DESIGN CRITERIA FOR OUTER STRUCTURES AT FERRY LANDINGS

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16. ABSTRACT

In this research, global positioning system (GPS) technology was used to track the velocity and position of ferry vessels during berthing maneuvers, and vessel characteristics that affect berthing maneuvers were reviewed. Ferry vessels were tracked for 24 berthing maneuvers and five complete crossings. The research team found that the plot of vessel speed vs. distance from the landing structure was consistent and that the crews used a consistent sequence of throttle settings as they approached the berth. Changes of slope in a speed vs. distance plot were correlated to changes in throttle setting. Vessels used a variety of approach paths when they were more than 1,000 ft from the landing; however, the paths converged when the vessels were within 500 ft of the landing. Records of sea trials provided information on vessel turning and stopping ability. On the basis of the findings, a velocity vs. distance envelope was developed for use as ferry landing design criteria. The report recommends that GPS tracking could become a regular part of the ferry terminal design procedure and that future vessel tracking be conducted during sea trials and difficult landing situations.

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Research Project T9233, Task 23
Ferry Landing Design Criteria—Phase II

DESIGN CRITERIA FOR OUTER STRUCTURES AT FERRY LANDINGS

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SUMMARY

The Washington State Ferry system (WSF) is developing new plans for terminal structures. These new structures are expected to have a longer service life, require fewer repairs, use less creosoted timber (a toxic substance), and absorb berthing energy more effectively. These new designs should be based on rational design criteria, unlike previous, empirically based designs.

In past research sponsored by WSDOT closed circuit video cameras observed berthing events for the last 5 to 15 ft of the ferries' approach to the wing walls. On the basis of these observations, rational design criteria were developed for the wing walls. Except for the previously mentioned study, research and design criteria have concentrated on side berthing vessels. Because WSF uses end berthing vessels, such research and design criteria are of limited value.

Beyond the criteria for the wing walls, WSDOT would like to develop rational design criteria for the outer landing structures and to improve the geometry of the landings. To accomplish these tasks, WSDOT supported this study. One objective of this study was to track vessels' approach for their last 5,000 ft to the berth. Another objective was to investigate how vessel characteristics affect vessel maneuverability during berthing events. This additional information was expected to allow development of improved design criteria.

Twenty four berthing events and five complete crossings were tracked with global positioning system (GPS) technology. The results showed that the approach paths varied by as much as 2,250 ft when the vessels were more than 1,000 ft from the berth. Correlations could not be found between these approach paths and surrounding circumstances. However, when the vessels were within 500 ft of the landing, all of the paths were within 90 ft of each other.

Plots of velocity vs. distance from the landing showed a remarkable amount of consistency. The vessels cross the sound at 26 to 29 ft/sec. At a distance of approximately 1,500 ft from the landing structure, the vessels uniformly decreased velocity until they were approximately 500 ft from the landing structure, at which time the vessels' velocity was 10 to 15 ft/sec. Deceleration then increased and the velocity was reduced to 6 to 8 ft/sec at 150 ft from the landing structure. From there the velocity was reduced until the vessels arrived at the landing structure with a speed of less than 1 ft/sec. When the vessels passed the outer landing aids, the velocity was 7 to 11 ft/sec.

The consistency of the velocity plots resulted from the consistency with which the crew changed throttle settings. Conversations with the captains indicated that experienced crews made their initial throttle reductions when the vessel was a quarter-mile from the landing. Inexperienced pilots were advised to make a throttle reduction three-eights of a mile from the landing. Crews used the following sequence of throttle settings during each berthing event: full ahead, slow ahead, slow astern, half astern. Subsequently, the throttle was varied as necessary to complete the landing.

Design criteria for outer landing structures should include the approach velocity and approach angle of the vessel. Based on the GPS observations, 12 ft per second is the recommended approach velocity criterion. Based on the literature review, (1) an approach angle of 15 degrees is recommended

Other types of design criteria were considered as part of this study. Some of the major elements in roadway design criteria may prove helpful in the development of ferry landing design criteria. Roadway designers use vehicle stopping and turning standards as they develop the geometry of highways and streets. Stopping distance is used in designing vertical curves, and turning circles are used in designing cul de sacs, bus terminals, and loading docks. Similar standards should be developed for ferry landing designers on the basis of sea trial data and further GPS tracking studies. The results of sea trials for WSF's Super class ferries showed that the stopping distance from full

throttle (28 ft/sec or 17 knots) is 892 ft; and the diameter of the turning circle at full and half ahead ranges from 1,893 to 2,638 ft. GPS tracking could be used on nonrevenue sailings to obtain additional data for vessels operating at lower power settings or without power. These data would give designers insight about designing landing structures for distressed vessels that have partial power or no power during berthing.

The researchers recommend that GPS vessel tracking become a regular part of the ferry landing design process. It will increase understanding of how vessels use landing aids and will provide more information on approach velocities and approach paths. Data should be collected for difficult berthing situations such as adverse weather. Capability should be added to collect wind and vessel heading data. Development of a real-time display of vessel position on a computer graphic navigation chart should also be considered.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the study.

- Plots of velocity vs. distance from the landing structure indicated a consistent pattern in vessel operation. This pattern showed that WSF vessels cross the Puget Sound at 26 ft/sec to 29 ft/sec. At a distance of approximately 1,500 ft from the structure, the vessels begin to decrease their velocity. At 500 ft from the structure their velocity is 10 ft/sec to 15 ft/sec, and at 150 ft from the structure their velocity is 6 ft/sec to 8 ft/sec. The approach velocity at the landing structure is less than 1 ft/sec. In the area of the outer landing aids (250 ft from the dock) the vessels travel at 7 ft/sec to 11 ft/sec.
- Crews use the following sequence of throttle settings during each berthing event: full ahead, slow ahead, slow astern, half astern. Subsequently, the throttle was varied as necessary to complete the landing. Changes in throttle setting correlated to a change in slope of the velocity vs. distance plot.
- Plots of vessel position showed a variety of approach paths when the vessels were more than 1,000 ft from the landing structure; however, the vessel tracks converged when the ferries were within 500 ft of the landing. At 5,000 ft the vessel tracks varied by as much as 2,250 ft, while at 500 ft, the vessel paths were within 90 ft of each other.
- Data collected during sea trials provide information on the ability of a vessel to turn and stop with full power. However, they do not provide information on the ability of a vessel to stop with limited or no power.
- The results of physical model studies may be used for approximate calculations of vessel deceleration in case of a power loss. These

calculations should be used with caution because the model resistence may vary from the actual resistance.

- Full scale GPS measurements may be used to obtain vessel maneuverability information that is not available from sea trials and to check calculations.

The following recommendations are made.

- A design velocity of 12 ft/sec and an approach angle of 15 degrees are recommended design criteria for the outer landing aids that are placed 250 ft from the landing structure.
- GPS vessel tracking should become a regular part of the ferry landing design process. It will increase understanding of how vessels use landing aids and will provide more information on approach velocities and approach paths. Data should be collected for difficult berthing situations such as adverse weather.
- The GPS tracking system should be enhanced to record wind speed, wind direction, and vessel heading. The capability should also be developed to display the vessel position on computer graphic charts in real time.
- Vessels should be tracked with GPS technology during sea trials In addition, non-revenue sailings should be conducted for GPS tracking. During these sailings, data on vessel maneuverability under low power or with no power may be collected.
- WSF should develop a manual that summarizes vessel characteristics that are pertinent to landing designers.

INTRODUCTION

Ferries are an integral part of the transportation system in the Puget Sound region. In comparison to other vessels, ferries land more often and spend a greater proportion of time using terminal facilities. Therefore, the proper design of landing structures is crucial to the efficient operation of the Washington State Ferries (WSF). Structures at a typical ferry landing include a transfer bridge that connects the ferry and the land, a pair of wing walls that absorb berthing impacts, and dolphins that guide the ferry into the berth The dolphins also hold the ferry in place while it is at berth despite cross currents and winds (Figure 1).

WSF's vessels range in displacement from 1,350 to 4,336 long tons (Table 1) and are double ended, i.e., they have pilot houses, propellers, and rudders at both ends to eliminate the necessity of turning at the terminals. Like many ferries, WSF vessels head directly into the berth instead of approaching from the side. During the berthing maneuver, the ferry slows by reversing the thrust of its propulsion system. Contact with the wing walls and other structures brings the vessel to a complete stop.

Table 1. Vessel Characteristics

Class	Length ft (m)	Beam ft (m)	Draft ft (m)	Displ. lt[1] (mt)
Jumbo	440 (134)	87 (26)	18 (5.5)	4336 (4405)
Super	382 (116)	73 (22)	16 (4.9)	3283 (3335)
Issaquah	328 (100)	78 (24)	16 (4.9)	2943 (2990)
Evergreen State	310 (94)	73 (22)	15 (4.6)	2062 (2095)
Steel Electric	256 (98)	74 (23)	12 (3.7)	1806 (1834)
Rhododendron (typical small ferry)	226 (69)	63 (19)	12 (3.7)	1350 (1372)

[1]lt = long ton = 2240 lb.

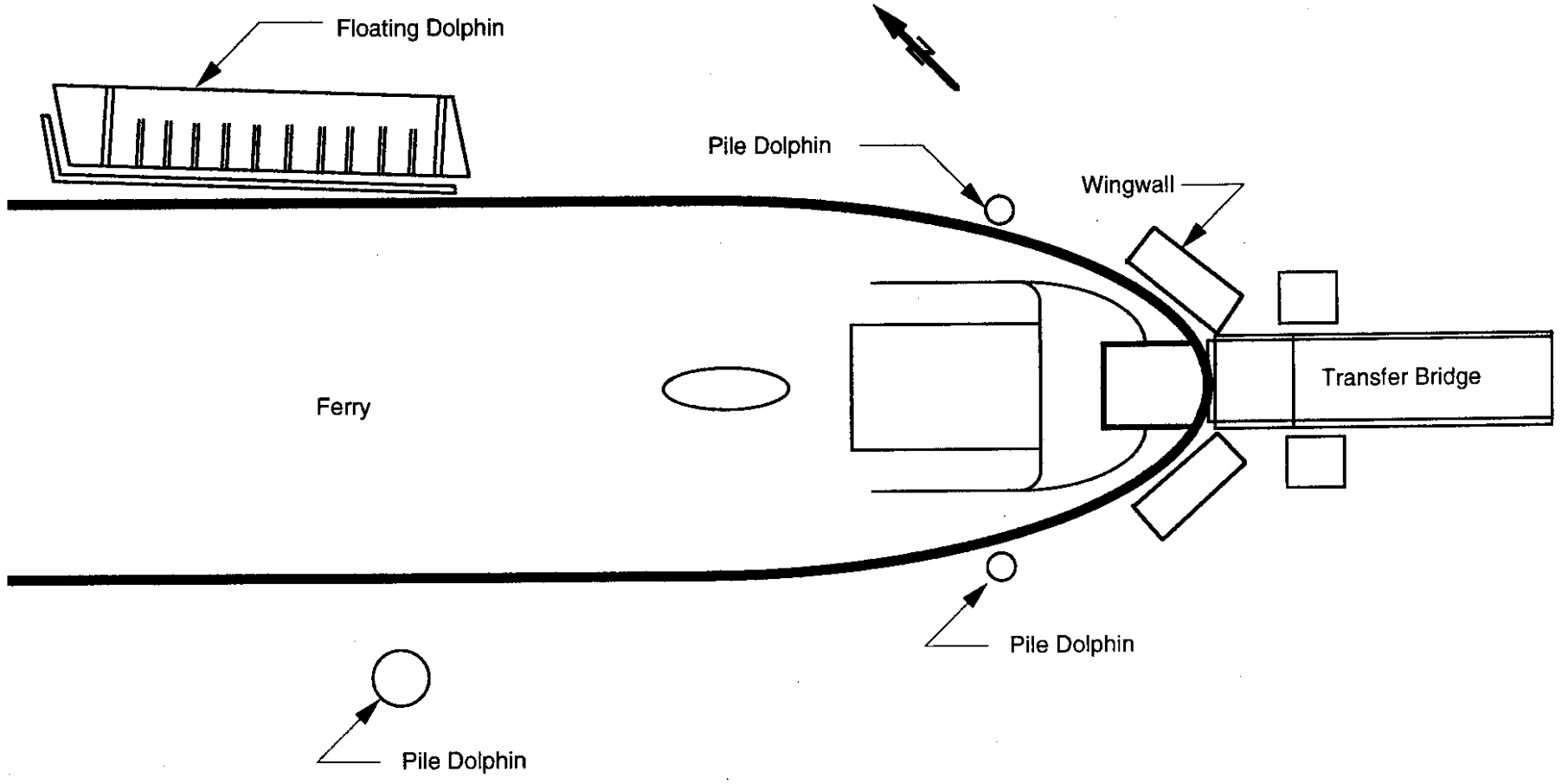

Figure 1. Layout of Edmonds Terminal

WSF is currently developing new designs for terminal structures. The following improvements are anticipated:

- longer service life and fewer repairs,
- less use of toxic materials, particularly creosoted timbers, and
- more effective energy absorption during berthing events, especially extreme events.

Unlike previous, empirically based designs, these new designs should be based on rational design criteria.

Previous research has concentrated on developing design criteria for side berthing vessels. (e.g., 2, 3, 1) Because WSF uses end-berthing vessels, such research is of limited value. In past research sponsored by WSDOT, berthing events were observed for the last 1.5 m to 4.5 m (5 ft to 15 ft) of approach to the wing walls with closed circuit video cameras. (4) On the basis of these observations, rational design criteria were developed for the wing walls.

WSDOT would like to develop similar rational design criteria for the outer landing structures to improve the geometry of the landings. However, it is not possible to accomplish these tasks without tracking the vessel during berthing events for a longer distance. Additional information on vessel maneuverability would also help designers develop credible, worst case berthing scenarios for distressed vessels (landing with engine failure, steering failure, or heavy weather) and to develop improved vessel operating policies.

In accordance with these goals, the objectives of this project were as follows:

- obtain more information on vessel characteristics and how they influence ferry landing design,
- develop methods for plotting vessel position and velocity during the entire berthing event, and
- recommend improved design criteria and design procedures.

REVIEW OF PREVIOUS WORK

This section reviews existing design criteria for ferry landing structures and summarizes salient information on vessel characteristics. Methods for tracking vessels are also discussed.

EXISTING DESIGN CRITERIA

Impact force is the criterion that frequently controls the design for landing structures. If the berthing energy, allowable deflection, and general form of the structure's force-deflection relationship are known, engineers may infer the maximum berthing force using the equation

$$E = \int_0^{s_{max}} F(s)ds \tag{1}$$

where E = energy absorbed by the structure,

s = deflection, and

F = force vs. deflection function.

Berthing energy may be estimated using the equation

$$KE = 1/2\,(w/g)\,C\,V^2 \tag{2}$$

where w = weight of the vessel,

V = approach velocity,

g = acceleration of gravity, and

C = a coefficient that accounts for the vessel's approach angle, the eccentricity of impact, and various hydrodynamic effects.

Because kinetic energy varies with the square of the velocity, proper selection of design velocity is imperative for a proper design.

Design criteria are developed to produce economical structures that can safely accommodate extreme situations. However, if the structure is designed to survive all impacts, no matter how catastrophic, the result will be uneconomical and possibly

dangerous; it is better for the structure to fail than to inflict damage to the vessel and injuries to its passengers.

Previous research performed by University of Washington researchers provided a base from which to launch this study. Jahren and Jones reported on the observation of over 500 landings at WSF's Edmonds terminal. (4) Most approach velocities were found to vary from 0.0 to 1.0 ft per second, and the mean was 0.5 ft/sec; 25 landings of greater than 1.0 ft/sec were observed, and the fastest landing observed was 2.0 ft/sec. The upper bound for the coefficient of Equation 2 was found to be 0.60. These conclusions were based on observations of the last 10 ft of the approach. Jahren and Jones recommended that the vessel's approach be observed from a longer distance so that the effects of wind, current, and interaction with other landing structures could be recorded.

Ishii surveyed WSFs on-board staff to determine how environmental factors, types of vessels, and locations of landings influence the berthing speed. (5) The study found that wind, current, and fog were the environmental factors that most influenced berthing speed and that terminals with strong, unpredictable currents were the most difficult landing locations. Most vessels were described as relatively easy to land; however, the respondents indicated a desire for a landing structure that could safely absorb emergency impacts associated with propulsion failures. Ishii went on to develop a preliminary design approach velocity for such catastrophic occurrences (V = 17 ft/sec) by observing the last 1,000 ft of approach of the ferries with a video camera. Velocity was inferred by scaling the video image with the ferry's known dimensions and computing the rate of change of position at various distances from the landing. The method yielded a considerable amount of information for a modest effort (Figure 2). After a literature review, Ishii selected a maximum deceleration of 0.17G to ensure the safety of the passengers. Finally, he developed five conceptual designs for emergency landing facilities that were responsive to the previously mentioned design criteria. The estimated cost for these facilities ranged from $250,000 to $750,000.

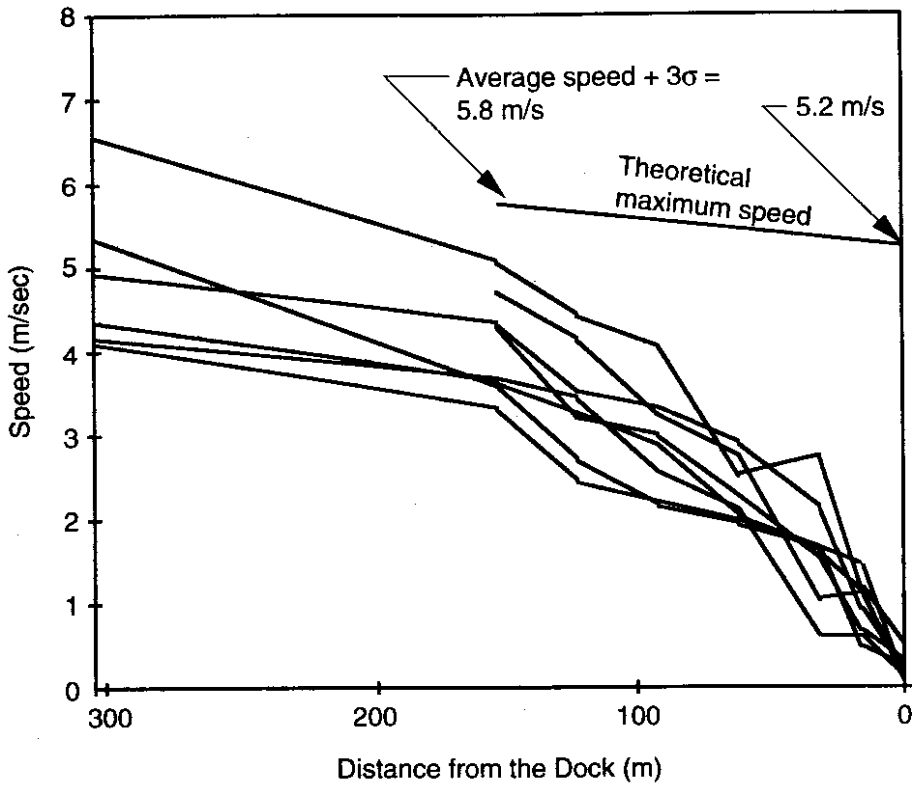

Figure 2. Speed vs. Distance (4)

VESSEL CHARACTERISTICS

Ferry landing designers could benefit by having more knowledge about the ability of a vessel to stop and turn. Information regarding specific vessels is available from engineering reports, records of physical model tests and records of sea trials.

The headreach is the distance that is required for a vessel to stop when it is running at full speed ahead. If the stopping distance is known for various speeds, operational policies may be developed to take emergency actions before the vessel passes the minimum safe stopping distance. The headreach may be predicted with the following formula:

$$s = \frac{D_i M V_1^2}{2R} \tag{3}$$

where D_i = dynamic potential

M = apparent vessel mass

R = vessel resistance

V_1 = initial vessel velocity

Dynamic potential is a dimensionless combination of several variables and is often estimated from curves, as shown in Figure 3. Because R varies with V_1^2, the curve marked "2" in Figure 4 is used to estimate D_i (V^n indicates use of the curve marked n). Dynamic potential is a function of the ratio of vessel resistence divided by the astern thrust (R/T). Reaction time and the time required to reach full-astern thrust from full ahead thrust are accounted for in the graph presented in Figure 3. (6)

Before WSF takes delivery of a vessel, its operating characteristics are evaluated in a series of tests known as sea trials. Included in the tests are turning circles and crash stops. Crash stops give the headreach distance. During the turning circle test, the information shown in Figure 4 is recorded. Figure 4 also describes the different phases of a turn.

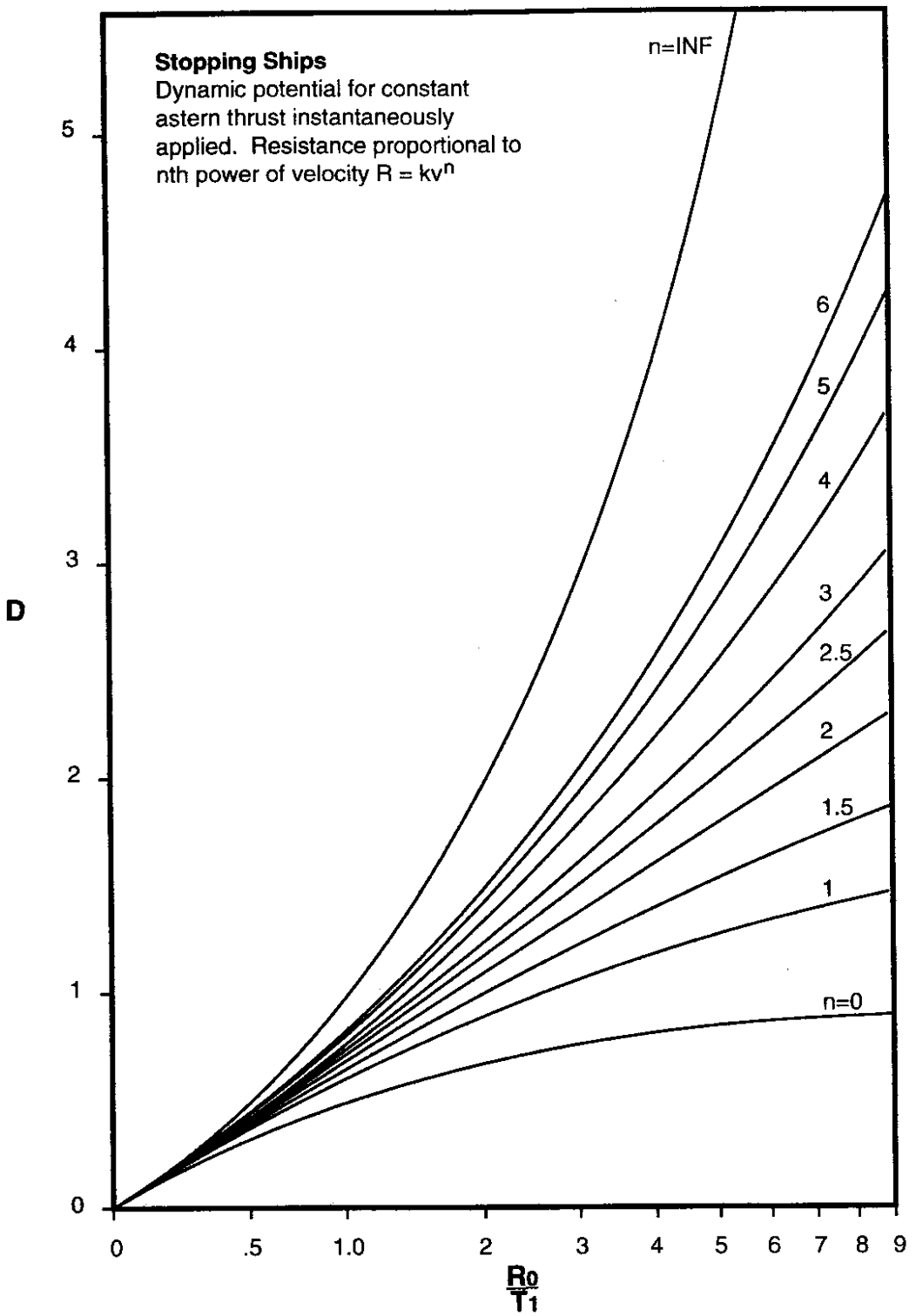

Figure 3. Stopping Ships. Dynamic potential for constant astern thrust instantaneously applied. Resistance proportional to nth power of velocity (6)

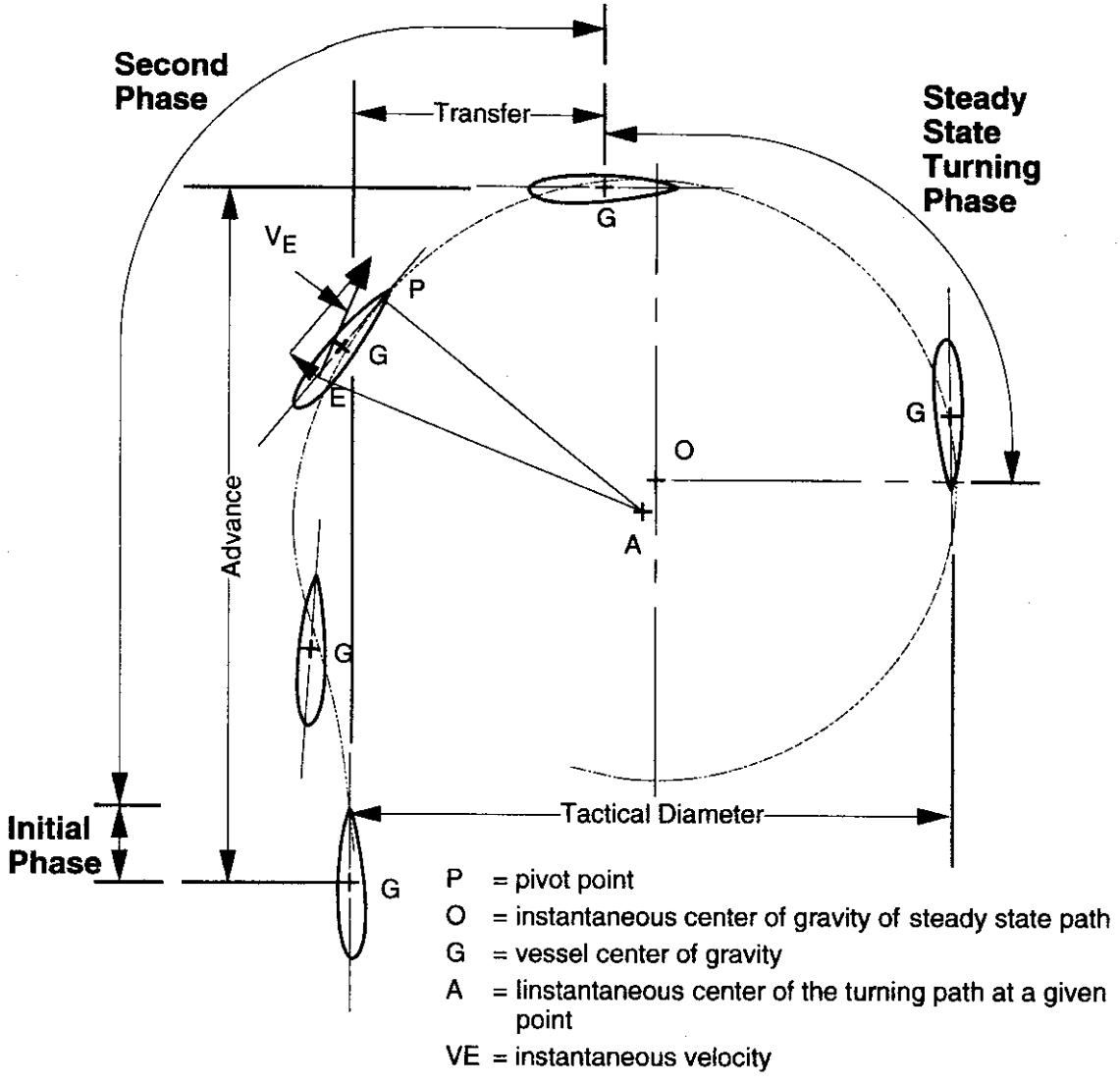

Figure 4. Motion of Vessel in Turning [7]

Advance = Distance moved by the vessel center of gravity in the direction of the orignal course from the point where the rudder is started over until the heading has changed 90 degrees.

Transfer = Distance moved by the vessel center of gravity at right angles to the original course from the point where the rudder is started over until the heading has changed 90 degrees.

Tactical Diameter = Distance at right angles to the original course gained by the vessel center of gravity in turning 180 degrees.

Phases in a Turn

1.Initial Phase
Turn begins when rudder is put over, vessel accelerates in an outward drift, experiences a reduction in speed, and rotates about a vertical axis in the direction of the desired turn.

2.Second Phase
Pressure distribution on the hull changes to a pressure increase along the outward side of the vessel, creating a force (and couple) which accelerates the turning motion. This accounts for the S - shaped path during the first 90 degrees.

3.Steady State Turning Phase
Equilibrium of forces causes the vessel to settle on the circular portion of the turning path. The vessel continues to be slowed and accelerated toward the center of the turning circle until acceleration and turning radius are constant.

Global positioning systems (GPS) are used for a variety of surveying and navigation tasks. GPS equipment calculates vessel position and velocity by processing signals from United States Department of Defense Satellites. Webb and Hewlett used GPS technology to track vessels as they met in a narrow ship channel. (8) The results were compared to physical model studies and ultimately used to improve design criteria for ship channel width.

PROCEDURES

The Edmonds to Kingston ferry crossing was selected as the study site for this project. Edmonds is 16 miles north of Seattle on the Puget Sound (Figure 5). Two vessels operate from 5:00 am to 9:00 pm, and one continues to operate until midnight. The crossing distance is approximately five miles; the crossing time is 30 minutes; and the service is provided every 45 minutes when two vessels are running and every 90 minutes when one vessel is running. Vessel tracking data were collected during July and August of 1992. At that time, two Super Class vessels were in use; therefore, the Super Class vessel was the study vessel for this project.

A differential GPS system was used to track the vessels. The system consists of two units, a mobile unit and a reference unit (see Figure 6). The mobile unit is located on the vessel, while the reference unit is located at a point of known longitude and latitude. The reference unit is required to record data that provide corrections to increase the accuracy of the mobile positions. Each unit interfaces with a personal computer that stores the data on a hard disk. Data from the mobile and reference units are merged and processed to provide an ASCII file that gave the longitude, latitude, velocity, and direction of travel at regular intervals of time. These files were converted to give coordinates in feet and velocities in ft/sec. Then plots of vessel position were developed. Plots of vessel speed vs. remaining distance from the landing structure were also developed.

Plots were successfully developed for 24 berthing events. Of the berthing events, 12 were at Edmonds and 12 were at Kingston. Data were recorded for 16 other berthing events. However, positioning data were not accurate because of poor satellite geometry or instrumentation error; thus plots were not developed. During 11 of the berthing events at Edmonds, records of the time of each throttle command were also kept. For two berthing events, these throttle commands were correlated with the plots of velocity vs.

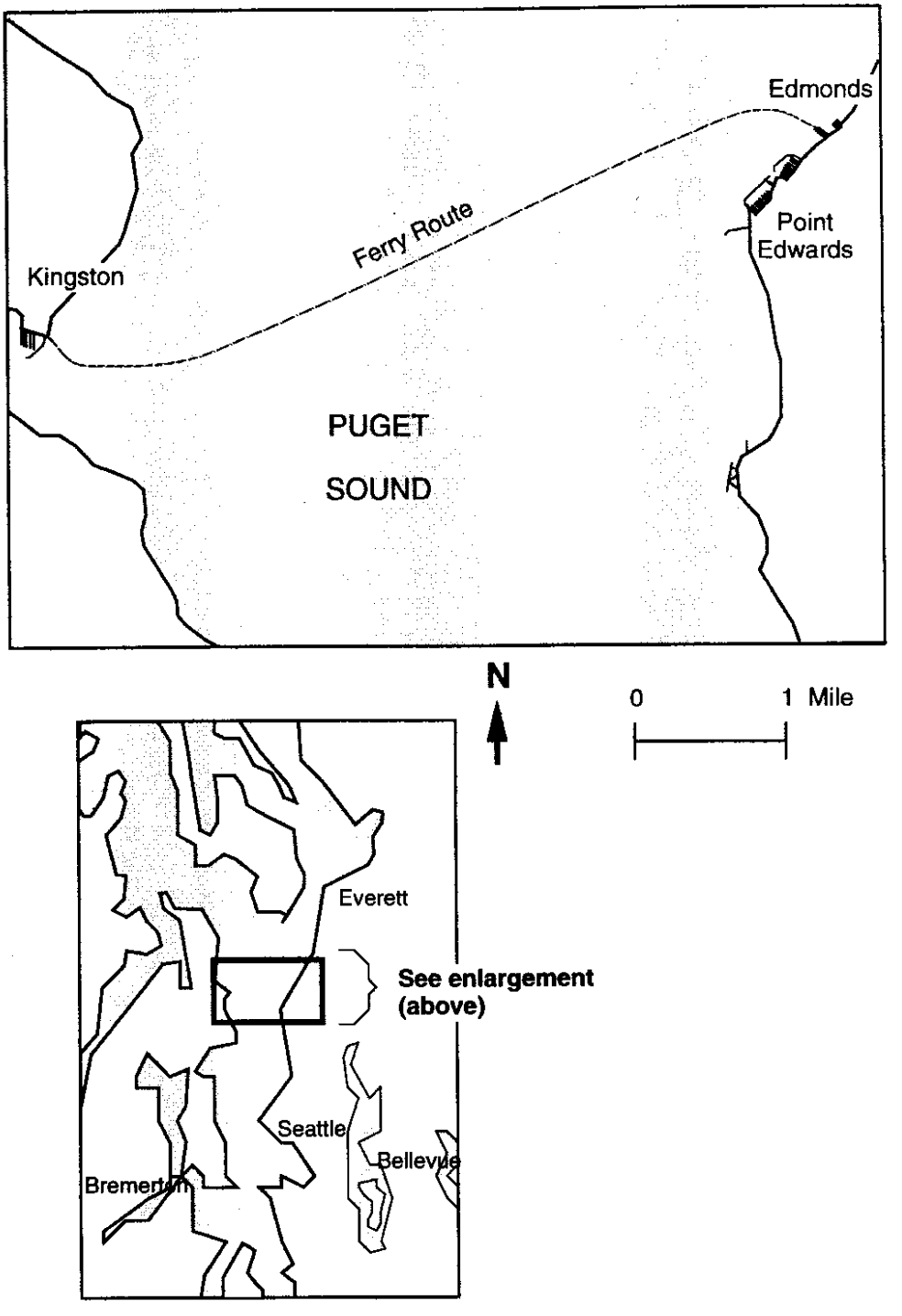

Figure 5. Edmonds to Kingston Ferry Route

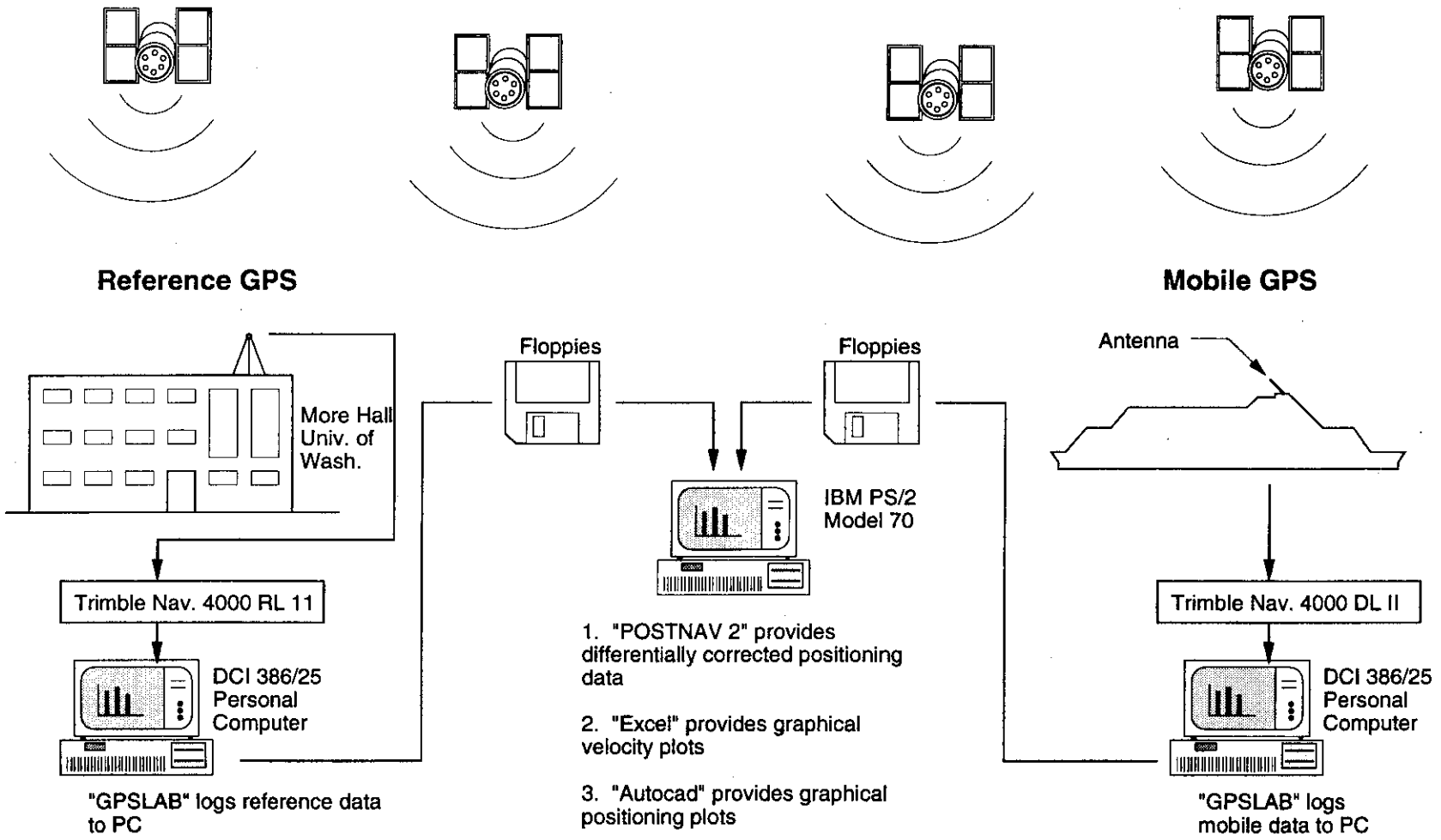

Figure 6. GPS Analysis Flow Chart

distance from the terminal. For the other berthing events for which throttle commands were recorded, the GPS data were not accurate.

Plots were also developed for five complete crossings of the Puget Sound from Kingston to Edmonds. During two of the crossings, the vessels lost power in the middle of the crossing because of engine failure. These events provided information on the deceleration characteristics of the vessels caused by hydrodynamic resistence during an engine failure. These characteristics are of interest to ferry landing designers because engine failures are possible during berthing maneuvers, when the ship's master is relying on the engine to provide reverse thrust to stop the vessel. In case of an engine failure, only hydrodynamic resistence would be available to slow the vessel. Designers could develop credible scenarios for engine failures during berthing events and predict impact speeds by using similar information.

DISCUSSION

The plots of the vessel position revealed that the vessels took a wide variety of paths when the vessels were more than 1,000 ft from the landing structure (Figures 7 and 8). It is apparent that vessels were committed once they were within 500 ft of the landing structure. At 500 ft, all of the tracks were within 90 ft of each other. As a comparison, at 5,000 ft, the vessel paths varied as much as 2,250 ft from one another. The research team, through discussions with the captains, found that each landing is highly dependent on many factors. These factors include marine traffic (such as fishing boats and cargo ships), wind, current, and the piloting techniques of the captain. The plots in Figures 7 and 8 include landings by four different captains. The captain associated with each landing is shown on the plot. The results indicate that each captain used a variety of approach paths when the vessels were more than 500 ft from the landing.

Plots of velocity vs. distance from the landing structure were analyzed for the final 5,000 ft prior to berthing. Figure 9 shows landings at both the Edmonds and Kingston terminals. The results indicate a consistent approach velocity pattern. The vessels crossed the Sound at 26 to 29 ft/sec. At a distance of approximately 1,500 ft from the landing structure, the vessels uniformly decreased velocity until they were approximately 500 ft from the landing structure, at which time the vessel velocities were 10 to 15 ft/sec. Deceleration then increased and the velocities were reduced to 6 to 8 ft/sec at 150 ft from the landing structure. From there the velocities were reduced until the vessels arrived at the landing structure with a speed of less than 1 ft/sec.

A plot of berthing velocity vs. distance from the landing for the last 300 ft of approach is shown in Figure 10. The outer landing aids are 250 ft from the landing structure. The results indicate that vessel velocity in these areas ranged from 7 to 11 ft/sec. The plot also indicates a landing velocity of less than 1 ft/sec. The berthing event that indicated a landing impact at 2 ft/sec was the result of instrumentation error.

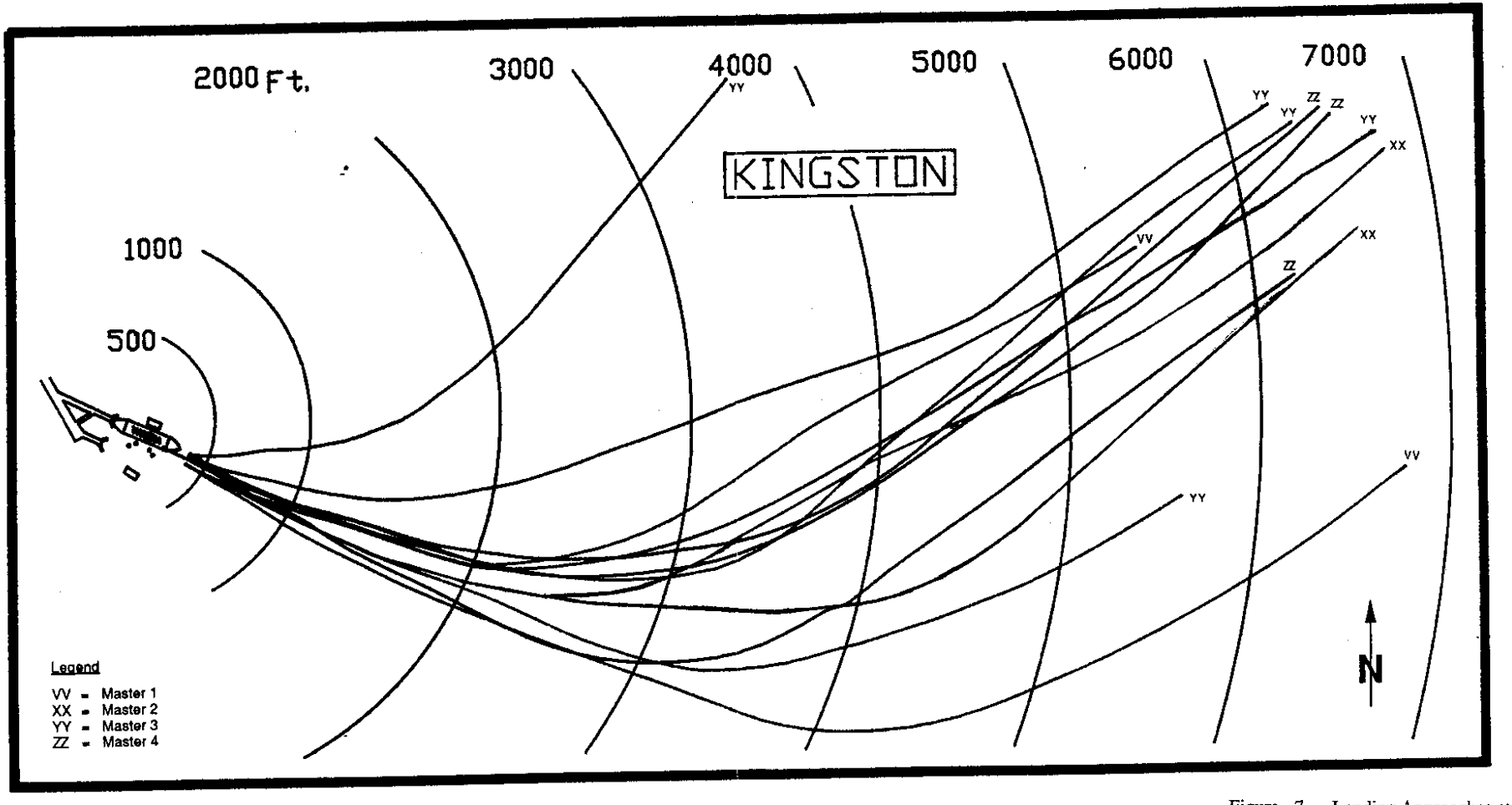

Figure 7. Landing Approaches at Kin

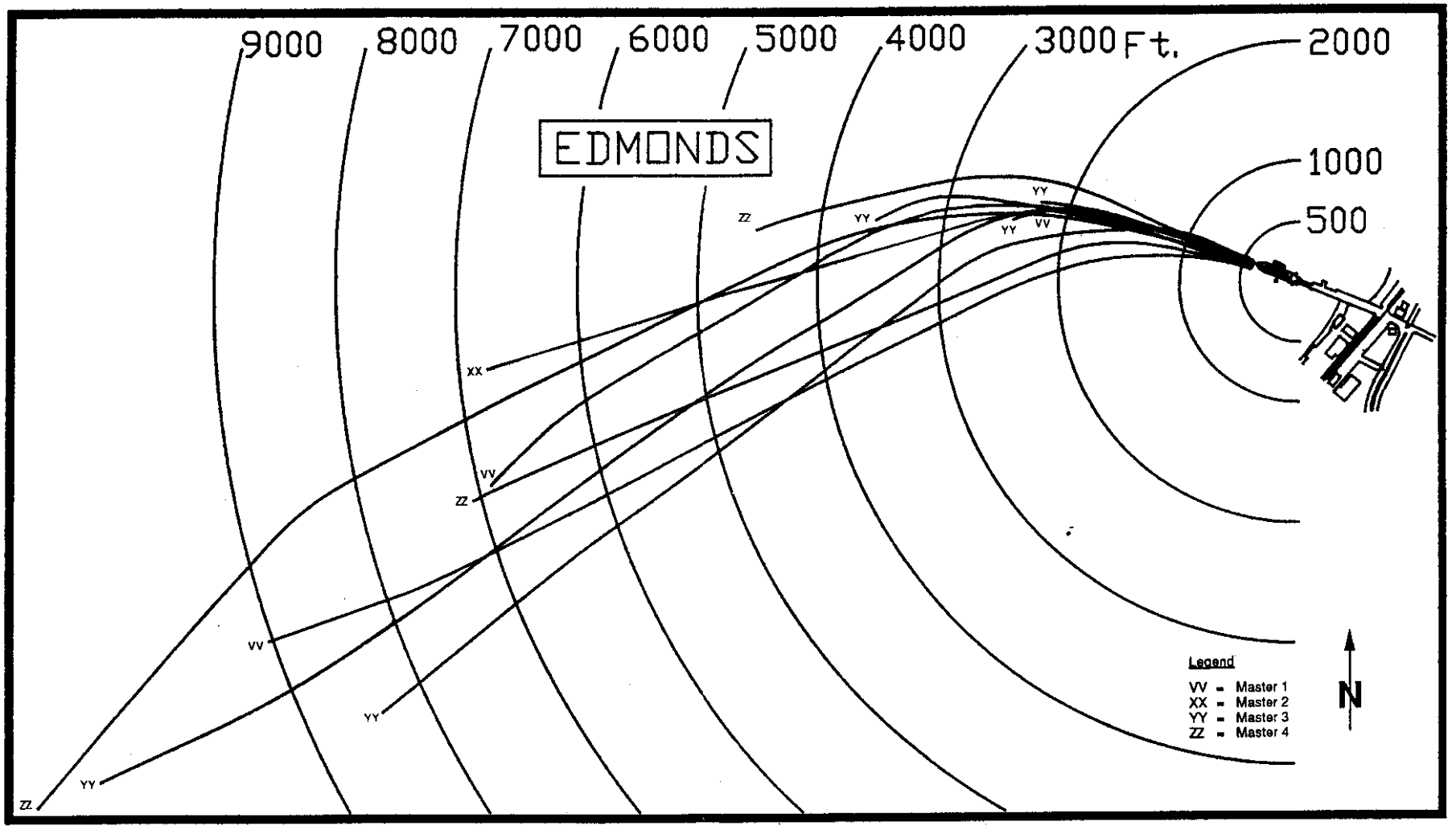

Figure 8. Landing Approaches at Edmo

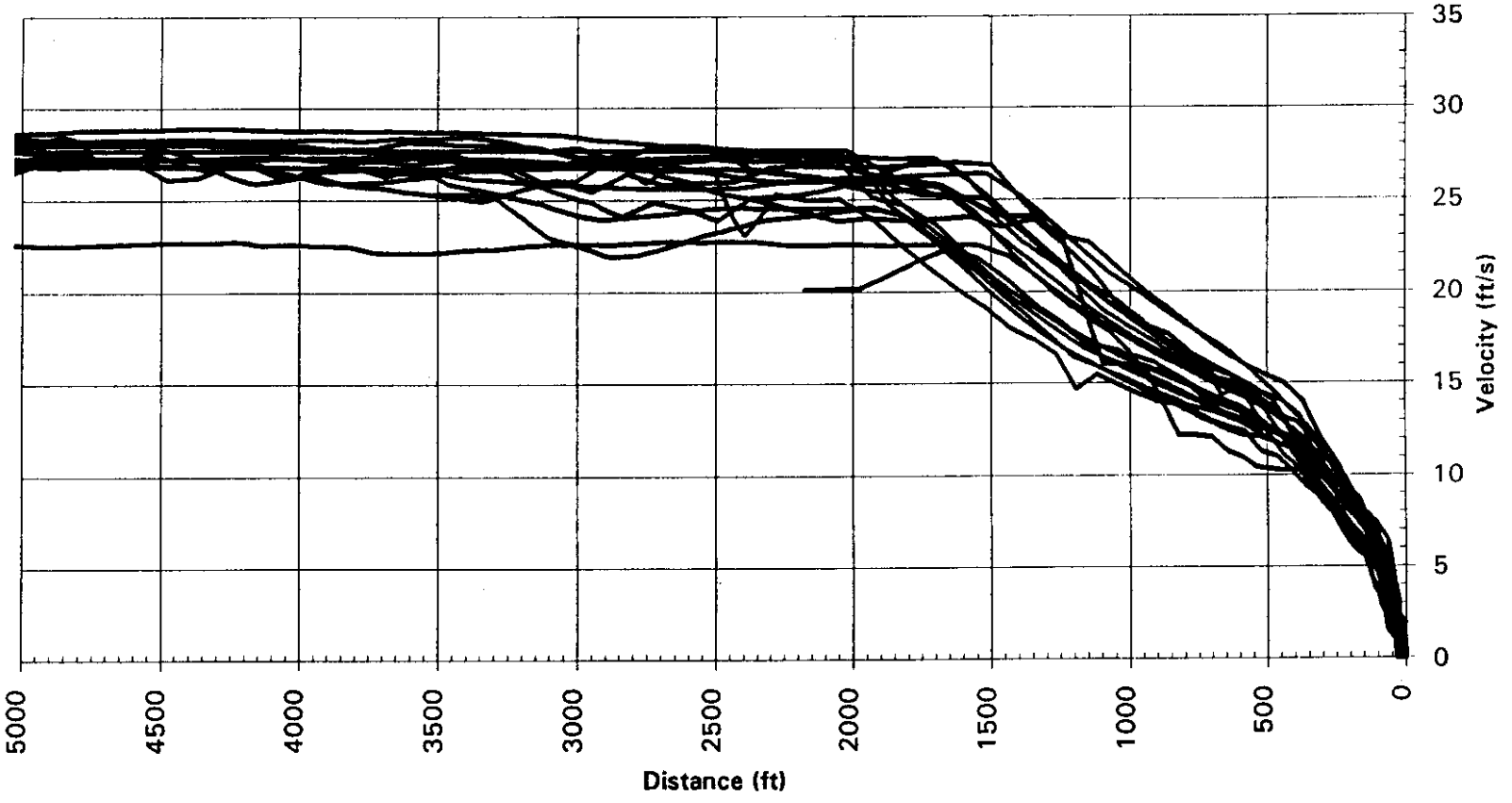

Figure 9. Velocity vs. Distance from Landing Structures (5,000 ft.)

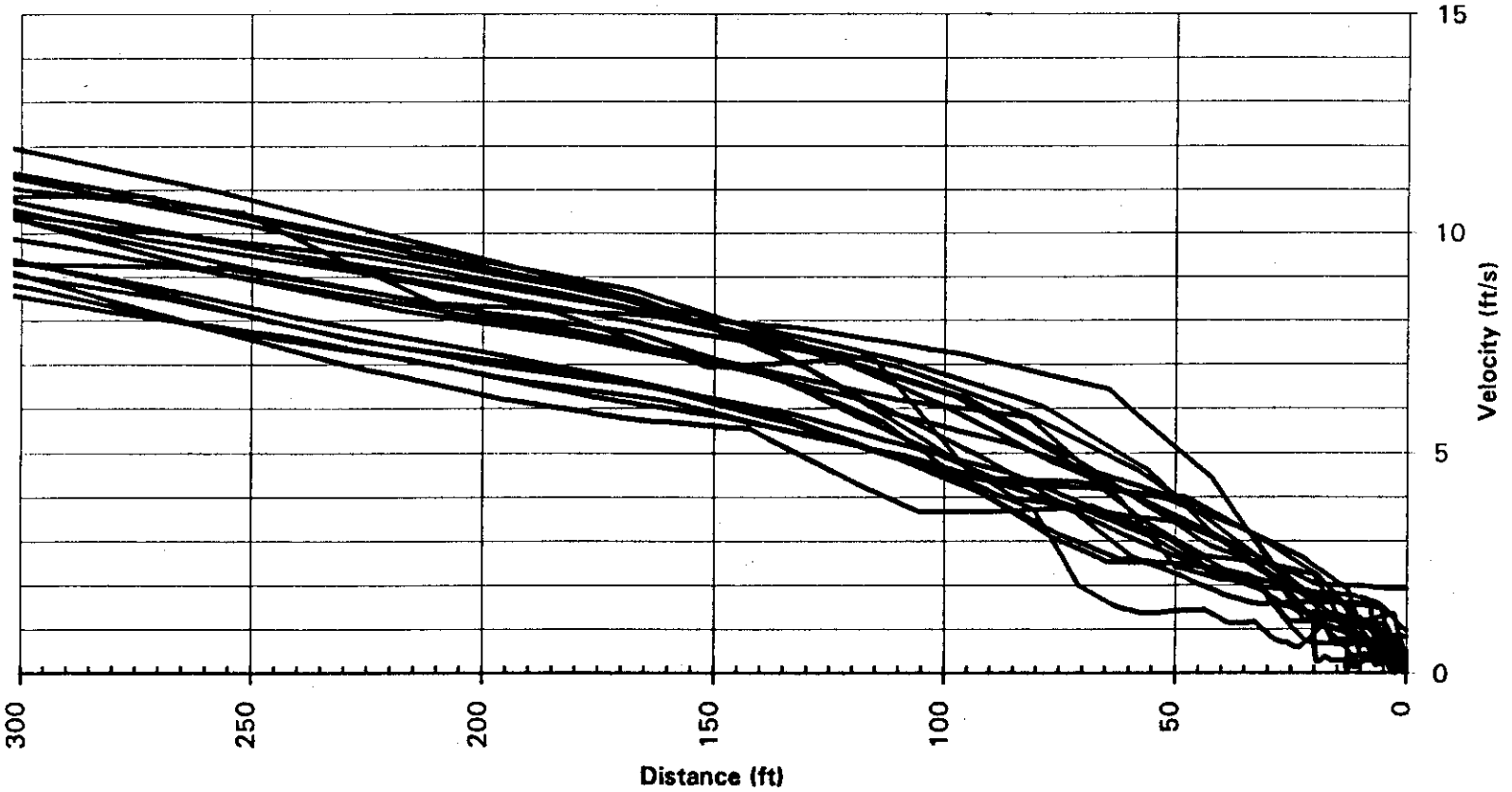

Figure 10. Velocity vs. Distance from Landing Structures (300 ft.)

These velocities can be correlated with throttle position (Figure 11). The findings indicate that the following series of throttle settings was used for the berthing events that were monitored. Vessels traveled at *full ahead* until they are 1,500 to 1,700 ft from the structure, at which point they decreased their power to *slow ahead.* Conversations with the captains indicated that most experienced crews made their initial throttle reductions when the vessel was a quarter mile from the landing. Inexperienced pilots were advised to make a throttle reduction three-eights of a mile from the landing. A delay of 7 seconds was apparent before the vessel reacted to the throttle change. This delay was the time needed for the captain to telegraph the engine room, for the engineer to make the throttle adjustments, and for the engine and drive train to respond. (The throttle was not directly controlled from the pilot house on the study vessel.) The next setting was *slow astern* at approximately 500 ft from the landing. At 100 ft from the landing, the throttle was often set at *half astern.* Subsequently, the throttle was varied as necessary to bring the vessel to a smooth stop. In no case was the *full astern* throttle setting used. Apparently the captains reserved that as an option of last resort.

Speed vs. distance plots were obtained for two regular crossings during which the vessels experienced a power failure. During one power failure, the vessel velocity decreased from 27 ft/sec to 6 ft/sec over a distance of 2,250 ft. During another power failure, the vessel velocity decreased from 26 ft/sec to 18 ft/sec in a distance of 800 ft (Figure 12).

A calculational procedure was developed in an attempt to simulate vessel deceleration caused by such power losses. The deceleration after the power loss was caused by vessel resistance forces. These resistance forces were estimated by reviewing physical model test results for the specific vessel. After the physical model test results for a Super Class Ferry were reviewed the following plot was developed:

R_f/D vs. $V/\sqrt{L}$

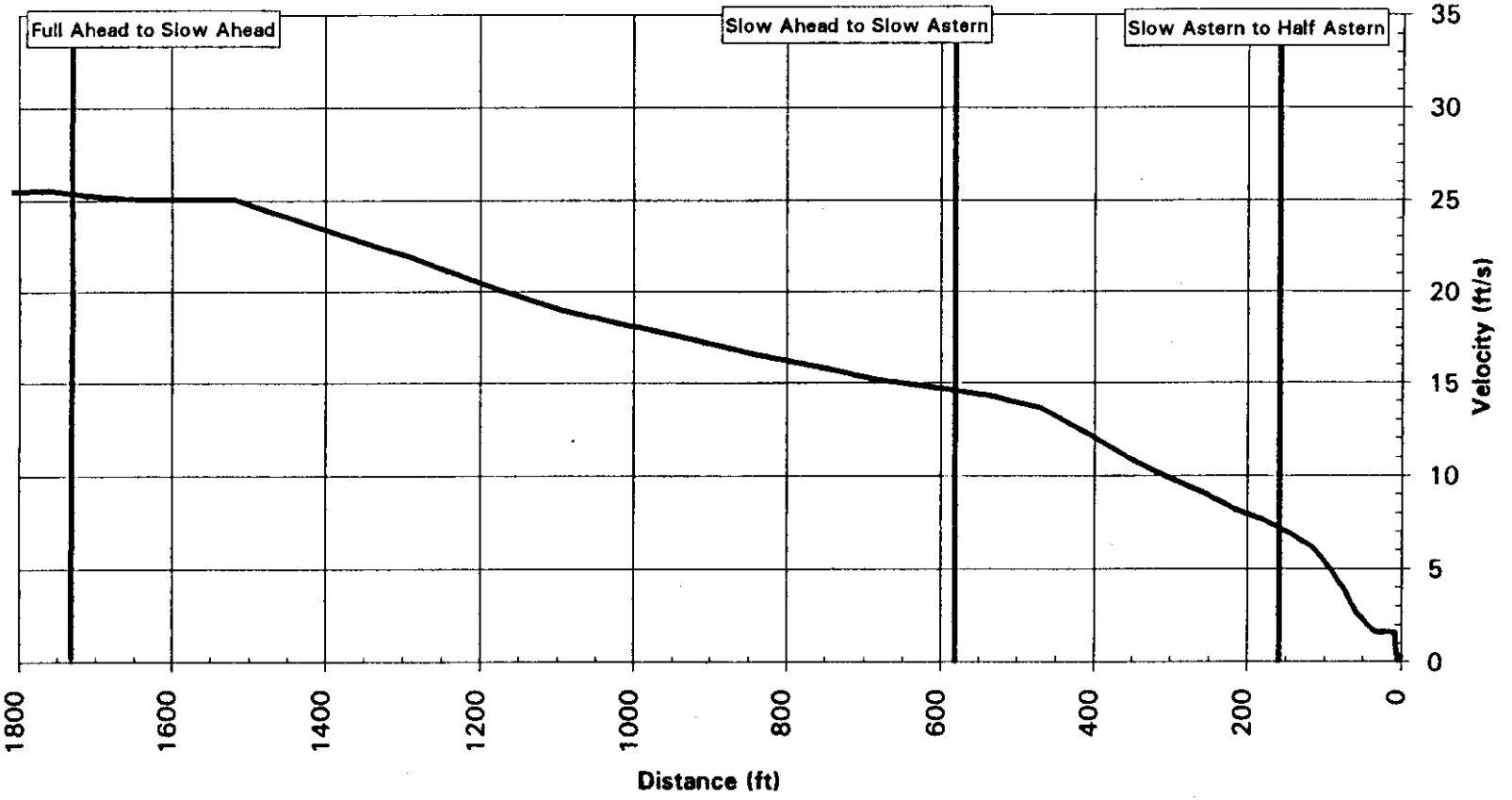

Figure 11. Adjustments to Throttle Settings for Edmonds Landing

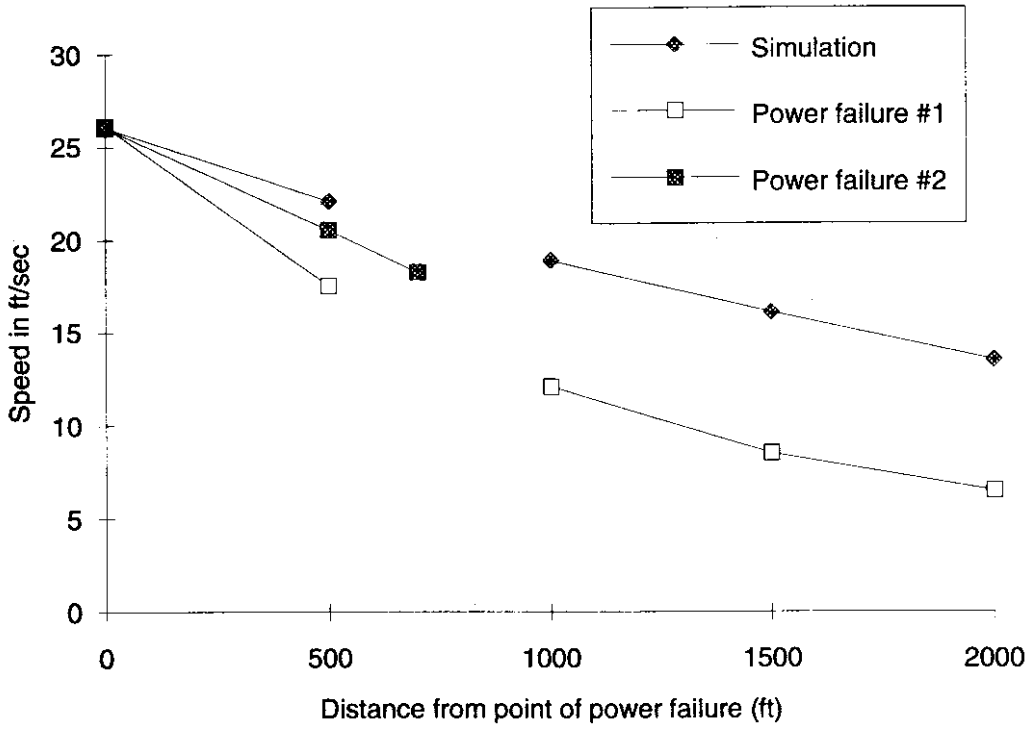

Figure 12. Distance from Point of Power Failure vs. Speed

The data points were fitted with an exponential regression curve using a least squares fit approximation (Figure 13). The resulting curve fit equation was as follows:

$$R_t/D = (1.21)10^{1.31(V/\sqrt{L})}$$

where R_t = total vessel resistance (pounds)

D = vessel displacement (long tons)

V = vessel velocity (ft/sec)

L = vessel length (ft)

When the vessel displacement is known, the total resistance force, F, may be calculated. Figure 13 is a typical vessel resistance curve. When $V/\sqrt{L}$ exceeds a certain magnitude, the resistance rises substantially because of wave-making resistance (Figure 14). Because the vessel resistance behaves in this way, vessels decelerate quickly at first, when the resistance per ton is the largest. After the vessels slow, the resistance per ton decreases and vessels can continue to coast at low speed for a very long distance.

The acceleration (in this case a negative acceleration or deceleration) was calculated as follows:

$$A = F/M$$

where A = acceleration

F = net force on vessel

M = vessel mass

The vessel resistance and, therefore, the deceleration varies with the vessel velocity. For the short increment of distance, the final velocity was estimated from the equations of motion:

$$V_1^2 = V_0^2+2As$$

where V_1^2 = vessel final velocity

V_0^2 = vessel initial velocity

A = acceleration

s = incremental distance traveled

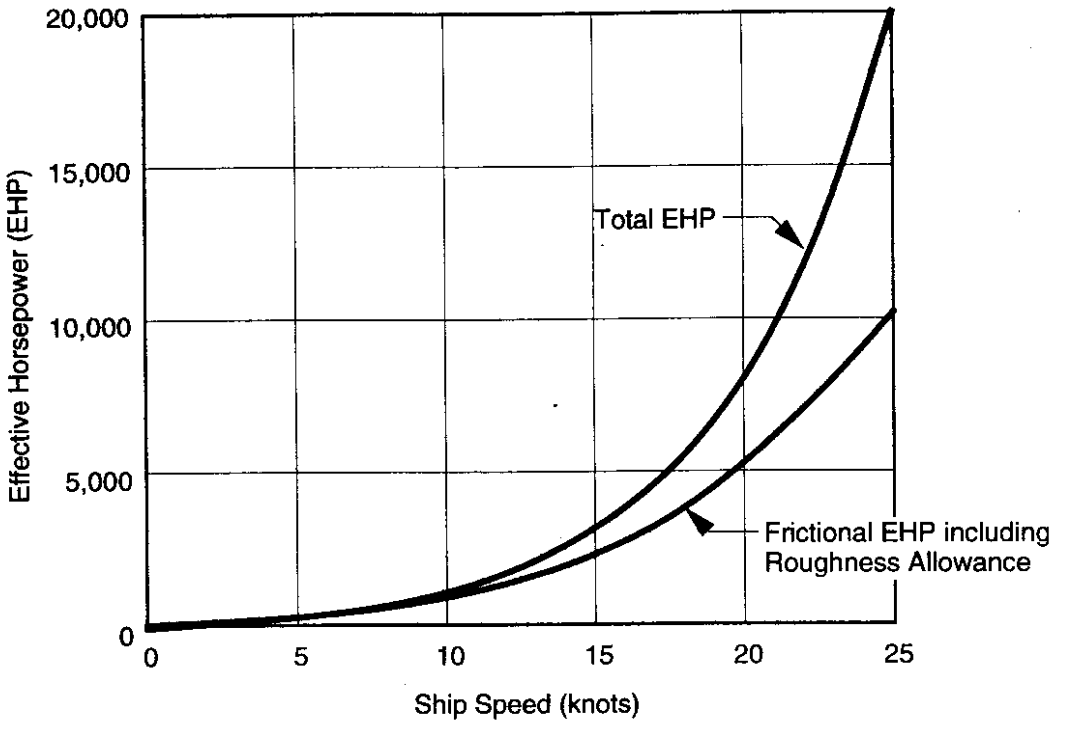

Figure 13. Typical Curves of Frictional and Total Effective Horsepower vs. Speed for a Large Displacement Ship [7]

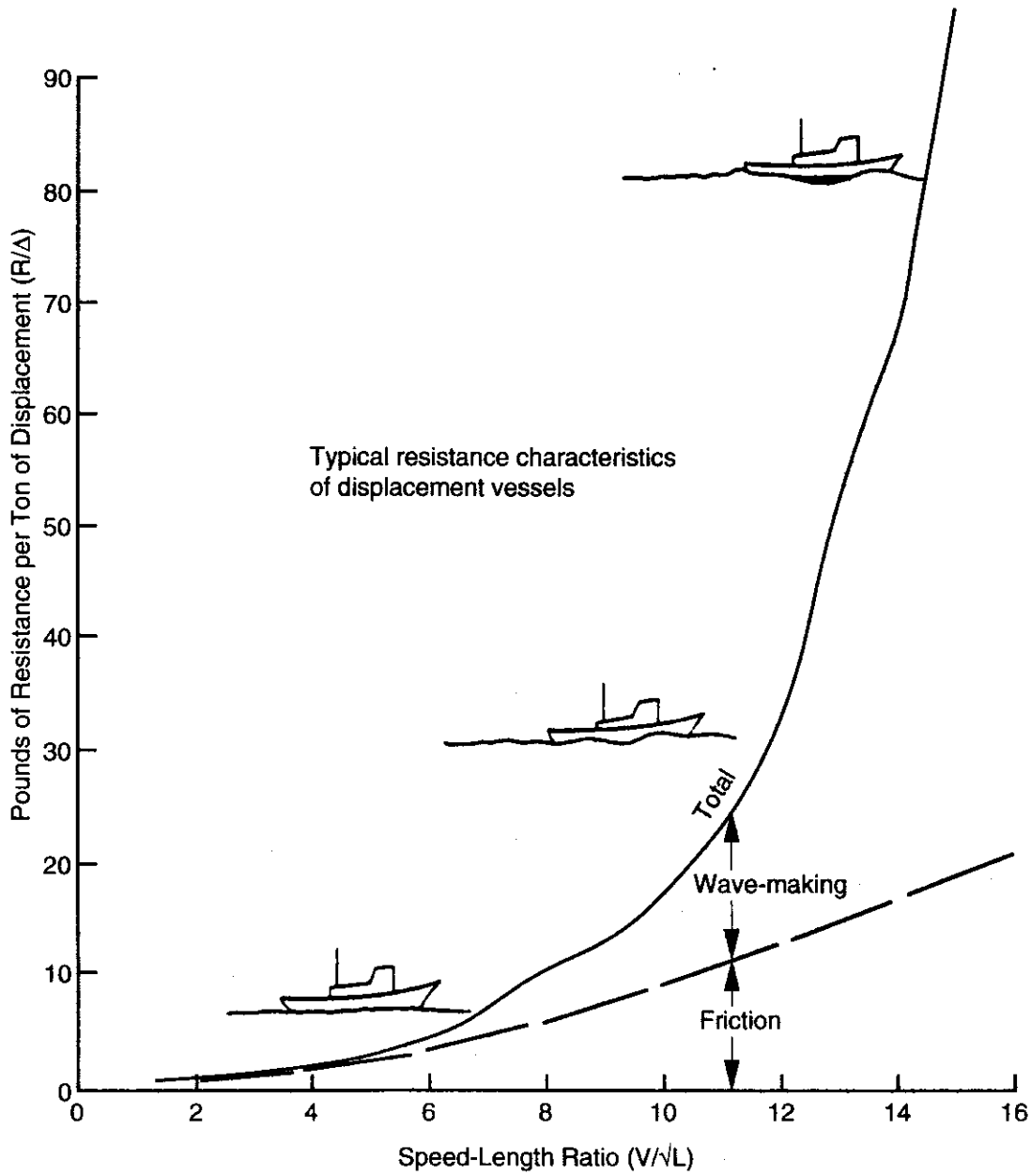

Figure 14. Resistance vs. V/√L in a Characteristic Speed-Power Curve for a Displacement Ship (Note the ship-wave profiles) [7]

Next, an iterative approach was used over 500 ft increments. V_1 from the previous increment became V_0 for the next increment. The resistance force for the next increment was calculated on the basis of the new V_0, and the next acceleration and final velocity were calculated. The results of this calculation are shown in Figure 12. The calculated deceleration was slower than the actual deceleration. Apparently, the model tests underestimated the resistance forces.

The researchers attempted to estimate vessel resistance by consulting tables in the literature. (9) These tables gave resistance per ton of displacement as a function of velocity, draft, beam, and displacement. The resulting calculations estimated a resistance that was approximately half the resistance calculated by the model tests.

Vessel position during four turns was also analyzed. The results showed the amount that the vessel slowed during the turn and the distance between the point that the turn was initiated in the wheel house and the point that the vessel started to turn (Figure 15 and Table 2). When vessels turn, such behavior is typical.

Review of the sea trial report provided information on the turning and stopping capabilities of the vessel. The tactical diameter ranged from 1,893 to 2,638 ft, and the advance (the distance required for a vessel to change its heading by 90 degrees) ranged from 1,266 to 1,946 ft. The headreach distance was 892 ft at a velocity of 27.5 ft/sec and 570 ft at 22.1 ft/sec. The crash stop distance was also calculated using Equation 3. These calculations overestimated crash stop distance by 16 to 38 percent.

Table 2. Summary of Full-scale Turning Measurements

Run	Throttle Setting	Rudder Position (degrees)	Velocity Loss (ft/sec)	Turning Rate (ft/degree)	Distance to Begin Turning (ft)
728EZZ3A	Full Ahead	35 Left	5.9	18.3	233.7
728EZZ3B	Full Ahead	35 Right	3.8	25.2	331.3
728EYY1	Slow Ahead	20 Right	10.3	39.3	135.5
730EXX1	Full Ahead	25 Right	2.6	31.1	198.3

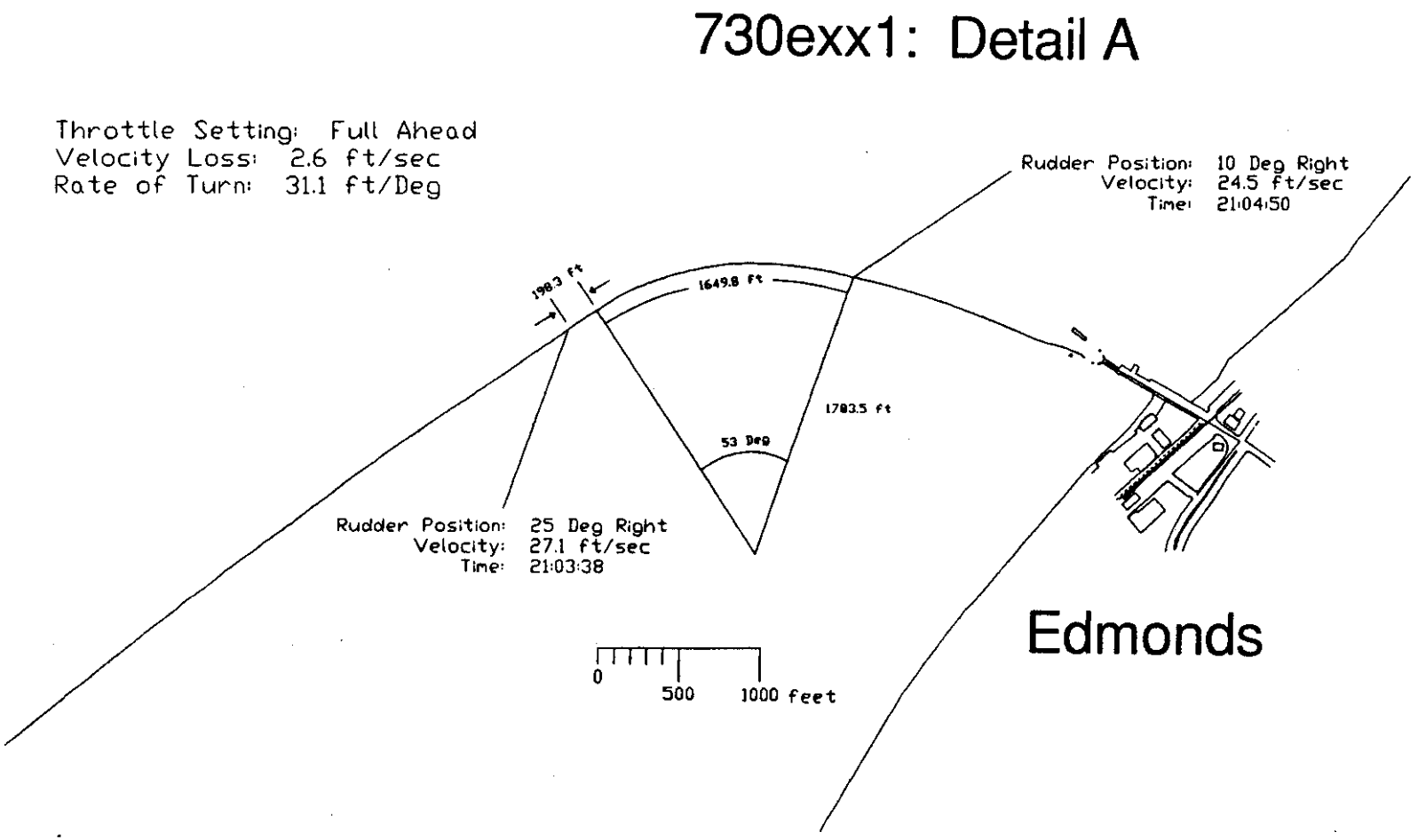

Figure 15. Detail of Right Turn with Rudder at 25°

APPLICATIONS/IMPLEMENTATION

The findings of this study may be used to develop improved design criteria for ferry landing structures. WSDOT should perform GPS tracking to make further improvements in design criteria and terminal layout. GPS tracking may also be used to track vessel position and velocity during sea trials.

Knowledge of vessel speed is necessary to properly design the outer landing structures at ferry terminals. An approach velocity envelope could be developed to provide design criteria at other distances (Figure 10). The envelope could be set three standard deviations above the average approach velocity. Because the outer landing aids are usually placed 250 ft out, the design approach velocity would be 12 ft/sec.

Ferries pass this point with a velocity between 7 and 11 ft/sec. PIANC (1) suggests a design approach angle of 15 degrees for such structures. PIANC's suggestion appears to be reasonable for WSF's outer landing structures.

Standards for stopping and turning should be developed for ferry landing designers on the basis of sea trial data and further GPS tracking studies. On the basis of the findings, a speed vs. stopping distance envelope could be developed for Super Class vessels. The findings suggest that the diameter of the turning circle could be as much as 2,700 feet. This type of information could also be used to facilitate operational decisions. For example, suppose that a ferry had to suddenly avoid a small vessel that had strayed into the entrance channel of the ferry landing. Would it be better to stop or turn? Comparison of the standards for stopping and turning could help in making the proper decision.

The GPS technology could be used to track vessels during sea trials. The results would provide accurate plots of turning circles and headreach tests.

GPS tracking sessions could be conducted during special, non-revenue sailings to gather additional information to improve design criteria. Tests should be conducted to assess vessel turning and stopping abilities in various situations.

Development of stopping distance envelopes for various reverse throttle settings would be desirable. A vessel that is traveling at maximum velocity should be brought to a stop with each reverse throttle setting while GPS data are recorded. This would produce distance to stopping distance vs. velocity curves for each throttle setting. Currently, only the stopping distance is available for a full astern throttle setting when the vessel is operating at full ahead and half ahead. Instrumentation could be developed that would measure the vessel speed and the distance from the landing structure to inform the crew of the reverse throttle setting that would be necessary to bring the vessel to a stop at the landing structure. Allowances would have to be made for reaction time and the effects of wind and current. Operational policies could be developed that prohibited operation in a range that would require a full astern power application to stop. Policies could also be developed that would allow for a safe landing in case of a power failure of a given length of time. In this case, full astern power would be used to stop the vessel.

Studies could be conducted to test the maneuverability of a vessel that was operating under reduced power or without power. A distressed vessel that is attempting to berth may be operating under these conditions. With better knowledge of the maneuverability of distressed vessels, ferry landing designers could develop more forgiving landing structures and vessel operators could make contingency plans for distress situations. During the test, the vessel should execute turns at the slow ahead and stop throttle settings, i.e., with the vessel coasting after normal operation had produced the initial velocity. A zig zag test could also be conducted at the slow ahead and stop throttle setting. The zig zag test is a series of predetermined turns in opposite directions. The rudder position and vessel position should be tracked during the test. Some of these

tests should be conducted on a windy day to assess the amount of added difficulty that the wind causes.

The GPS instrumentation package could be developed to measure and record wind and heading data. With wind data, researchers could find the effect of the wind on vessel operation. Because the direction and speed of the vessel would be known, the wind speed and direction could be computed with data from a vessel mounted anemometer. Because vessel heading and the direction of travel are not necessarily the same, it would be helpful to also record vessel heading information. The difference between vessel heading and direction of travel is especially apparent when the vessel is "crabbing" into the wind or current. Vessels also have a tendency to skid as they execute a turn and this would also result in a difference between vessel heading and the direction of travel. Such information would give researchers more complete knowledge of vessel maneuvering capability in difficult situations involving sudden changes in direction, wind and current.

A real-time graphic output could also be developed that would display the vessel position on a computer navigation chart. This would allow researchers to review the berthing event with the crew immediately after landing. If the system was sufficiently reliable, it might be useful as a navigational aid. Hardware that has the required capability is available from commercial vendors. Alternatively, an interface could be developed with a computer aided design program on a personal computer. To provide differentially corrected positions in real time, a data radio link would have to be developed between the vessel and the reference station. The differential corrections would be computed at the vessel in real time.

WSF should consider performing GPS tracking studies during the planning process for terminal construction. During the studies several vessel crews should be interviewed to obtain the following information:

- standard procedure for the berthing maneuver,
- circumstances that cause the berthing maneuver to be difficult,
- recommended procedure for berthing during difficult circumstances, and
- recommendations for improving landing geometry.

GPS data should be collected during difficult berthing situations so operational procedures may be studied in greater detail. Efforts should be made to improve the landing geometry as a result of the study.

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