding to 50 years, according to the middle series projections of Reference 6.

Natural channel width of West Channel is approximately 476 feet between the 5 fathom (30 foot) depth contours.

Potential groundings are events that would result in an actual grounding if extreme avoidance measures are not implemented in a timely manner.

Figure 4.23 presents a Type II extremal probability fit of the tail of the cumulative probability distribution for large cruise ships operating in West Channel. Also shown are 68% and 98% confidence bands for the fit. The narrowness of the bands indicates that an excellent fit was obtained (especially in the region of horizontal clearances between 500 and 1,000 feet). Above about 1,100 feet, the confidence bands widen. The number of ship transits is indicated by the vertical scale on the right.

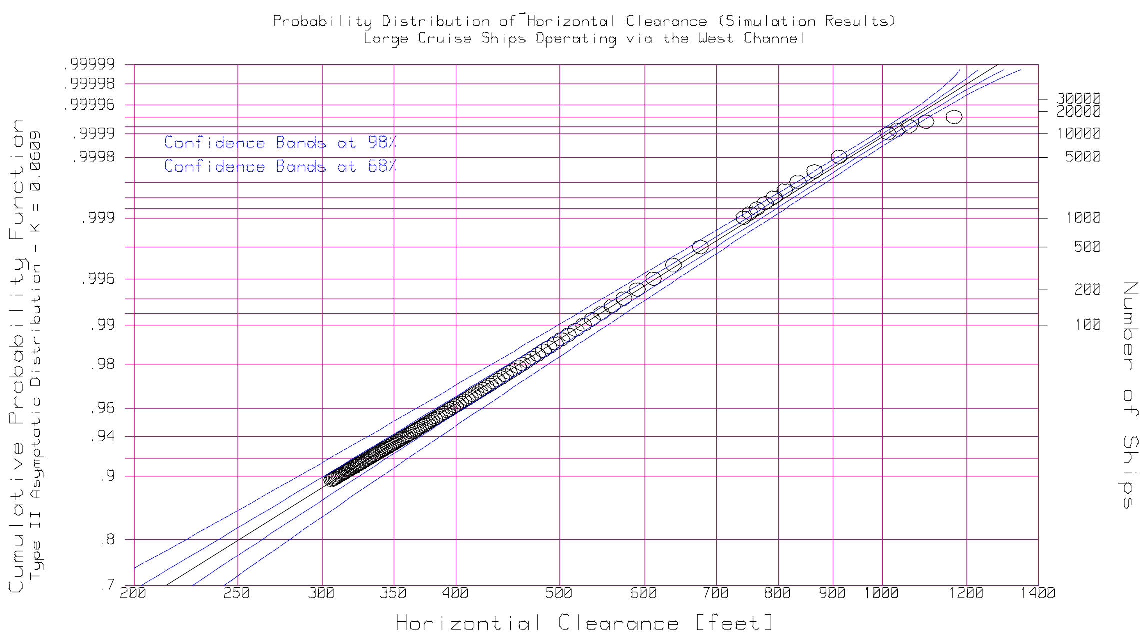

FIGURE 4.23
EXTRAPOLATION OF TYPE II EXTREMAL PROBABILITY FOR HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN WEST CHANNEL

4.5.4 Large Cruise Ship Traffic Through East Channel

East Channel is currently the preferred channel for arriving and departing large cruise ships as it lines up well with the existing cruise ship berths. Tracklines for large cruise ships operating through East Channel are depicted in Figure 4.24.

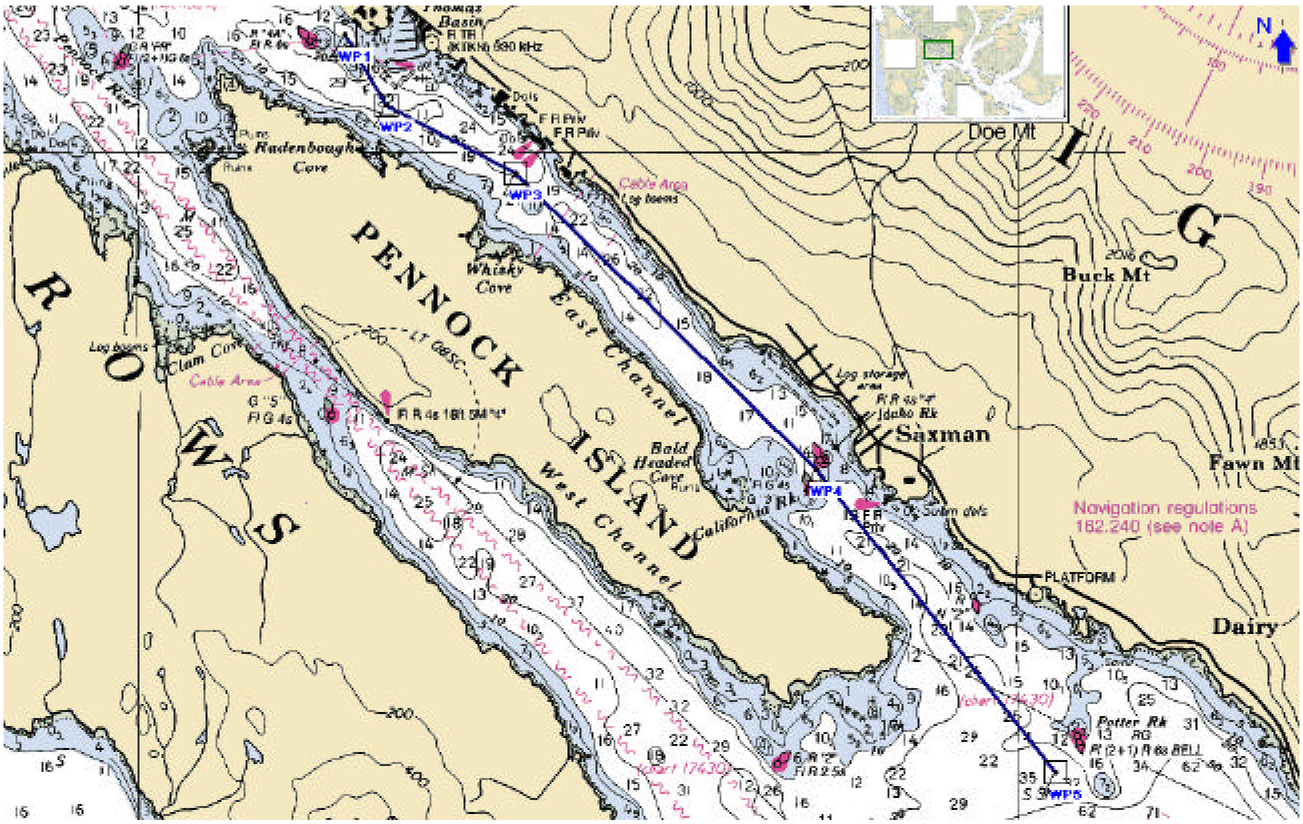

FIGURE 4.24
TRACKLINES FOR LARGE CRUISE SHIPS OPERATING THROUGH EAST CHANNEL

East Channel between Idaho Rock and California Rock represents the narrowest natural passage for large cruise ships in Tongass Narrows. As shown in Figure 4.25 the width between 5 fathom depth contours at Idaho Rock and California Rock is approximately 477 feet, which is essentially identical to the width of the West Channel passage and considerably less than the 687 foot width of the natural channel near Charcoal Point.

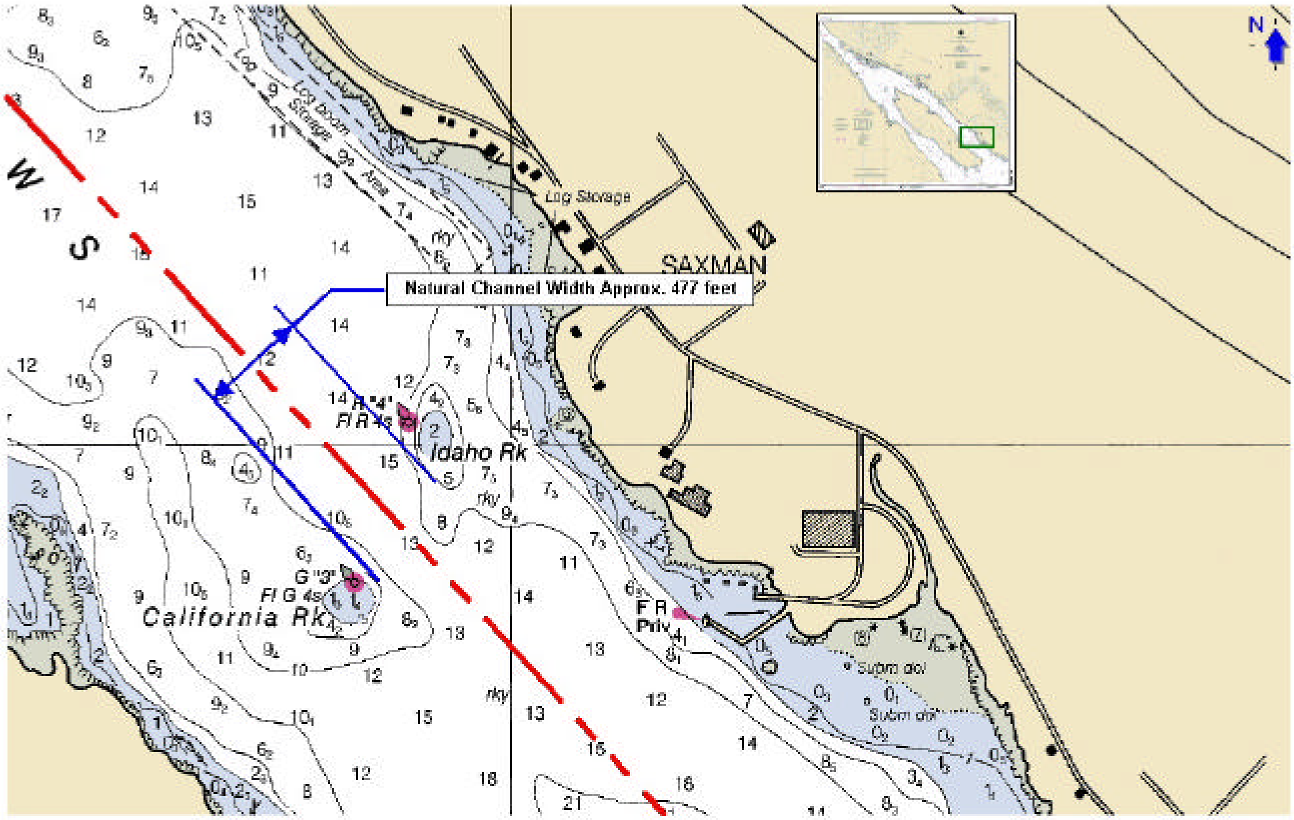

FIGURE 4.25
SHOWING THE NATURAL CHANNEL WIDTH BETWEEN IDAHO ROCK AND CALIFORNIA ROCK IN EAST CHANNEL

Figure 4.26 shows the cumulative probability distributions of east and west bank sweeps for both northbound and southbound large cruise ships in East Channel. At the 0.9 probability level, the width between east and west bank sweeps is approximately 262 feet; at the 0.99 level, the width is approximately 506 feet. This is respectively 51 feet and 20 feet less than the corresponding widths in West Channel, reflecting the improved large cruise ship trackline performance in East Channel. This improved large cruise ship trackline performance derives from improved initial conditions (i.e., position, heading, and residual yaw rate) resulting from being better able to line up for the passage of East Channel, especially for southbound vessels departing the Ketchikan cruise ship berths.

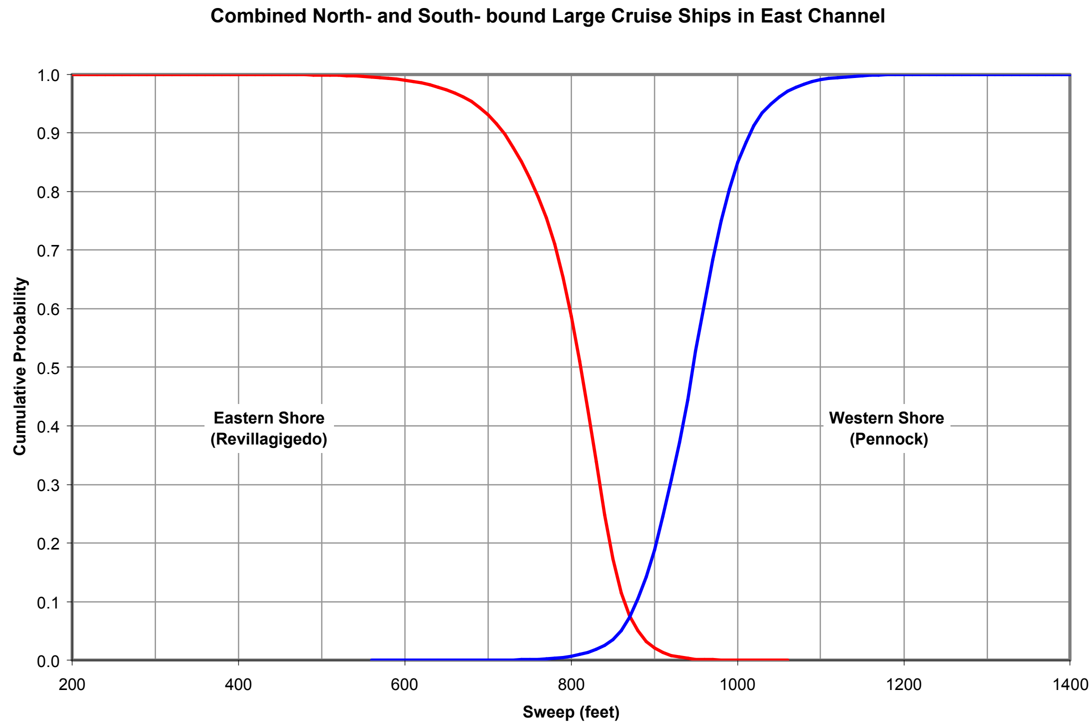

FIGURE 4.26
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN EAST CHANNEL

Figure 4.27 shows the probability density function for the horizontal clearance required by large cruise ships operating in East Channel. The most frequently occurring clearance is on the order of 129 feet, approximating the weighted average of the maximum beams of the cruise ships.

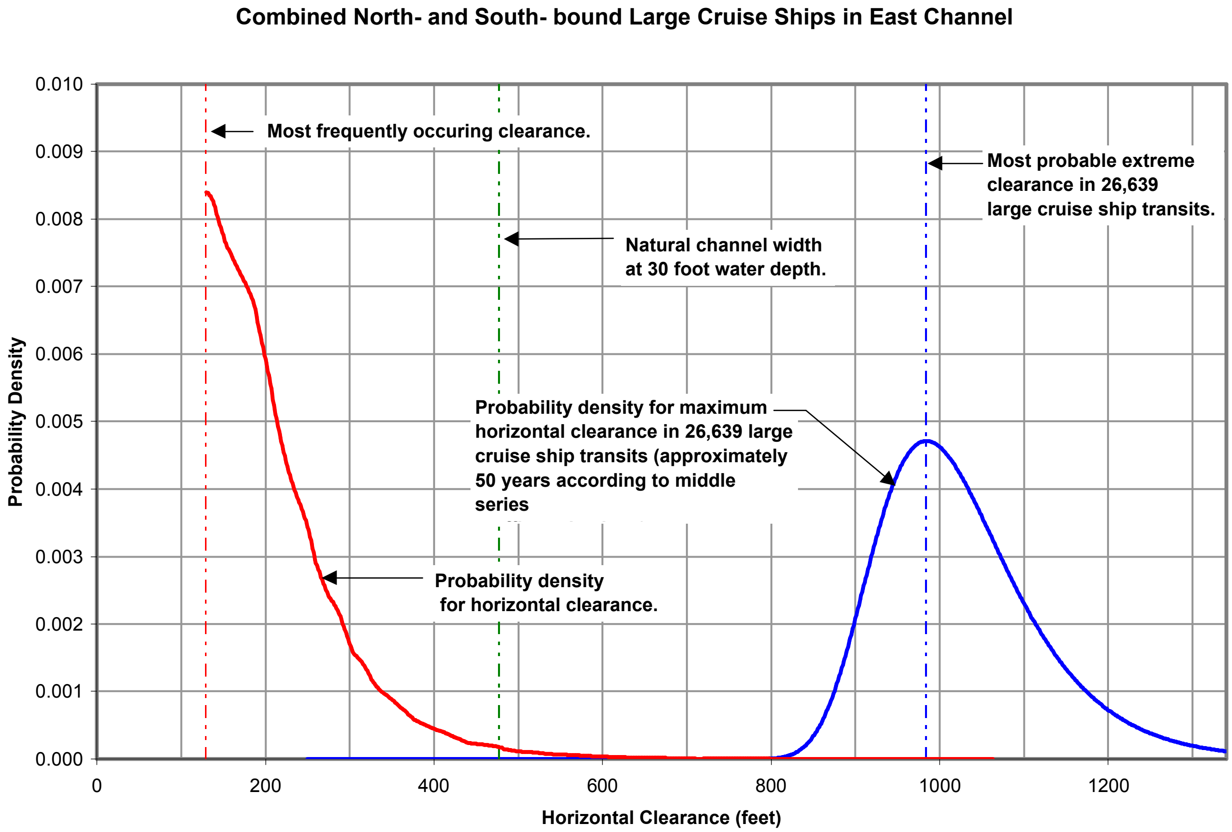

FIGURE 4.27
PROBABILITY DENSITY DISTRIBUTIONS OF HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN EAST CHANNEL

The distribution to the right in Figure 4.27 was developed using order statistics procedures applied to the cumulative and density distributions for large cruise ships operating in East Channel. The order statistics distribution given is the probability density function for the maximum horizontal clearance in 26,639 large cruise ship transits. That is the number of transits projected to occur over 50 years, according to the middle projection in Reference 6. The most probable extreme value is approximately 984 feet, a distance nearly double that of the available natural channel. Furthermore, the probability of exceeding this most probable value (in 50 years) is approximately 62%. With 50% confidence in 50 years, the horizontal clearance should be 1,011 feet. It is virtually certain that the 477 foot natural channel width will be exceeded in 50 years.

Table 4.12 provides statistics for large cruise ship potential groundings presuming that 26,639 large cruise ship transits were attempted in East Channel over 50 years without regard to the wind conditions. The most probable number of potential groundings in 50 years is 181, or 3.6 potential large cruise ship groundings per year. The expected number of potential groundings in 50 years is 1,353, or about 27 potential groundings per year. Potential groundings are events that would result in an actual grounding if extreme avoidance measures (e.g., crash stops, twin screw propulsive maneuvers, use of bow thrusters, deployment of anchors, or some combination) are not implemented in a timely manner. To the extent that effective extreme avoidance measures are employed, the actual groundings will be less than the potential groundings.

TABLE 4.12
50-YEAR ORDER STATISTICS FOR POTENTIAL GROUNDINGS OF LARGE CRUISE SHIPS OPERATING IN EAST CHANNEL

Most Probable Number of Groundings	*Probability of Exceeding Most Probable Number of Groundings*	*Median Number of Groundings*	*Expected Number of Groundings*	*Average Number of Groundings per Year*
181	0.865	523	1,353	27

Order statistics for 26,639 large cruise ship transits corresponding to 50 years, according to the middle series projections of Reference 6.

Natural channel width between Idaho Rock and California Rock in East Channel is approximately 477 feet between the 5 fathom (30 foot) depth contours.

Potential groundings are events that would result in an actual grounding if extreme avoidance measures are not implemented in a timely manner.

Figure 4.28 presents a Type II extremal probability fit of the tail of the cumulative probability distribution for large cruise ships operating in East Channel. Also shown are 68% and 98% confidence bands for the fit. The narrowness of the bands indicates that an excellent fit was obtained (especially in the region of horizontal clearances between 250 and 1,100 feet). Above about 1,100 feet, the confidence bands widen. The number of ship transits is indicated by the vertical scale on the right.

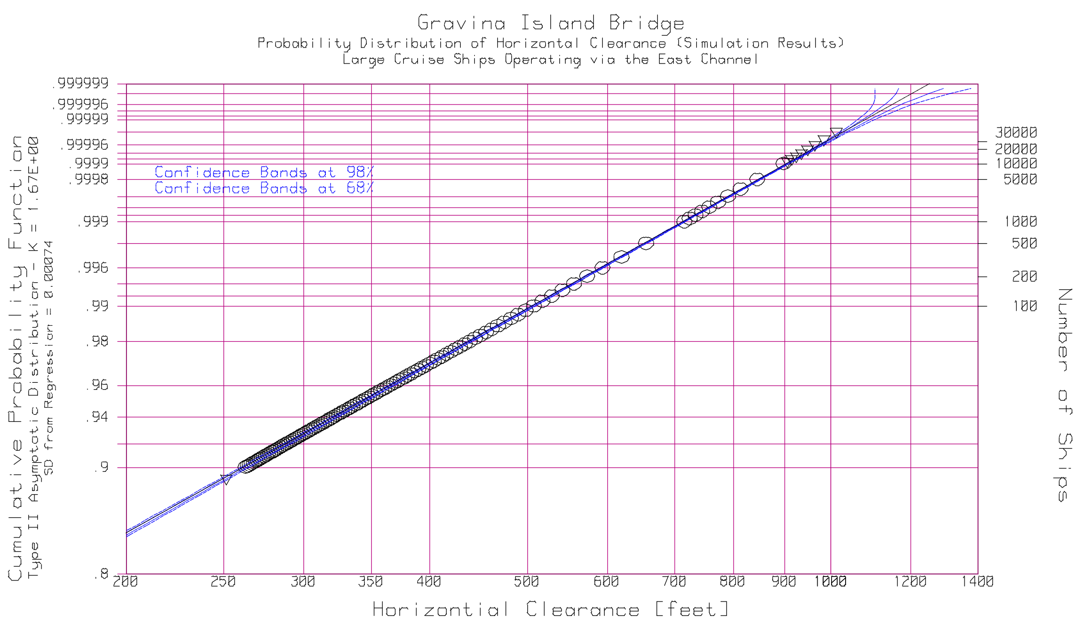

FIGURE 4.28
EXTRAPOLATION OF TYPE II EXTREMAL PROBABILITY FOR HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND LARGE CRUISE SHIPS IN EAST CHANNEL

4.6 Discussion of Large Cruise Ship Results

The results reported for Monte Carlo maneuvering simulations of large cruise ships in Section 4.5 indicate a high risk for potential groundings in the natural channels of Tongass Narrows and similarly high risks for potential allisions with bridges with effective horizontal clearances equal to, or less than, the width of those natural channels. The possible causes of these high measures of risk, and reasons why the historical record does not include such frequent groundings in the natural channel, include:

- The Monte Carlo maneuvering simulation model does not include extreme avoidance actions other than commands for maximum rudder angles. Extreme avoidance actions include: crash stops, twin-screw maneuvers, use of bow thrusters, and deployment of anchors. Thus all grounding and allision events predicted by this Monte Carlo maneuvering study are potential events that may be avoided if timely and effective avoidance actions are commanded. To the extent that such extreme avoidance measures are effective, this study over-estimates the number of actual groundings.
- The size of cruise ships calling at Ketchikan has been increasing very rapidly. Furthermore, the population of cruise ships used in this Monte Carlo study includes substitution of some new larger cruise ships for smaller cruise ships. Relatively little experience has yet accumulated with cruise ships of these large sizes operating in Tongass Narrows.
- This Monte Carlo maneuvering study does not consider the possibility that current large cruise ship operations engage in judicious avoidance actions such as choosing to arrive or depart via the north branch of Tongass Narrows under high wind conditions rather than use East Channel or delaying arrivals or departures for wind.
- Actual marine pilots apply skill that is not fully represented by the autopilot used by this Monte Carlo maneuvering simulator. Examples include:
    - Expert marine pilots have the ability to set a course that includes a small drift angle intended to compensate for steady wind acting at an angle to the trackline. The autopilot attempts to mimic this behavior but in a less intelligent fashion that results in the autopilot "*hunting*" for the appropriate drift angle. This hunting behavior introduces perturbations that potentially may grow under the influence of bank effects and unlucky encounters with wind gusts.
    - Expert marine pilots may have the ability to maintain smaller dead zones for off-track error and heading error than was represented in the autopilot for this Monte Carlo maneuvering simulator. This would best be investigated at a full-mission maneuvering simulator.
    - Expert marine pilots may have the ability to sense and respond to trackline and/or heading error derivatives not included in the present model. These might include the time rate of change for off-track distance or the time rate of change of the yaw rate (a second time derivative of heading error). This would best be investigated at a full-mission maneuvering simulator.
    - Expert marine pilots may apply non-uniform weights to the error terms considered by the autopilot. The constants c_1, c_2 and c_3 may not in fact be constants but rather functions of heading error, yaw rate error and off-track distance.
- Bank suction effects were established based on idealized theoretical considerations and may be over-represented. Physical model tests, computational fluid dynamic (CFD) analysis, or subjective calibration exercises with marine pilots in a full-mission simulator are the recommended approaches to refine bank suction models.

Respecting these considerations, it is suggested that a comparative risk approach will provide the greatest insight into the Gravina Access Project alternatives. Table 4.13 presents the relative risk associated with the existing natural passages near Charcoal Point and in East and West Channels respectively. Also provided in Table 4.13 are the relative risks associated with bridges with various effective horizontal clearances at C3(a) and C4.

TABLE 4.13
COMPARATIVE RISK OF POTENTIAL GROUNDINGS/ALLISIONS OF LARGE CRUISE SHIPS OPERATING IN TONGASS NARROWS

	Width (feet)	Cumulative Probability	Probability of Exceedance	Expected No. of Potential Groundings/Allisions in 50 Years	Normalized Risk Factor Relative to Natural Channel near Charcoal Point
Charcoal Point	687	0.998439	0.001561	244	1.00
East Channel	477	0.986481	0.013519	1,353	8.66
West Channel	476	0.983258	0.016742	1,583	10.72
C3(a) or C4	500	0.989498	0.010502	1,120	6.73
	550	0.993803	0.006197	746	3.97
	600	0.996293	0.003707	496	2.37
	650	0.997754	0.002246	330	1.44
	687	0.998439	0.001561	244	1.00
	700	0.998624	0.001376	220	0.88

The probability of exceeding the natural channel near Charcoal Point is considerably less than one-percent while the corresponding probabilities in East and West Channels both exceed one-percent. The passage risk in East Channel is 8.66 times greater than the risk of passage near Charcoal Point and the passage risk in West Channel is 10.72 times greater (or 24% greater than that in East Channel). It would require a bridge at C3(a)/C4 with an effective horizontal clearance of 687 feet to equal the passage risk near Charcoal Point but a bridge at that location with a 550 foot horizontal clearance would present less than half of the relative risk associated with the current passage of East Channel.

5—AMHS Ferry Simulation Results for Alternatives C3(b) and D

The vertical clearance of bridge Alternatives C3(b) and D will permit passage by AMHS ferries, but not by large cruise ships. AMHS ferries are expected to be the largest vessels to routinely pass beneath bridge Alternative C3(b) or D. Unlike the large cruise ships that operate in Alaska seasonally between May and September, the AMHS operates year-round.

5.1 AMHS Ferry Principal Dimensions

Principal dimensions of the six AMHS ferries modeled for both northbound and southbound transits are given in Table 5.1.

TABLE 5.1
DIMENSIONS OF AMHS FERRIES

Ship	% of Transits	LWL (feet)	Maximum Beam (feet)	Draft (feet)	Displacement (Long Tons S.W.)
Aurora/LeConte	0.67%	216	57	13.67	2,132
Taku	0.13%	327	74	17.00	4,319
Malaspina	0.01%	383	74	16.83	5,501
Matanuska	0.10%	384	74	17.17	5,664
Columbia	0.05%	392	85	17.51	7,684
Kennicott	0.04%	366	85	17.50	7,504

LWL = Length at water line; AMHS = Alaska Marine Highway System

5.2 AMHS Ferry Maneuvering Characteristics

The zigzag trials results, in the present study, for the AMHS ferry *Kennicott* are shown in Figures 5.1 and 5.2. These were compared with simulated results for the same ferry to ensure that the models behave reasonably.

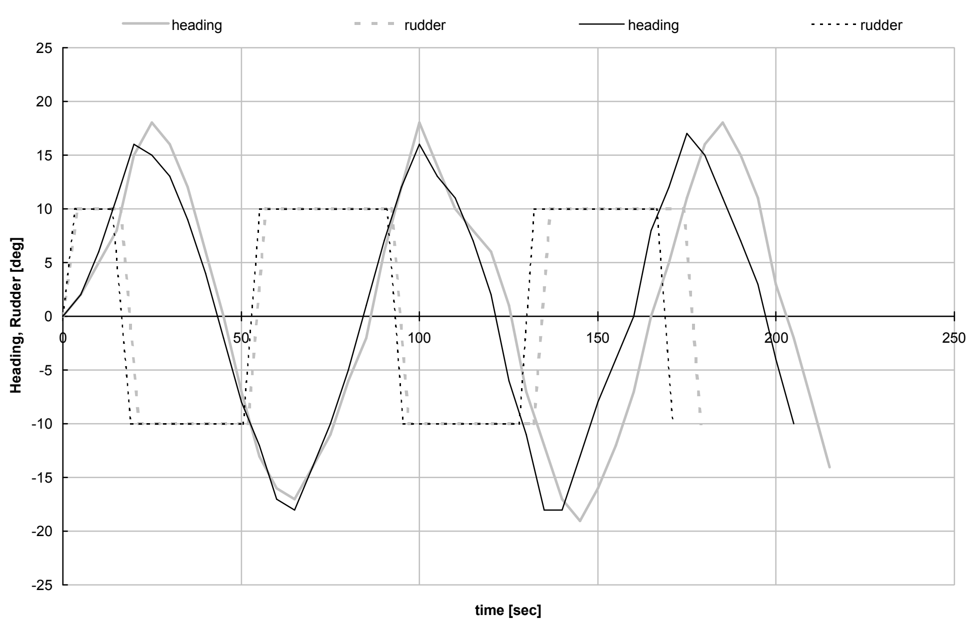

FIGURE 5.1
RESULTS OF THE 10°/10° ZIGZAG TEST FOR THE *KENNICOTT*

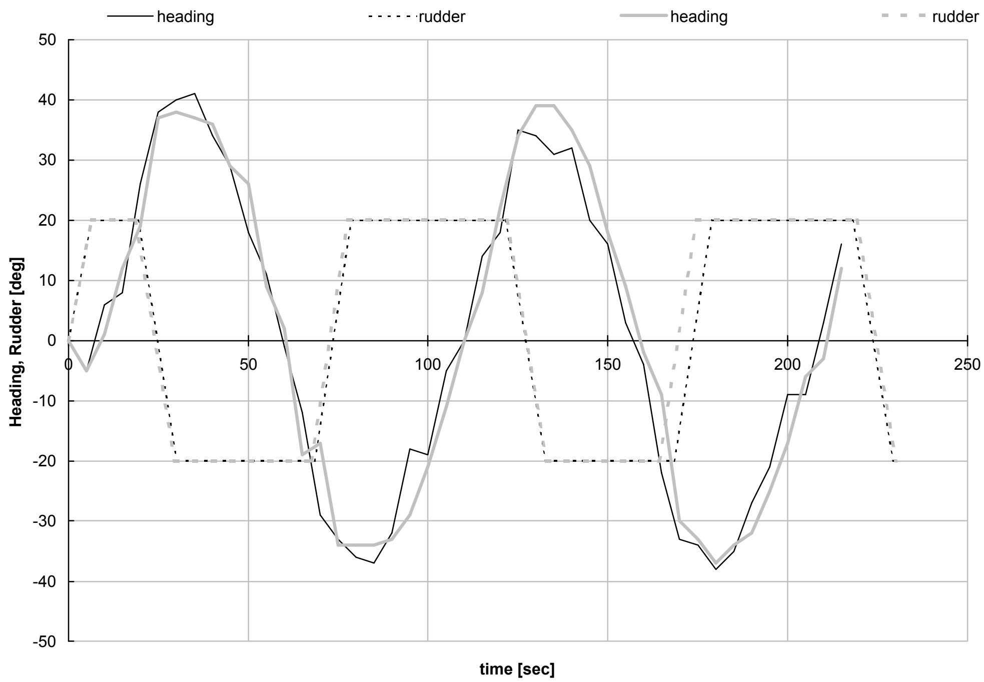

FIGURE 5.2
RESULTS OF THE 20°/20° ZIGZAG TEST FOR THE *KENNICOTT*

The International Maritime Organization (IMO) adopted Resolution A.751 (18), "Interim Standards for Ship Maneuvering" at their 18th Assembly Session in 1993. These interim standards establish recommended performance as measured by the 10°/10° and 20°/20° zig-zag maneuvers, and turning circles. The salient measures predicted by the fast-time simulator for the Alaska Marine Highway System ferry vessels used in this Monte Carlo study are summarized in Table 5.2.

TABLE 5.2
SUMMARY MANEUVERING CHARACTERISTICS OF AMHS FERRIES AS SIMULATED

	10°/10° Zig-Zag		*20°/20° Zig-Zag*		
Ship I.D.	*1st Overshoot Angle, deg*	*2nd Overshoot Angle, deg*	*1st Overshoot Angle, deg*	*Ratio of Tactical Diameter to Ship Length*	*Satisfies IMO Recommendations*
Aurora/Le Conte	7	9	14	3.8	YES
Taku	6	6	12	3.5	YES
Malaspina	5	5	10	3.5	YES
Matanuska	5	5	10	3.5	YES
Columbia	5	6	10	3.7	YES
Kennicott	5	6	10	3.8	YES

All of the AMHS ferries simulated in this study satisfy IMO interim standards for maneuvering performance.

5.3 Wind

The wind climatology for AMHS ferries was modeled similarly to that for the large cruise ships, but using probability distributions that reflect the year-round service by AMHS. The wind climatology for the Monte Carlo maneuvering simulations of AMHS ferries was developed as a weighted annual climatology where the weighting function was the percentage of AMHS port calls at Ketchikan in each month. That climatology is given in Tables 5.3 and 5.4.

TABLE 5.3
CUMULATIVE PROBABILITY, P(U), OF WIND SPEED AT KETCHIKAN AIRPORT—WEIGHTED ANNUAL DISTRIBUTION (PERIOD OF RECORD, 1974-1999)

U (knots)	*P(U)*	*U (knots)*	*P(U)*
0	0.000000	30	0.999614
2	0.000903	32	0.999805
4	0.103750	34	0.999820
6	0.287177	36	0.999876
8	0.554768	38	0.999898
10	0.680920	40	0.999919
12	0.841784	42	0.999934
14	0.921810	44	0.999942
16	0.947799	46	0.999959
18	0.970574	48	0.999966
20	0.990738	50	0.999980
22	0.992343	52	0.999987
24	0.997307	54	0.999993
26	0.998537	56	1.000000
28	0.999352	—	—

Weighting of each month in the annual distribution was by the percentage of AMHS port calls at Ketchikan in each month.

TABLE 5.4
WEIGHTED ANNUAL CUMULATIVE CONDITIONAL PROBABILITY, P(U_DIR|U), OF WIND DIRECTION (DEGREES–TRUE) GIVEN WIND SPEED AT KETCHIKAN AIRPORT
(PERIOD OF RECORD, 1974-1999)

	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
0 kts	0.000000	0.060748	0.084588	0.110211	0.156097	0.309854	0.417892	0.530498	0.610711	0.701386	0.801042	0.916295	1.000000
2 kts	0.000000	0.060748	0.084588	0.110211	0.156097	0.309854	0.417892	0.530498	0.610711	0.701386	0.801042	0.916295	1.000000
4 kts	0.000000	0.020384	0.030557	0.044042	0.094865	0.271653	0.455302	0.600106	0.685740	0.751651	0.832346	0.932026	1.000000
6 kts	0.000000	0.017519	0.021882	0.029110	0.086199	0.327933	0.538425	0.665005	0.692094	0.713868	0.768509	0.905047	1.000000
8 kts	0.000000	0.020287	0.022237	0.026136	0.080868	0.350142	0.545815	0.633586	0.640227	0.643928	0.678016	0.849474	1.000000
10 kts	0.000000	0.022812	0.024029	0.026155	0.068670	0.342020	0.532114	0.597781	0.601115	0.602823	0.632429	0.805657	1.000000
12 kts	0.000000	0.021783	0.022443	0.024459	0.055277	0.358551	0.592536	0.649131	0.651749	0.653338	0.669864	0.801982	1.000000
14 kts	0.000000	0.014587	0.014817	0.016559	0.036410	0.430441	0.750693	0.790931	0.793148	0.793819	0.804913	0.879099	1.000000
16 kts	0.000000	0.006837	0.007110	0.008605	0.024507	0.480764	0.843377	0.864240	0.865278	0.865425	0.874348	0.931909	1.000000
18 kts	0.000000	0.002679	0.002679	0.004475	0.021265	0.531245	0.923669	0.937940	0.939504	0.940048	0.945769	0.973080	1.000000
20 kts	0.000000	0.000351	0.000730	0.001096	0.015139	0.583356	0.967540	0.976648	0.977393	0.977393	0.978375	0.992742	1.000000
22 kts	0.000000	0.000000	0.000000	0.000000	0.015606	0.639761	0.986094	0.993226	0.997635	0.997635	0.997635	0.997635	1.000000
24 kts	0.000000	0.000000	0.000000	0.000000	0.013594	0.615328	0.990677	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
26 kts	0.000000	0.000000	0.000000	0.000000	0.026281	0.596902	0.969680	0.991362	0.991362	0.991362	0.991362	1.000000	1.000000
28 kts	0.000000	0.000000	0.000000	0.000000	0.013751	0.585940	0.980003	0.995343	0.995343	0.995343	0.995343	1.000000	1.000000
30 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.386388	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
32 kts	0.000000	0.027818	0.027818	0.027818	0.066438	0.666796	0.958624	0.976910	0.976910	0.976910	0.976910	1.000000	1.000000
34 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.260546	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
36 kts	0.000000	0.000000	0.000000	0.000000	0.067823	0.392569	0.931899	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
38 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.650178	0.650178	1.000000	1.000000	1.000000	1.000000	1.000000
40 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.666667	0.666667	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
42 kts	0.000000	0.000000	0.000000	0.000000	0.260198	0.519334	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
44 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.500000	1.000000	1.000000	1.000000
46 kts	0.000000	0.000000	0.000000	0.000000	0.500000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
48 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.500000	1.000000	1.000000	1.000000	1.000000	1.000000
50 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.263317	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
52 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.500000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
54 kts	0.000000	0.500000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
56 kts	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.500000	1.000000	1.000000	1.000000

1. *Weighting of each month in the annual distribution was by the percentage of AMHS port calls at Ketchikan in each month.*
2. *Row headings are wind speed (knots).*
3. *Column headings are wind direction, degrees (true).*
4. *Table entries are conditional cumulative probabilities for direction, given the wind speed.*

Gusting wind for Alaska ferries is modeled in the time domain by the Monte Carlo simulator as described in Section 4.3.2, "Pseudo-Time Domain Gusting Wind."

5.3.1 Windage Area of AMHS Ferries

The longitudinal and lateral windage areas of the AMHS ferries modeled for northbound and southbound transits are given in Table 5.5. Wind forces and moments were modeled using methods set forth for ferries in Reference 4.

TABLE 5.5
WINDAGE AREAS OF AMHS FERRIES

Ship	% of Transits	LWL (feet)	Draft (feet)	Longitudinal Windage Area (square feet)	Lateral Windage Area (square feet)
Aurora/LeConte	0.67%	216	13.67	2,542	8,478
Taku	0.13%	327	17.00	4,015	15,377
Malaspina	0.01%	383	16.83	4,027	18,531
Matanuska	0.10%	384	17.17	4,002	18,356
Columbia	0.05%	392	17.51	5,312	21,521
Kennicott	0.04%	366	17.50	5,780	22,430

LWL = Length at water line; AMHS = Alaska Marine Highway System

5.4 Results

5.4.1 Bridge Alternative C3(b)

As shown in Figure 3.1, the bridge alignment of Alternative C3(b) crosses Tongass Narrows north of Alternatives C3(a) and C4. As indicated in Table 3.2, the Alternative C3(b) bridge has a vertical clearance of 120 feet, which permits passage by all existing large AMHS ferries, but prevents passage by all large cruise ships.

Figures 5.3, 5.4, and 5.5 show cumulative probabilities for east and west bank sweeps for bridge Alternative C3(b), for (respectively) southbound ferries, northbound ferries, and combined north- and southbound ferries.

Figure 5.3 shows the cumulative probability distributions of east and west bank sweeps for southbound AMHS ferries for bridge Alternative C3(b). At the 0.9 probability level, the width between east and west bank sweeps is approximately 127 feet; at the 0.99 level, it is approximately 190 feet.

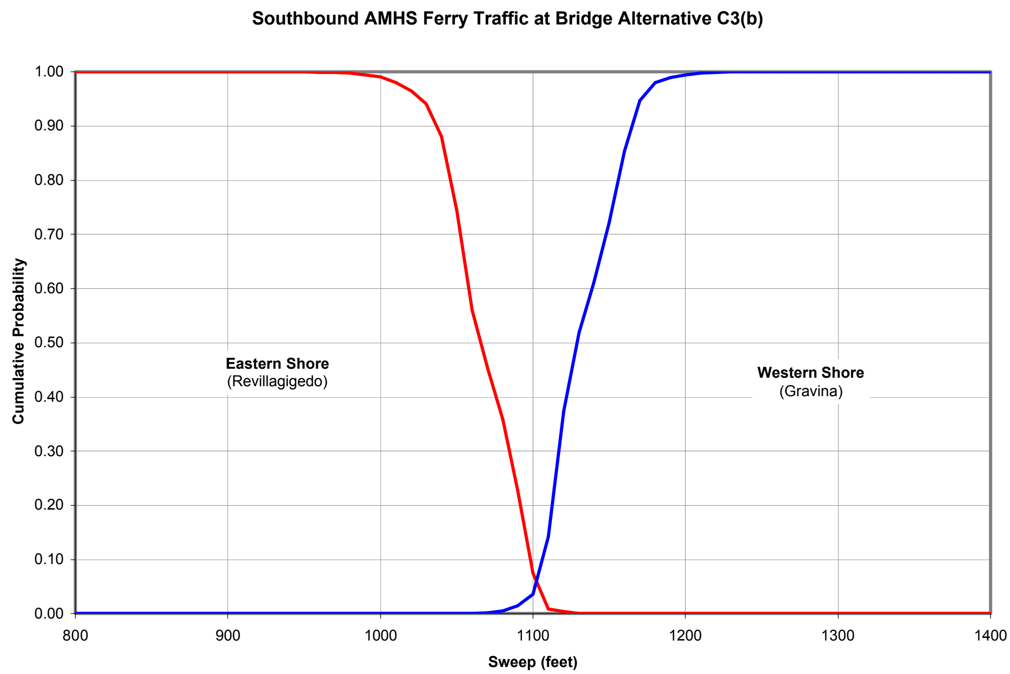

FIGURE 5.3
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE C3(B)

Figure 5.4 shows the cumulative probability distributions of east and west bank sweeps for northbound AMHS ferries for bridge Alternative C3(b). At the 0.9 probability level, the width between east and west bank sweeps is approximately 122 feet; at the 0.99 level, it is approximately 174 feet.

Figure 5.5 shows the cumulative probability distributions of east and west bank sweeps for combined north- and southbound AMHS ferries for bridge Alternative C3(b). At the 0.9 probability level, the width between east and west bank sweeps is approximately 124 feet; at the 0.99 level, it is approximately 184 feet.

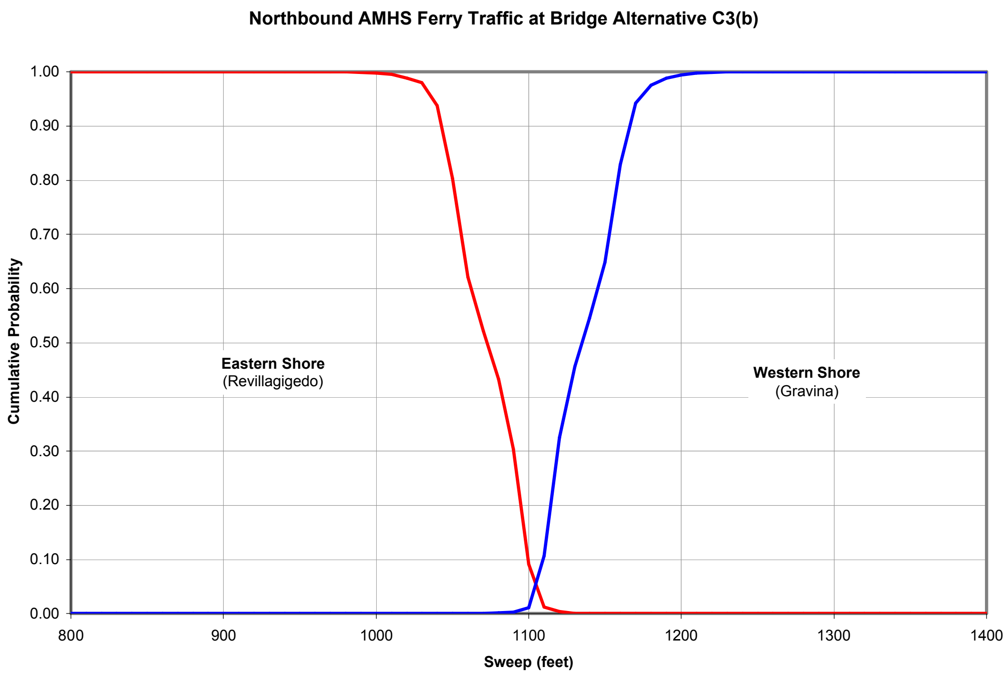

FIGURE 5.4
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR NORTHBOUND AMHS FERRIES FOR ALTERNATIVE C3(B)

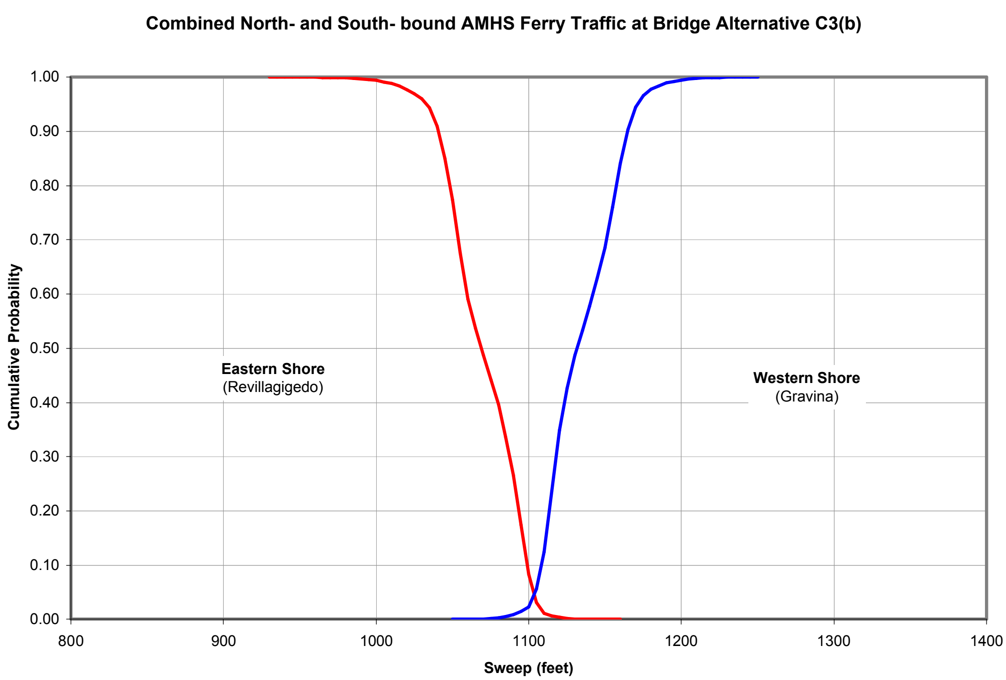

FIGURE 5.5
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR COMBINED NORTH- AND SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE C3(B)

Figure 5.6 shows the probability density function for the horizontal clearance for bridge Alternative C3(b). The most frequently occurring clearance is on the order of 100 feet.

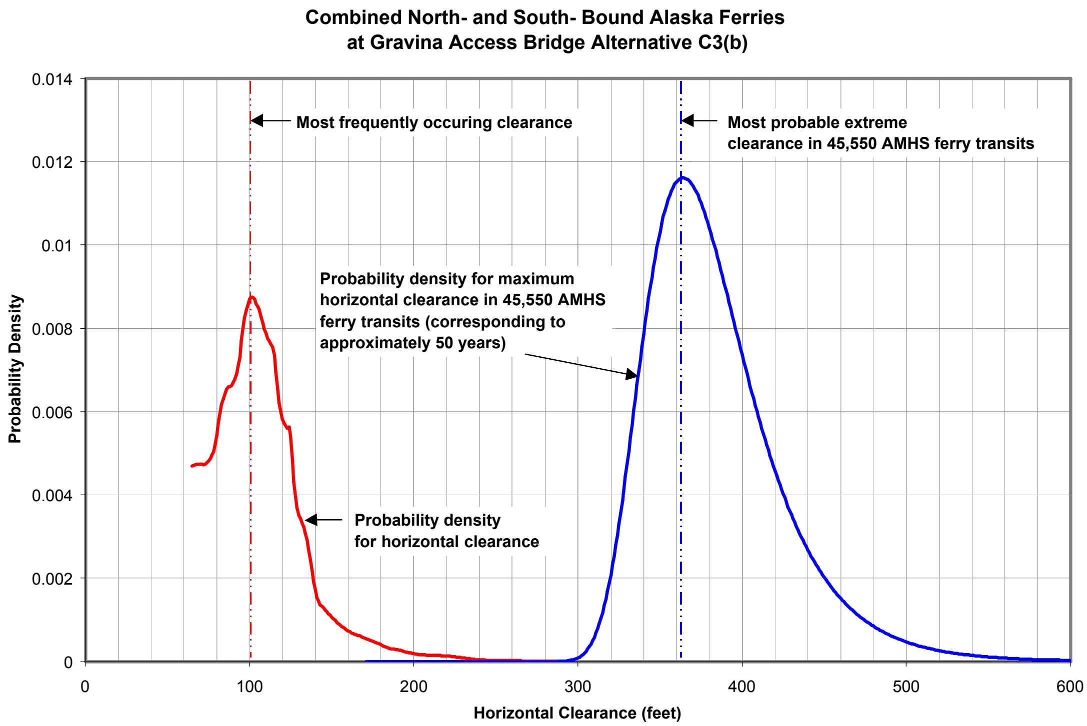

FIGURE 5.6
PROBABILITY DENSITY DISTRIBUTIONS OF HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE C3(B).

The difference between east and west bank sweeps in Figure 5.5 is the basis for the probability density distribution for horizontal clearance given on the left in Figure 5.6.

The distribution to the right in Figure 5.6 was developed using order statistics procedures applied to the cumulative and density distributions for bridge Alternative C3(b). This distribution is the probability density function for the maximum horizontal clearance in 45,550 AMHS ferry transits, which is the number projected to occur over 50 years at the 1998 rate of 911 transits per year. The most probable extreme value is approximately 364 feet. However, the probability of exceeding this most probable value (in 50 years) is nearly 64%. With 50% confidence, in 50 years the horizontal clearance should be 377 feet.

Table 5.6 provides order statistics for the horizontal clearance for bridge Alternative C3(b). Order statistics are provided for the horizontal clearance expected to be violated by one, two, three, four, and five ships over a 50-year period corresponding to 45,550 AMHS ferry transits.

TABLE 5.6
50-YEAR ORDER STATISTICS
FOR HORIZONTAL CLEARANCE FOR BRIDGE ALTERNATIVE C3(B)

Number of AMHS Ferries	*Most Probable Horizontal Clearance (feet)*	*Probability of Exceeding Most Probable Horizontal Clearance*	*Horizontal Clearance (feet) with Exceedance Probability of 0.99999*	*Average Return Period (Years)*
1	364	0.64	296	50.0
2	342	0.64	275	25.0
3	330	0.63	263	16.7
4	321	0.64	255	12.5
5	314	0.64	248	10.0
Order statistics for 45,550 AMHS ferry transits corresponding to 50 years at the 1998 rate of 911 transits per year				

The fourth column of Table 5.6 gives the horizontal clearance that is expected to be exceeded with near certainty (a probability of 0.99999). Thus, over a 50-year period, it is nearly certain that at least one AMHS ferry would violate a 296-foot horizontal clearance. Likewise, it is nearly certain that at least five AMHS ferries would violate a 248-foot horizontal clearance over the same period. The most probable clearance that would be expected to be violated by one AMHS ferry in 50 years is 364 feet. The probability of exceeding that clearance in 50 years is 64%. The final column of Table 5.6 gives the average return period between potential ferry allision events. Thus, if there are five potential ferry allision events in 50 years the average return period is ten years.

Figure 5.7 presents a Type II extremal probability fit of the tail of the cumulative probability distribution for large conventional AMHS ferries for bridge Alternative C3(b). Also shown are 68% and 98% confidence bands for the fit. The narrowness of the bands indicates that an excellent fit was obtained, especially in the region of horizontal clearances between 200 and 300 feet. Above about 305 feet, the confidence bands widen. Based on a constant number of 911 annual transits, the return period (in years) is indicated at the vertical scale on the right.

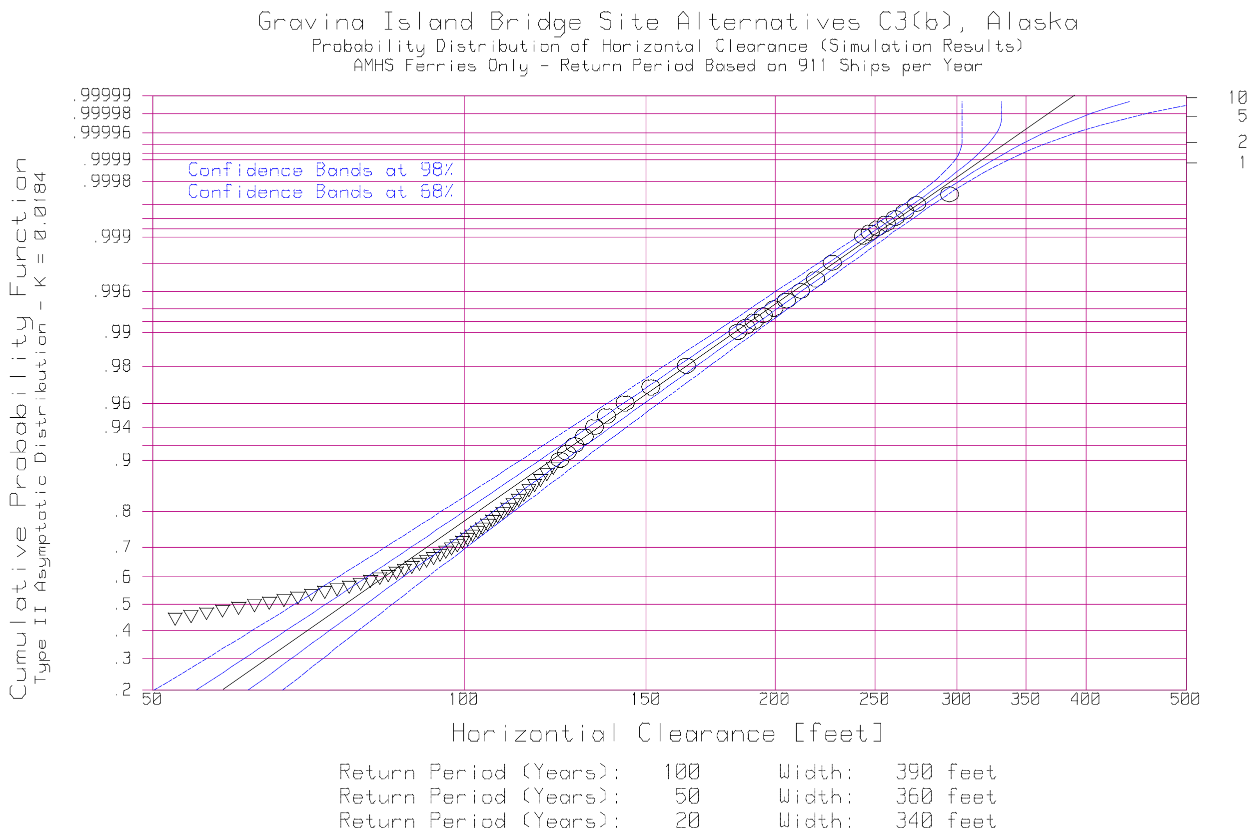

FIGURE 5.7
EXTRAPOLATION OF TYPE II EXTREMAL PROBABILITY FOR HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE C3(B)

5.4.2 Bridge Alternative D

As shown in Figure 3.1, Gravina Access bridge Alternative D crosses Tongass Narrows south of Alternatives C3(a) and C4 near the track of the current Ketchikan airport ferry. As indicated in Table 3.2, Alternative D has a vertical clearance of 120 feet, which permits passage by all existing large AMHS ferries, but prevents passage by all large cruise ships.

Figures 5.8, 5.9, and 5.10 show cumulative probabilities for east and west bank sweeps for bridge Alternative D for, respectively southbound ferries, northbound ferries, and combined north- and southbound ferries.

Figure 5.8 shows the cumulative probability distributions of east and west bank sweeps for southbound AMHS ferries for bridge Alternative D. At the 0.9 probability level, the width between east and west bank sweeps is approximately 131 feet; at the 0.99 level, the width is approximately 198 feet.

Figure 5.9 shows the cumulative probability distributions of east and west bank sweeps for northbound AMHS ferries for Alternative D. At the 0.9 probability level, the width between east and west bank sweeps is approximately 119 feet; at the 0.99 level, the width is approximately 173 feet.

Southbound AMHS Ferry Traffic at Bridge Alternative D

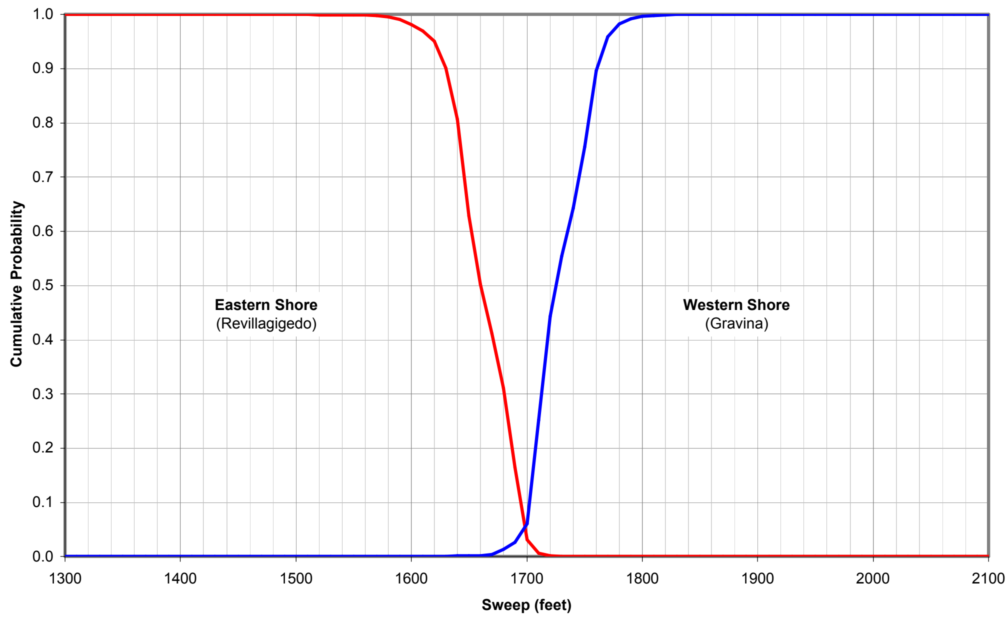

FIGURE 5.8
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE D

Northbound AMHS Ferry Traffic at Bridge Alternative D

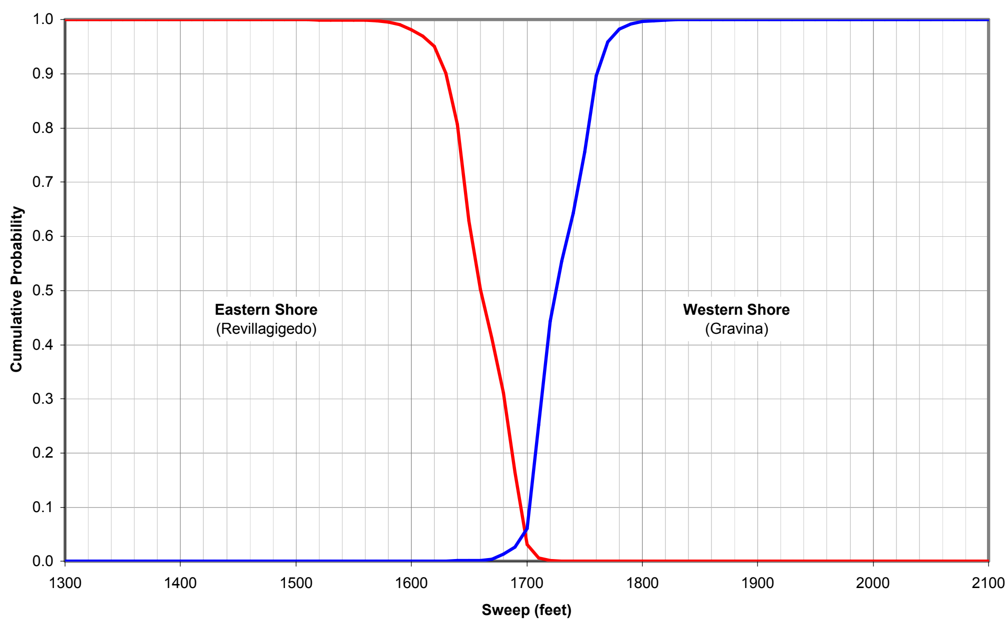

FIGURE 5.9
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR NORTHBOUND AMHS FERRIES FOR ALTERNATIVE D

Figure 5.10 shows the cumulative probability distributions of east and west bank sweeps for combined north- and southbound AMHS ferries for bridge Alternative D. At the 0.9 probability level, the width between east and west bank sweeps is approximately 125 feet; at the 0.99 level, the width is approximately 185 feet.

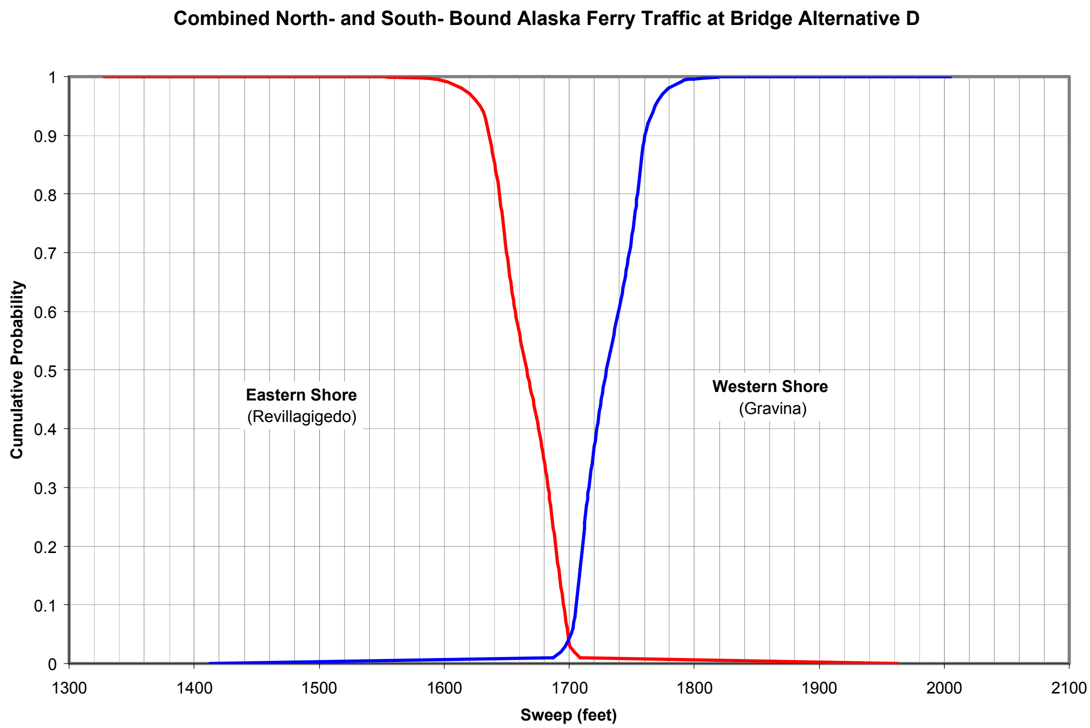

FIGURE 5.10
CUMULATIVE PROBABILITY DISTRIBUTIONS OF EAST AND WEST BANK SWEEPS FOR COMBINATION OF NORTH- AND SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE D

Figure 5.11 shows the probability density function for the horizontal clearance for bridge Alternative D. The most frequently occurring clearance is on the order of 110 feet.

The difference between east and west bank sweeps in Figure 5.10 is the basis for the probability density distribution for horizontal clearance given on the left in Figure 5.11. The distribution to the right in Figure 5.11 was developed using order statistics procedures applied to the cumulative and density distributions for bridge Alternative D.

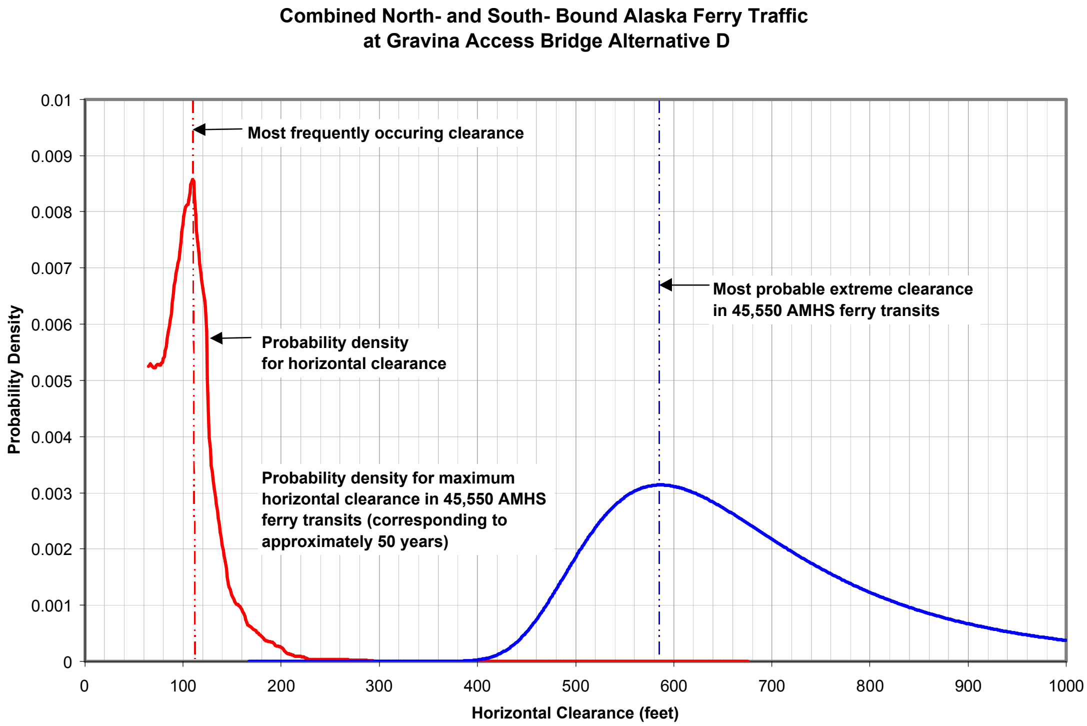

FIGURE 5.11
PROBABILITY DENSITY DISTRIBUTIONS OF HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTHBOUND AMHS FERRIES FOR ALTERNATIVE D

The distribution given on the right in Figure 5.11 is the probability density function for the maximum horizontal clearance in 45,550 AMHS ferry transits, which is the number projected to occur over 50 years at the 1998 rate of 911 transits per year. The most probable extreme value is approximately 587 feet. However, the probability of exceeding this most probable value (in 50 years) is nearly 70%. With 50% confidence, in 50 years the horizontal clearance should be 653 feet.

Table 5.7 provides order statistics for the horizontal clearance for bridge Alternative D. Order statistics are provided for the horizontal clearance expected to be violated by one, two, three, four, or five ships over a 50-year period corresponding to 45,550 AMHS ferry transits.

TABLE 5.7
50-YEAR ORDER STATISTICS FOR HORIZONTAL CLEARANCE FOR ALTERNATIVE D

Potential Number of AMHS Ferry Allisions	*Most Probable Horizontal Clearance (feet)*	*Probability of Exceeding Most Probable Horizontal Clearance*	*Horizontal Clearance (feet) with Exceedance Probability of 0.99999*	*Average Return Period (Years)*
1	587	0.70	393	50.0
2	512	0.70	343	25.0
3	473	0.70	317	16.7
4	447	0.70	300	12.5
5	427	0.70	287	10.0

Order statistics for 45,550 AMHS ferry transits corresponding to 50 years at the 1998 rate of 911 transits per year

The fourth column of Table 5.7 gives the horizontal clearance that is expected to be exceeded with near certainty. Thus, over a 50-year period, it is nearly certain that at least one AMHS ferry would violate a 393 foot horizontal clearance. Likewise, it is nearly certain that at least five ferries would violate a 287 foot horizontal clearance over the same period. The most probable clearance that would be expected to be violated by one AMHS ferry in 50 years is 587 feet. The probability of exceeding that clearance in 50 years is 70%. The final column of Table 5.7 gives the average return period between potential ferry allision events. Thus, if there are five potential ferry allision events in 50 years the average return period is ten years.

Figure 5.12 presents a Type I extremal probability fit of the tail of the cumulative probability distribution for large conventional AMHS ferries for bridge Alternative D. Also shown are 68% and 98% confidence bands for the fit. Based on a constant number of 911 annual transits, the return period (in years) is indicated at the vertical scale on the right.

The extremal fit in Figure 5.12 is not nearly as good as those for the large cruise ships in Figure 4.14 or AMHS ferries for bridge Alternative C3(b), as shown in Figure 5.7. This can be observed from how the sample points meander about the mean fit line in Figure 5.12 and from the width of the confidence intervals. Thus, lower confidence can be associated with the results for bridge Alternative D compared to similar results for bridge Alternatives C3(a), C3(b), or C4. The explanation for these results is not entirely obvious, but speculation is that ship maneuvers in the vicinity of the Alternative D bridge are more affected by bank suction effects than at the other three sites, because Tongass Narrows channel is narrowest in the vicinity of the Alternative D bridge.

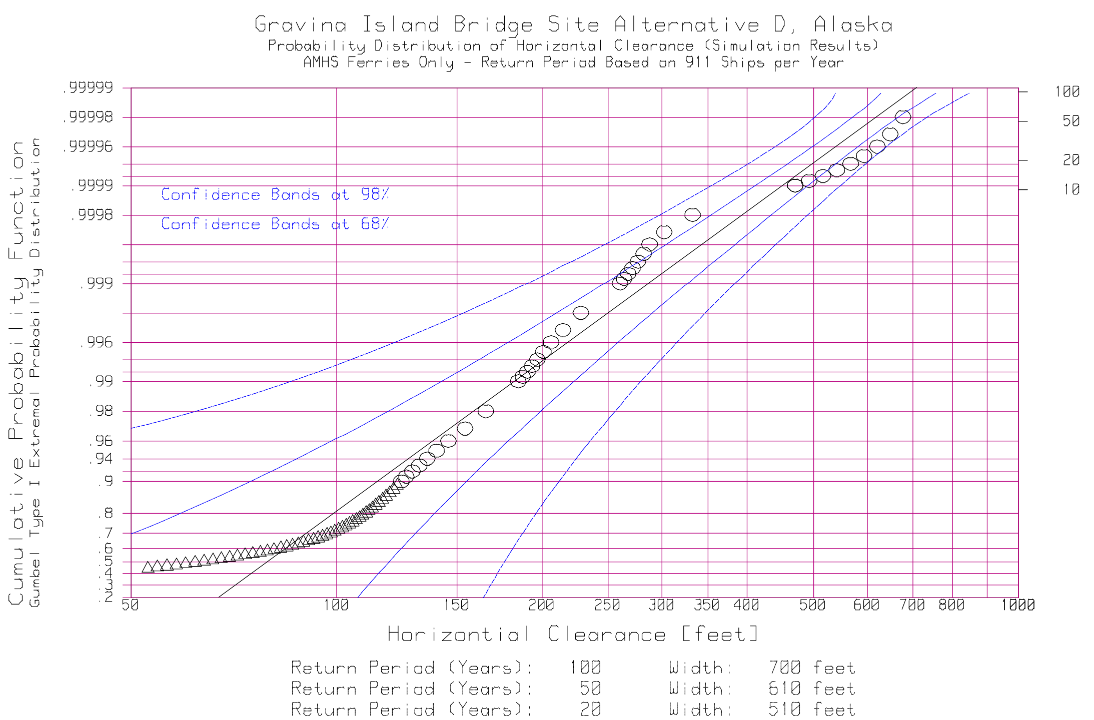

FIGURE 5.12
EXTRAPOLATION OF TYPE-I EXTREMAL PROBABILITY FOR HORIZONTAL CLEARANCE FOR COMBINED NORTH- AND SOUTH- AMHS FERRIES FOR ALTERNATIVE D

6—Summary and Conclusions

Monte Carlo maneuvering simulations have been carried out for the Gravina Access Project for 49,804 large cruise ship transits for bridge Alternatives C3(a) and C4. Simulations of large cruise ships were also performed in West Channel as large cruise ships arriving from, or proceeding to, the south would presumably use West Channel if Alternative F3 were implemented. In order to complete the calibration of passage risk for large cruise ships, simulations were also performed in East Channel in order to gage the risk of the passage between California Rock and Idaho Rock relative to the corresponding risks near Charcoal Point or in West Channel.

Monte Carlo maneuvering simulations were also carried out for 59,982 transits of large conventional AMHS ferries for bridge Alternatives C3(b) and D.

There are real, nonzero 50-year probabilities for large cruise ship excursions extending to the limits of the various natural channels. If bridge piers are located within the limits of the natural channel, then pier protection is required.

This Monte Carlo maneuvering study did not consider the mitigating effects of emergency actions to avoid grounding or allision with bridge piers. These actions, which may be anticipated in actual practice, include crash-stop maneuvering with the main propulsion, applying bow thrusters, twin screw propulsion maneuvers, and/or dropping one or both anchors. The ameliorating effects of these actions have not been simulated or otherwise measured in this study, but may be anticipated to reduce the probability of groundings and/or allisions, and also to reduce the speed at which impacts (if any) occur. Because these extreme avoidance actions have not been included, any groundings or allisions predicted by this Monte Carlo maneuvering study must be regarded as potential groundings and potential allisions. To the extent that timely and effective extreme avoidance actions are employed the actual groundings and allisions will be less than the potential groundings and allisions predicted by this study.

Gusting wind has been identified as the principal cause of the rare large off-track excursions; when such excursions occur, they are exacerbated by bank suction effects.

The ameliorating effect of imposing wind speed limits on large cruise ship transits under bridges C3(a) or C4 was investigated. For a bridge with a 550 foot horizontal clearance a limiting wind speed of 11.8 knots would result in a probability of allision similar to that associated with the 687 foot natural channel near Charcoal Point in the absence of wind speed limitations (i.e., the current natural risk). If the horizontal clearance were to be increased to 650 feet the corresponding wind speed limit could be increased to 17.9 knots.

Large cruise ship operations in West Channel as a consequence of bridge alternative F3 were also investigated. The controlling width of this natural channel is only about 466 feet.

Bridges alternatives C3(a) or C4 with horizontal clearances exceeding 687 feet have lower risk of large cruise ship allision than the corresponding grounding risk for large cruise ships forced to make use of West Channel by bridge alternative F3.

As set forth in Table 4.13 the existing passage risk for large cruise ships in East Channel is 8.66 times greater than the passage risk in the north branch of Tongass Narrows near Charcoal Point and the passage risk for West Channel is 10.72 times greater. Bridge alternatives C3(a) or C4 with an effective horizontal clearance of 550 feet would present a passage risk 3.97 times greater than that of Tongass Narrows near Charcoal Point, which is less than half of the risk currently accepted by large cruise ships in the East Channel passage between Idaho and California Rocks. A bridge at this site with a 650 foot effective horizontal clearance would present a passage risk only 1.44 times that of Tongass Narrows near Charcoal Point.

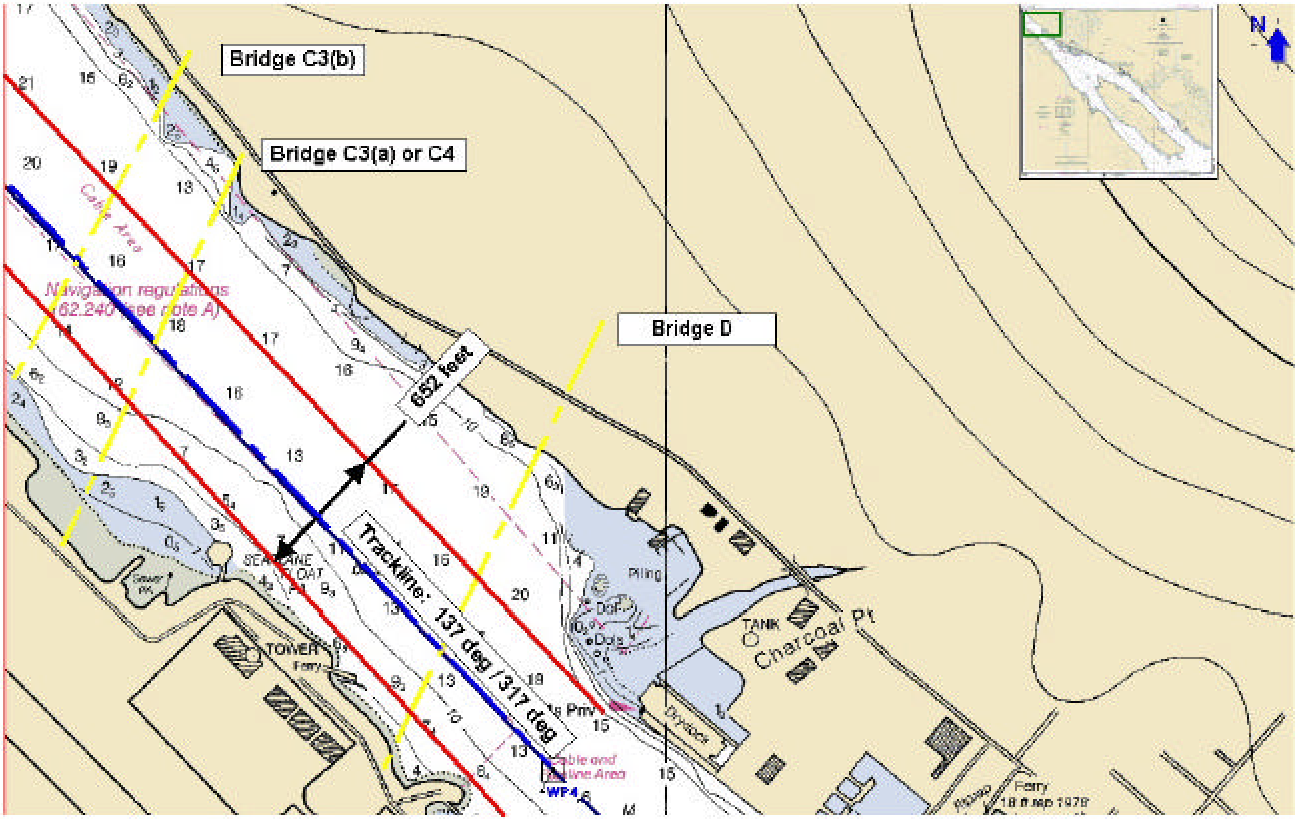

FIGURE 6.1
LARGE CRUISE SHIP TRACKLINE, GRAVINA ACCESS BRIDGE ALIGNMENTS, AND PARALLEL SIDED 5-FATHOM (30 FOOT) CHANNEL

Figure 6.1 shows the large cruise ship trackline in way of bridge alignment alternatives C3(a)/C4, C3(b) and D. Due to differences in vertical clearance only alternatives C3(a) and C4 permit the passage of large cruise ships. Also shown in Figure 6.1 are natural channel boundaries that are parallel to the trackline and tangent to the 5 fathom (30 foot) depth contours. The width of this parallel sided natural channel in way of C3(a) and C4 is 652 feet. To the extent possible it is recommended that the horizontal clearance of any bridge located at C3(a)/C4 be centered about the large cruise ship trackline.

7—References

1. Permanent International Association of Navigation Congresses (PIANC). 1997. "Approach Channels – A Guide for Design" PTC II-30 Final Report, Supplement to Bulletin No. 95.

2. The Glosten Associates, Inc. Revised August 2000. "Wind Climatology," Gravina Access Project technical memorandum, prepared for HDR Alaska, Inc.

3. Ang, Alfredo H-S and Tang, Wilson H. 1984. *Probability Concepts in Engineering Planning and Design, Volume II – Decision, Risk, and Reliability*. John Wiley & Sons.

4. Martin, L.L. 1980. "Ship Maneuvering and Control in Wind," Society of Naval Architects and Marine Engineers (SNAME) Transactions, Vol. 88, pp. 257-281.

5. Newman, J.N. 1965. "The Force and Moment on a Slender Body of Revolution Moving Near a Wall," DTMB Report 2127.

6. The Glosten Associates, Inc. September 2001. "Cruise Ship Traffic Projections," Gravina Access Project technical memorandum, prepared for HDR Alaska, Inc.

Appendix A
Ketchikan Airport Wind Climatology
(1974-1999)

TABLE A.1: JOINT PROBABILITY P (U,U_DIR), OF WIND SPEED (KNOTS) AND DIRECTION (DEGREES-TRUE) AT KETCHIKAN AIRPORT (PERIOD OF RECORD, 1974-1999)—MAY THROUGH SEPTEMBER

	2 kts	4 kts	6 kts	8 kts	10 kts	12 kts	14 kts	16 kts	18 kts	20 kts	22 kts	24 kts	26 kts	28 kts	30 kts	32 kts	34 kts	36 kts	38 kts	40 kts	42 kts	44 kts	46 kts	48 kts	50 kts	
30°	0.005	0.128	0.114	0.128	0.042	0.048	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	0.478
60°	0.002	0.102	0.076	0.028	0.008	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	0.218
90°	0.003	0.145	0.158	0.084	0.017	0.020	0.005	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	0.435
120°	0.006	0.605	1.341	2.085	0.767	0.673	0.159	0.034	0.019	0.006	0.002	0.002	0.003	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	5.702
150°	0.015	1.873	4.865	8.876	4.123	5.481	2.676	0.871	0.626	0.411	0.028	0.088	0.008	0.005	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.003	0.00	0.000	29.950
180°	0.005	1.787	3.561	5.167	2.494	3.648	2.014	0.719	0.577	0.337	0.019	0.068	0.008	0.005	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	20.407
210°	0.006	1.115	1.703	1.474	0.467	0.452	0.127	0.015	0.012	0.006	0.002	0.002	0.003	0.002	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.002	5.388
240°	0.005	0.630	0.331	0.094	0.017	0.019	0.005	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.002	0.00	0.00	0.000	0.000	0.00	0.000	1.104
270°	0.005	0.463	0.260	0.053	0.006	0.012	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	0.803
300°	0.003	0.600	0.741	0.736	0.354	0.213	0.070	0.015	0.011	0.002	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.002	0.000	0.00	0.000	2.747
330°	0.005	1.012	2.494	5.182	2.602	2.469	0.600	0.147	0.050	0.020	0.000	0.000	0.002	0.000	0.00	0.002	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	14.583
360°	0.011	0.838	2.238	5.485	3.493	4.543	1.295	0.223	0.057	0.002	0.000	0.000	0.000	0.000	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000	0.000	0.00	0.000	18.185
	0.070	9.298	17.882	29.393	14.389	17.581	6.967	2.028	1.355	0.784	0.050	0.159	0.023	0.011	0.00	0.002	0.00	0.00	0.002	0.00	0.00	0.002	0.003	0.00	0.002	100.000

Column headings are wind speed (knots)
Row headings are wind direction, degrees (true)
Table entries are joint probabilities (percent)

TABLE A.2: JOINT PROBABILITY P(U,U_DIR) OF WIND SPEED (KNOTS) AND DIRECTION (DEGREES-TRUE) AT KETCHIKAN AIRPORT (PERIOD OF RECORD, 1974-1999)—WEIGHTED ANNUAL

	2 kts	4 kts	6 kts	8 kts	10 kts	12 kts	14 kts	16 kts	18 kts	20 kts	22 kts	24 kts	26 kts	28 kts	30 kts	32 kts	34 kts	36 kts	38 kts	40 kts	42 kts	44 kts	46 kts	48 kts	50 kts	52 kts	54 kts	56 kts	
30°	0.006	0.208	0.181	0.173	0.048	0.051	0.011	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.682
60°	0.002	0.139	0.133	0.104	0.027	0.032	0.014	0.004	0.004	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.460
90°	0.004	0.523	1.047	1.465	0.536	0.496	0.159	0.041	0.038	0.028	0.003	0.007	0.003	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.353
120°	0.014	1.818	4.434	7.206	3.448	4.879	3.153	1.186	1.161	1.146	0.100	0.299	0.070	0.047	0.010	0.011	0.000	0.002	0.000	0.001	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	28.988
150°	0.010	1.889	3.861	5.236	2.398	3.764	2.563	0.942	0.894	0.775	0.056	0.186	0.046	0.032	0.016	0.006	0.001	0.003	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	22.680
180°	0.010	1.489	2.322	2.349	0.828	0.910	0.322	0.054	0.033	0.018	0.001	0.005	0.003	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	8.348
210°	0.007	0.881	0.497	0.178	0.042	0.042	0.018	0.003	0.004	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	1.674
240°	0.008	0.678	0.399	0.099	0.022	0.026	0.005	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.239
270°	0.009	0.830	1.002	0.912	0.373	0.266	0.089	0.023	0.013	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	3.521
300°	0.010	1.025	2.504	4.588	2.185	2.125	0.594	0.150	0.062	0.029	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.275
330°	0.008	0.699	1.742	4.028	2.452	3.185	0.968	0.177	0.061	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.334
360°	0.002	0.106	0.221	0.422	0.255	0.310	0.107	0.017	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.447
	0.090	10.285	18.343	26.759	12.615	16.086	8.003	2.599	2.277	2.016	0.161	0.496	0.123	0.082	0.026	0.019	0.001	0.006	0.002	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	100.000

Column headings are wind speed (knots)
Row headings are wind direction, degrees (true)
Table entries are joint probabilities (percent)
Weighting is by AMHS ferry transits by month