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A CONCEPTUAL AND ANALYTICAL STUDY
OF THE UTILITY OF SPEED IN NAVAL OPERATIONS
VOLUME I

JULY 1976

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A conceptual and analytical study of the utility of speed in naval operations, specifically to include transit, maneuver, search, pursuit, escape and convoy operations; the analysis to cover the full range of available speeds for current and future ships and aircraft types, including hydrofoil craft, surface effect ships, and SWATH ships.

The rationale of the need for speed in the various naval functions studied was documented and a determination of those

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE speed ranges wherein future platforms, existent or nonexistent, employing such speeds could increase the effectiveness of future naval operations was made.

A CONCEPTUAL AND ANALYTICAL STUDY OF THE UTILITY OF SPEED IN NAVAL OPERATIONS

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SECTION I. INTRODUCTION, FINDINGS AND CONCLUSIONS

A. INTRODUCTION

The Santa Fe Corporation has undertaken a conceptual and analytical study of the utility of speed in future operations, to include the risks associated with not achieving an appropriate speed and the political implications of speed in naval warfare.

Three specific tasks were:

1. Conduct a conceptual analytical study of the utility of speed in naval operations, specifically to include transit, maneuver, search, pursuit, escape and convoy operations; the analysis to cover the full range of available speeds for current and future ship and aircraft types, including hydrofoil craft, surface effect ships, and SWATH ships.
2. From the analysis in Task 1, document the rationale of the need for speed in the various naval functions studied.
3. Determine those speed ranges wherein future platforms, existent or nonexistent, employing such speeds could increase the effectiveness of future naval operations.

The findings and conclusions which follow provide a summary of the study results. Each conclusion is followed by page references to the detailed analysis from which it was derived.

Section II contains the rationale for the need for speed (Task 2) and the speed ranges wherein future platforms could increase future effectiveness (Task 3). Section II also serves as an executive summary for the reader whose interest is primarily in broad illumination of the utility of increased speeds of naval vehicles, of the general analytic approach used in the study, and of the relationship of this effort to the overall Advanced Naval Vehicles Concepts Evaluation (ANVCE) Program.

Sections III through VIII provide the analytical details of the utility of speed in each of the vehicle functions listed in Task 1.* The figures and tables (incorporated in each of the referenced sections) illustrate the functional relationships and potential trade-offs between vehicle speed and the other parameters of vehicle capability.

The Appendix (Volume II) contains the details of assumed geometry, mathematical derivation of the equations used in the analysis, and the associated calculations.

*During the study, the vehicle function of "escape" was logically divided into two subfunctions, escape by counterattack and escape by avoidance. These are analyzed in SECTIONS VII, ATTACK AND COUNTERATTACK, and VIII, MANEUVER AND AVOIDANCE.

B. FINDINGS AND CONCLUSIONS

General

1. Increased speed capability enhances the options of a naval vehicle (or force) to choose the time and circumstance of engagement as well as the option of avoiding engagement. (pp VI-9, 12, 17, 23; VII-5 through 9, VIII-8 through 13)

2. In most naval vehicle functions, efforts to increase effectiveness will involve consideration of design trade-offs of vehicle speed with other parameters, such as surveillance capabilities and weapon ranges. (pp IV-20 through 26; V-18, 20, 22; VI-14, 23, 26; VII-9, 13 through 17; VIII-10 through 13)

3. However, effectiveness in a given total mission generally incorporates several of the vehicle functions (e.g., an escort vehicle must be effective in convoy, search, pursuit, attack and counterattack, and maneuver and avoidance). Increased speed capability can contribute to effectiveness in all of the functions involved. Improvements in other parameters may not. The utility of speed in this context is judgemental in nature and should be considered as such.

4. In crises or confrontation situations, increased naval vehicle speeds may be essential for effectiveness, for deterrence, or for political reasons. (pp II-35, 36)

Transit

5. Increased vehicle transit speed can reduce force level requirements for an operation requiring continuously maintaining a given number of vehicles "on station" at any appreciable distance from the base. The important measure is the product of transit speed and total endurance. (pp II-7 through 9; III-5)

6. Current displacement ships and wide-bodied jet aircraft combine speed and operating costs (per ton hour) to provide efficient transportation of cargoes of appropriate value. From a purely economic point of view, this is not true of currently operating advanced naval vehicles. Emerging designs, such as the large SES, may be comparatively efficient in this respect. (pp II-12; III-16, 19, 22, 24)

7. Transport of military cargo involves additional considerations of military worth which can far exceed basic dollar costs and can be a highly time dependent function. These are, however, subjective judgments which are scenario dependent. (pp II-10; III-9)

8. For sustained logistic support (maintenance of a pipeline of goods), increasing vehicle speed operates to reduce the number of platforms required to maintain a given rate of flow. The important measures are: (1) the product of speed and capacity, and (2) the loading/unloading rates. For a given speed-capacity product, there are preferred loading/unloading rates. (pp II-14; III-27, 28)

Convoy

9. Future submarine threats dictate much higher convoy speeds. A current limit on convoy speed is the maximum speed of escorts conducting continuous acoustic search. Advanced naval vehicles, employing sprint (or flying) drift tactics, can provide effective protection at much higher speeds. (pp II-17; IV-20)

Search

10. Optimum acoustic search speeds (10 to 20 knots) are inadequate against high speed submarines. Sprint (or flying) drift vehicles can achieve much

higher effective search speeds. An important parameter in the design of such vehicles is the "virtual speed" which is the detection range while drifting divided by the drift time required. Sprint speed to virtual speed ratios greater than about 1.2 have low payoff. Thus, higher sprint speeds will be more effective if accompanied by increased detection ranges and reduced drift times. (pp II-20-23 ; V-8, 10, 20, 22)

Pursuit

11. Effective pursuit speeds are 1.5 to 3.0 or more times the speed of the pursuee. Therefore, pursuit by like vehicles is limited in effectiveness. Pursuit of high speed submarines by displacement ships is similarly limited, even if the problem of effective acoustic search speed can be solved. (pp II-25; VI-9, 12, 14)

12. When the pursuit mission culminates in attack, there is a direct trade-off between increased effective weapon range and increased pursuit speed ratios. Longer weapon range is perferable to higher speed when the time within which the attack must be consummated is short. (pp II-26; VI-14)

Attack and Counterattack

13. Increasing vehicle speed provides additional options in attack and counterattack. These options allow the tactical commander to consider other factors, such as the expected military value of the outcome. (II-27 through 29; VII-4 through 9)

14. In potential attack-counterattack situations, there are design trade-offs between vehicle speed and the capabilities of surveillance and weapon systems. (pp VII-4 through 9, 13 through 17)

Maneuver and Avoidance

15. When a pursuer has continuous information, there is little that a pursuee can accomplish by maneuver, unless he has speed advantage. If, however, the pursuer has only intermittent information and the pursuee has at least equal information, the pursuee can use the "blind" periods to maneuver to increase the area of uncertainty and in some cases escape. (pp II-31; VIII-3)

16. When pursuer and pursuee have comparable information, relative weapon capabilities, as well as relative speeds, determine the options and potential outcome. (pp II-31; VIII-3)

17. The utility of speed in maneuvers to avoid detection by a searcher (or search system) depends on the nature of the search (barrier, area) and the characteristics of the search system (continuous, intermittent, active, passive). (pp II-31, 32; VIII-4 through 7)

18. Increased vehicle speed can contribute to the ability to maneuver to escape the lethal area of attacking weapons. Success against modern weapons requires high maneuverability at high speeds. (pp II-33; VIII-11-13)

Political Implications

19. While the political benefits of increasing the speed of naval vehicles are intangible and not directly quantifiable, they are real. A navy with higher speeds can enhance the image of the United States and contribute to deterrence. Examples include the following:

- The advantage of being the first naval force on the scene.
- Effectiveness in policing and enforcing U.S. rights under international agreements.
- The national and international value of being viewed as "the best."

- Timeliness of response to disasters.
- Technology transfer with the private sector.

(pp II-35 through 38)

The next section contains the rationale for speed and the executive summary.

SECTION II. RATIONALE FOR SPEED

A. INTRODUCTION

1. General Observations

There are naval functions and scenarios where increased vehicle speed produces substantial payoff. Any continuing mission which must be performed at great distances from bases (e.g., barrier operations at key choke points) requires that some portion of the force be involved in transit to and from the barrier. Increasing transit speed capability reduces the transit time and (depending on the effect on total endurance) may operate to reduce the percentage of the force in (nonproductive) transit. Said another way, increased transit speed can decrease the number of platforms necessary to conduct the operation.

As one might expect, there are also substantial increases in mission utility by combining speed increases with improvements from changes in other key parameters. An example is that of a naval vehicle pursuing a datum with a time-late problem. The probability of detecting its target is improved by increasing the detection range of its on-board sensor through increase in its search width. It can also be improved by increasing speed (which reduces the time-late and the area of possible target location). Concurrent increases in both produce considerably greater increments in detection probability.

However, there are some foreseeable scenarios and/or operations in which increased speed has little or no utility. Consider, for example, a continuing convoy operation in the face of a threat consisting of a broad ocean surveillance system with a near real time data link to submarines armed with tactical ballistic missiles. If the missiles have a range capability of several hundred miles, the threat is essentially indifferent to convoy speeds. More generally, increased detection ranges and long-range smart weapons on one side will generally overcome increased speed on the other side.

There is some finite limit on the total military utility which one can reasonably design into a given naval vehicle and thus, a question of how much of the "package" should be allotted to speed. There are, therefore, several trade-offs between speed and other key performance parameters (such as surveillance and search capabilities; weapon range, accuracy, and lethality; and various endurance factors). Many of these trade-offs occur over definable pertinent speed ranges.

An understanding of the utility of vehicle speeds in naval functions must also include consideration of vehicle missions which can be expected to combine several of the basic naval functions analyzed.

For example, consider an escort vehicle. The total mission may include searching while escorting, pursuit of contacts, and attack and counterattack, and expeditious return to convoy station. Viewing the vehicle in each function in isolation may give indications of alternatives other than speed for accomplishing the same increases in utility of the platform. In search activities, increased detection range substitutes for speed in improving search rate; increased weapon range may enhance the pursuit and the attack/counterattack functions. However, across the whole spectrum of functions involved in the mission, increased speed could be the better choice. By inference, increased speed may require even more emphasis in designs of multi-mission platforms.

2. Relationship of the Analysis to the Advanced Naval Vehicles Concepts Evaluation (ANVCE) Program

This analysis investigated the utility of speed in the following naval vehicle functions:

a. Transit

b. Convoy

c. Search

d. Pursuit

e. Attack and Counterattack

f. Maneuver and Avoidance

During the course of this study, the ANVCE Program, of which it is a part, developed the following "hierarchy" of military activities, derived by synthesis from "Project 2000," "Study of Missions Involving General Purpose Forces," and "CNO Policy and Planning Guidance for FY 78-82":

1. National Military Missions

2. Naval Objectives

3. Naval Functions

4. Naval Operations and Tasks

5. Naval Warfare Areas

Traditional naval warfare areas such as ASW are intimately linked with specific platforms and weapons systems; hence, focusing attention at level 5 would constrain the analysis to being highly platform dependent. Accordingly, in the initial stages of the program, it was decided to focus attention at level 4, i.e., naval operations and tasks. Twelve basic naval operations were defined by the ANVCE Study Director as:

1. Barrier Operations

2. Sea-Launched Ballistic Missile Defense

3. Mine Warfare

4. Surveillance and Reconnaissance

5. Naval Force Protection

6. Shipping Protection

7. Open Ocean Operations

8. Offshore Resource Protection

9. Logistic Support

10. Strike Against Land Targets

11. Inshore Warfare

12. Amphibious Operations

The vehicle functions in this report are not to be confused with the "Naval Functions" at level 3 of the hierarchy above (Sea Control and Power Projection). Collectively, they are applicable to all of the twelve basic naval operations of level 4 (the focus of the overall ANVCE Program) as indicated in Table II-1.

Table II-1 only serves retrospectively to relate loosely the twelve basic naval operations to the six functions of this report. In fact, the twelve basic naval operations were finally defined about halfway through the study effort on speed. Table II-1 is subjective, and different authors might relate the operations and functions slightly differently.

Table II-1. Applicability of Vehicle Functions to Various Naval Operations

VEHICLE FUNCTIONS / NAVAL OPERATIONS	TRANSIT	CONVOY	SEARCH	PURSUIT	ATTACK & COUNTER-ATTACK	MANEUVER & AVOIDANCE
1. Barrier Operations	X		X	X	X	
2. SLBM Defense	X		X	X	X	
3. Mine Warfare	X					
4. Surveillance and Reconnaissance	X	X	X			
5. Naval Force Protection	X	X	X	X	X	X
6. Shipping Protection	X	X	X	X	X	X
7. Open Ocean Operations	X		X	X	X	X
8. Offshore Resource Protection	X		X	X	X	
9. Logistic Support (including UNREP)	X	X	X	X	X	X
10. Strike Against Land Targets	X				X	
11. Inshore Warfare	X			X	X	
12. Amphibious Operations	X	X			X	X

3. Relationship of Speed Ranges to Vehicle Types

The detailed analysis of the utility of speed in the vehicle functions (Sections III thru VIII) was conducted without regard for a particular naval vehicle. The results of the analysis are related to speed ranges of specific vehicle types in the following subsections, which also develop the rationale for speed in each specific function.

Speed intervals were chosen to correspond approximately to representative current technology of advanced naval vehicles. (The interval limits can be expected to change as vehicle technology progresses). The speed ranges and corresponding vehicle concepts are listed below:

Speed Range (knots)	Vehicle Concept
15-35	Displacement Ship, SWATH, Planing Craft
35-60	Hydrofoil
60-100	ACV, SES
100-200	WIG, LTA (WIG speed range is about 150-250)
200-600	Fixed-Wing Aircraft (Air Loiter, Sea Loiter)

B. TRANSIT

Transit of a naval vehicle is the function of proceeding to and from a vehicle mission. Three aspects have been considered. In each, there are incentives to reduce the time spent in transit and therefore, to increase transit speed. Key observations from each case follow.

Case I. <u>Transit To and From a Station</u>

For this function, a useful utility measure is that of the base loss factor (BLF), which is generally defined as the number of vehicles required in order to keep one on station, i.e., conducting its mission.

When endurance is insensitive to speed (e.g., nuclear propulsion) or limited by other factors (e.g., pilot fatigue), increased transit speed shows clear gains in utility. Otherwise, the problem becomes one of design trade-offs among transit speed, mission performance speed, total endurance as a function of these two speeds and the required transit distance.

In any event, there are practical limits on how small a BLF can be achieved (by whatever means). Below about 1.5, further decreases come only by achieving very large increases in the product of transit speed (V) and total endurance time (T), the VT product. Even in case of a total endurance which is insensitive to transit speed, reducing the BLF from 1.5 to 1.25 would require almost doubling the transit speed.

Characteristically, for a typical mid-Atlantic mission (3000-nm round trip transit) base loss factors of about 1.5 are probably achievable for some current displacement hulls. Current patrol aircraft (P-3) are capable of similar missions, but only at BLFs of about 6. One might expect that the best BLFs that technology can reasonably expect to achieve for advanced naval vehicles will be bounded by these two values, as indicated by the analysis in Section III.

Table II-2a shows the product of VT (in units of miles) necessary to achieve the indicated BLF for the indicated two-way transit distances.

Table II-2a. Transit Speed-Endurance Products (VT) and Base Loss Factors (BLF)

BLF \ Dist. nm	500	1000	1500	3000
1.5	1500	3000	4500	9000
6.0	600	1200	1800	3600

Table II-2b shows, as an example, the endurance in hours required for a two-way transit distance to achieve the indicated BLF in the speed intervals noted. For simplicity, the calculation is made for the mid-point of each speed interval.

Table II-2b. Required Endurance (For Various Speeds) to Achieve BLFs

(1000 nm Two Way Distance)

BLF \ Speed	15-35	35-60	60-100	100-200	200-600
1.5	120	63	38	20	8
6.0	48	25	15	8	3

Thus, an 80-knot ACV or SES requires about 38 hours of endurance to be able to maintain a 1.5 base loss factor at 1000-mile, two-way transit distance.

Table II-3 shows how the endurance requirement changes as the two-way distance to station changes for an 80-knot vehicle.

Table II-3. Required Endurance (Hours) to Achieve BLFs at Various Transit Distances

(80-Knot Vehicle)

BLF \ Distance nm	500	1000	1500	2000	2500	3000
1.5	19	38	56	75	94	113
6.0	8	15	23	30	38	45

The important point is that the design of an 80-knot ACV or SES must meet certain mission distance/endurance constraints if force levels are to be reasonable. Current technology indicates a <u>total</u> range of about 1500 nm for an 80-knot SES, which results in an endurance at this speed of about 19 hours. This endurance corresponds to a BLF of about 3 for a round trip distance of 1000 nm. At 50 knots the endurance is about 40 hours and the BLF is 2. Thus, it is not sufficient to choose speed intervals in vacuo for consideration of transit to station, but rather a set of consistent parametric values must be designed into the vehicle and the vehicle mission.

The 60-100 knot interval was used as an example. A similar table can be constructed and conclusions drawn for each speed interval.

Case II. <u>Transit to a Destination</u>

The transit to destination analyses consist of an investigation of utility of speed of naval vehicles over a potential variety of transport missions. In a general economic sense, the cost of a given transport mission depends on three factors:

1. Cost of the goods being transported, since there is an opportunity cost of alternatively investing this dollar value. (The cost of the goods x the interest rate per unit time x the time in transit.)

2. The platform daily or hourly operating costs which are essentially independent of speed (<u>time dependent costs</u>).

3. The <u>speed dependent</u> cost of energy consumption.

The analysis of this case in Section III addresses this problem and indicates that the principal impact of speed may lie in the maritime and/or air transport realm.

There is a potentially important parallel consideration for the design of future naval vehicles. Conceptually, item 1 above can be considered as a time dependent military utility function. That is, the military value of the delivery depends on its deterrent value or its subsequent military effectiveness and it may also depend on the transit time required to make the delivery. No attempt was made to determine this highly scenario dependent "value" of a military cargo.

However, some insight into the effectiveness of naval vehicle speeds in this type of transit function can be gained by using a range of dollar values (per ton) as a proxy for military utility of cargo. Combining these values with optimal speeds for a realistic range of fixed operating costs per ton hour produces a set of curves of desired speed ranges at which to transport such cargo. This is done in the analysis in Section III (Transit); Table II-4 indicates results of this analysis.

Table II-4. Optimum Speed Intervals for Various Cargo Values and Operating Costs

Cargo Value ($/Ton)	Fixed Operating Cost ($/Ton Hour)	Optimum Speed Intervals (Knots)
1-10	.001	0-10
10-100	.001-.01	10-25
100-1000	.01-.1	25-40
1000-10000	.1-1	40-85
10000-100000	1-10	85-185
> 100,000	> 10	> 185

More generally, corresponding to each range of cargo value there is an optimum speed of transit and associated operating cost which minimize the total transportation cost. As operating costs increase there is a range of cargo values which are insensitive to transit speed up to a critical value. Beyond this value the optimum speed of transit is a monotonically increasing function of cargo value. For example, for an operating cost of $10/ton hour, the optimum speed of transit is insensitive to cargo value until cargo value reaches a range of $10,000 to $100,000/ton; it then increases monotonically with cargo value.

For comparison, Table II-5 indicates representative values of payloads and fixed operating costs of various types of vehicles.

Table II-5. Estimated Payloads and Fixed Operating Costs for Various Types of Existing or Proposed Vehicles*

Speed Range (Knots)	Vehicle	Payload (Tons)	Fixed Operating Costs ($/Ton Hour)
15-35	Displacement Ship	5000-15,000	0.1-1.0
35-60	Hydrofoil	15	21
60-100	ACV	75	27
	SES	~ 30	10
100-200	LTA		
	WIG		
> 200	a/c (C-130)	22.5	42
	a/c (747)	~ 85	250

At their present stage of development, advanced vehicles would be far below optimum in transport missions. For example, an 60-knot SES which could achieve fixed operating costs of about $1/ton hour would be an optimum vehicle for transporting cargo in the $1000-$10,000 per ton range. The table indicates that one current SES has fixed operating costs of about $10/ton hour. This particular vehicle has a payload of 30 tons. A much larger proposed SES (50 knots, payload about 1300 tons) and other larger and faster future versions are under consideration. These may be competitive in the region of higher cargo values assuming that larger capacities will result in lower fixed operating costs ($/Ton Hour).

Case III. Sustained Logistic Support

The sustained logistics support operation can be considered as a pipeline of goods, wherein a large amount of the material in the system is en route.

*References for estimated operating cost data include The Utility of High Performance Watercraft for Selected Missions of the United States Coast Guard (U), Project 721530, Center for Naval Analyses, November 1972, AD 754 917.

The principal measure of the effect of speed in a pipeline is the number of platforms required to sustain a given rate of delivery.

The critical parameters associated with a pipeline operation are the speed of transit, the payload capacity of the platform, and the loading and unloading rates at the end points.

Emphasis is on speeds between 35 and 200 knots since these speeds correspond to the majority of advanced naval vehicles being considered by ANVCE. It should be noted that the speed regions below 35 knots (displacement ships) and above 200 knots (fixed-wing aircraft) are occupied by logistics systems developed from mature technology. The 35-200 knot speed region is characterized by new concepts. Comparable technological development may result in much higher performance levels in this speed range in the future.

The vehicles in the speed region of interest represent a generic set in its technological infancy. Some of these vehicles were not in existence a decade ago; others, such as lighter-than-air, represent re-emerging technology. The wing-in-ground concept was a technological curiosity until brought to fruition by the Soviets in such vehicles as the giant "Caspian Sea Monster."

An important relationship which emerged from the analysis of the sustained logistics support problem was the speed-capacity product (VC). The advanced vehicles in the speed region of interest are capable of satisfying the speed requirements, but are deficient in their payload capacity. However, this deficiency may be corrected with some of the planned advanced vehicles (such as the large SES) making these platforms more attractive for use in a sustained pipeline operation.

The analysis shows that the required number of platforms in the pipeline operation can be reduced by increasing the loading/unloading rate, but that decreasing marginal returns occur at high rates. For a VC of 35,000 $\frac{\text{ton-mile}}{\text{hour}}$ (characteristic of a C-5A, for example), an unloading rate of more than about 200 tons/hour (20-30 minutes unloading time) does not yield significant reduction in the number of platforms needed; for a VC of 400,000 (characteristic of a modern cargo ship), unloading rates of 350-400 tons per hour continue to produce appreciable reductions in the number of platforms required.

C. CONVOY

The convoy function can be viewed as a special case of the "pipeline" problem. However, the element of survivability of the platform is added. From the point of view of advanced naval vehicles, the effect of the relative speed capabilities of the convoy ships, escorts, and threat vehicles on pipeline survivability is of primary interest.

To this end, vehicle speed per se is an inadequate measure to determine convoy survivability. Therefore, speed ratios between convoy and attacker, and escort and attackers, are introduced. To focus on these speed ratios and the effectiveness of increasing them, the potential outcome of attacks is ignored and only the probability of occurrence is addressed. Similarly, micro-tactics are not considered.

1. Effects of Convoy Speed

Case I. Convoy Speed Greater Than Attacker Speed

For the case of convoy speed greater than attacker speed, the convoy employs speed continuously to reduce the instantaneous threat area from which it could be threatened.

Where the convoy uses its own speed advantage, the region of interest in the convoy to attacker speed ratio, as seen in Section IV, is between 1.5 and 3. If the major threat to convoys in the future will be attack submarines and surface ships, the maximum speed of the threat will lie between about 30-40 knots. This places convoy speed requirements in the range of 45-120 knots. If the major threat will be aircraft, then increased convoy speed is not very useful, except to reduce the single glimpse probability of detection as discussed in Subsection F of this Section.

As is shown in Section IV (Convoy Operations), the threat area can be reduced by maintaining a speed advantage of about 1.5 to 3 over the attacker; however, the attacker can compensate for the speed deficiency by increasing his detection and weapon ranges. For instance, an attacker with half the speed of the convoy can quadruple the threat area against the convoy by using a weapon with a range equal to his detection range, as shown in Figure IV-3.

It should be noted that the convoy threat area represents an area of potential threat to the convoy; this area exists whether or not the convoy has knowledge of an attacker's presence in the area. If the convoy is aware of the attacker's presence through intelligence or by employing counter detection, the higher the convoy-to-attacker speed ratio, the more likely the convoy could successfully evade the attacker.

Case II. Attacker Speed Greater than Convoy Speed

In the preceding case, the convoy had a speed advantage over the potential attacker. This may be a realistic assumption if one regards convoys and threats to convoys in the traditional sense, i.e., submarines armed with torpedoes versus convoy ships. In the modern environment this assumption may not be very realistic since the threats to future convoys may be high-speed submarines armed with cruise missiles and long-range aircraft with stand-off missiles.

In a practical sense, when the convoy has a long distance to travel to its destination and the attacker has the speed advantage, the attacker having detected the convoy can eventually overtake it. Further, with external surveillance and targeting, the attacker armed with long-range missiles can attack the convoy from some distance astern.

In this case speed alone may be of limited utility to the convoy, and the effectiveness of escorts as a function of their speed must be considered.

Case III. Escort Speed Requirements

In order to counter the threat from a high-speed attacker, the convoy must improve its counter detection and counterattack capability through the use of escorts.

There are two important escort speed ratios: escort-to-attacker speed ratio and escort-to-convoy speed ratio. The first ratio is required to insure timely closing and counterattacking the threat; the second is required to maintain the escort's own detection capability over the assigned area relative to the convoy.

To be effective, the first speed requirement that an escort must fulfill is to possess a speed capability greater than the convoy. Thus, convoy speed requirements such as those in Case I (45-120 knots) imply escort speeds of about 50-150 knots. Continuous acoustic search would be ineffective at such speeds. Sprint-drift tactics are required if the escort is to provide protection to the convoy against submarine threats by employing acoustic search.

The general sprint-drift search tactic is defined and discussed in the following subsection on search (pages II-19 through 23). Sprint-drift acoustic search by a convoy escort is a special case in that each escort* must cover an assigned sector (relative to the convoy) and do so at an overall speed at least equal to that of the convoy. The detection range while drifting, the drift time

*See pages IV-24 through 26 for a discussion of "leap-frogging" sprint-drift search by a pair of escorts and the implied trade-off between force level requirements and vehicle capabilities.

required to complete a search, and the sprint speed and distance between searches combine to fulfill this requirement. The search subsection introduces the concept of "virtual speed" which facilitates the analysis of the effects of sprint speed on overall search capability.

For the case where escort speed is greater than convoy speed but less than the attacker speed, the number of escorts required can be reduced by increasing the weapon range of the escort, as shown in Table II-6.

Table II-6. Escort Requirements as a Function of Speed and Weapon Range

Attacker/Escort Speed Ratio	Escort Weapon Range/ Detection Distance	Number of Escorts
1	.25	5.2
	.50	2.8
2	.25	6.9
	.50	3.6
3	.25	7.8
	.50	3.8

Case IV. Independent Sailing

The preceding discussions on convoy-to-attacker and escort-to-attacker speed requirements open the question of independent sailings versus convoys. There are certain conditions under which one or the other may be a logical choice.

Independent sailing may be the proper choice, if the pipeline is composed of high-speed ships and the attacker's capabilities are limited such that this speed can produce small and narrow threat areas. If such "convoy" speeds are also essentially beyond the speed capability of effective escort, independent sailing is a clear choice. If, however, the enemy threat (surveillance and weapon ranges) is relatively insensitive to convoy speed, and escorts can provide effective protection, convoying may be the proper choice.

D. SEARCH

In investigating the utility of speed and optimum speed ranges for conducting acoustic search by a single unaided searcher, two cases are examined:

- Barrier Search
- Open Area Search

Emphasis is on acoustic search for enemy submarines. In this case there are optimum search speeds because the increased speed increases the length of the area searched per unit time, but increasing speed reduces the detection range (which determines the width of the area searched). For other types of sensors and targets, detection ranges tend to be insensitive to search vehicle speeds; search rates, therefore, increase linearly with speed.

In both the barrier and open area cases, three search modes were investigated:

- Continuous Search
- Sprint-Drift Search
- Flying-Drift Search

1. Barrier Search

The barrier case represents a well-defined area to be searched with the expectation that a target (in this case, an enemy submarine) may attempt to travel through the barrier.

Continuous acoustic search was investigated for sensor systems exploiting two types of target characteristics:

- Active sonar search or passive search utilizing narrow band detection of a non-propulsion-related noise source. In this case, detection range is independent of target speed. (The effect of target aspect was not considered.)
- Broad band passive detection of propulsion-related noise. In this case, detection range is target speed dependent.

In either case an optimum range of searcher speeds can be expected. This optimum is primarily due to the degradation of acoustic sensor capability with the speed of the search vehicle (i.e., the benefit derived from increased speed in the form of increased sweep speed is offset by the degradation of sensor capability with increasing flow noise). It has been observed by other investigators* that the sensor capability is degraded to 30% of its maximum value at a speed of 15 knots, a result consistent with this analysis. Hence, continuous acoustic search in a barrier is limited to search speeds below the speed capability of present naval vehicles and higher speed capability would be of questionable benefit in this vehicle function.

In order to utilize the speed capabilities of high speed vehicles in acoustic search, either sprint-drift or flying-drift tactics must be employed. Sprint-drift is the tactic of a submarine, surface or near surface ship sprinting while not searching, then searching while at zero speed, then sprinting again. Flying-drift is the tactic of aircraft capable of hovering (air loiter) or sitting on the water (sea loiter) during the listening period. The aircraft employs essentially the same basic tactic as sprint-drift, i.e., flying while not searching, then searching while hovering or sitting, then flying again. It differs from sprint-drift in that additional time is required to deploy and

*Black Lace, Vol. 3 Barrier Patrol, Report TP462, Westland Aircraft, Ltd., East Cowes, Isle of Wight, November 1961.

retrieve the sensor. Hence, the benefit derived from higher flying speed is offset by the additional dead time during the drift period. Using this search tactic, no clear-cut optimum speed emerges, since parameters other than speed, such as detection range and drift time, impact on the effectiveness of search. A "virtual speed" can be defined (which others have referred to as a "search efficiency ratio" or "search efficiency parameter"), i.e., the drift detection range divided by the drift time. Note that the virtual speed indeed has the unit of speed. The equation

$$\frac{1}{V'} = \frac{1}{\bar{V}} + \frac{1}{V_v}$$

is easily derived from equation C-8 in the Appendix, where V' is the overall speed of advance of the searcher, $\bar{V}$ is the sprint speed, and V_v is the virtual speed, i.e., detection range while drifting divided by required drift time to complete a search. It is seen that even if $\bar{V}$, the sprint speed, increases beyond all bounds, the speed of advance cannot exceed the virtual speed (assumes searcher sprints a distance equal to his detection range). This results from the fact that the searcher is only effective for searching during the drift time.

For low values of virtual speed, i.e., in the order of 15-35 knots, sprinting at high speed would be a wasteful tactic, since any sprint speed greater than about 40-50 knots contributes very little to the advance. When the virtual speed has a value of 80 or greater, then sprinting at high speed becomes a more attractive tactic.

Looking at the problem in a different way, if a desired speed of advance is specified for a given virtual speed, then the required sprint speed can be calculated. For instance, if the specified operation is to escort a task force at 40 knots, then the required relationships are given in Table II-7.

Table II-7. Example of Required Sprint Speeds and Virtual Speeds to Escort (Convoy Speed = 40 Knots)

Virtual Speed (Knots)	Required Sprint Speed (Knots)
84	76.4
167	52.6
250	47.6

Note that increasing the virtual speed allows for sprinting at slower speed while still maintaining the desired speed of advance.

Flying-drift search displays similar characteristics; however, if the search sensor is a towed array additional time will be required to deploy and retrieve the array. This has the effect of increasing the total drift time and decreasing the virtual speed and thus the speed of advance of the searcher. For example, for a surface vehicle the nominal drift time is approximately 0.3 hours, and for an air vehicle it is about 1.5 hours. If the detection range in both cases is equal, perhaps 15 nm, then the virtual speed of the surface vehicle is 50 knots and for the flying vehicle it is 10 knots.

Again we see the necessity, in choosing speeds for naval vehicle designs, to balance speed with other factors. As can be seen from the above table, doubling the 84 knot virtual speed by combinations of improved detection ranges and reduced drift time, reduces the sprint speed required from 76 to 53, maintaining the same speed of advance.

Case II. Open Area Search

The open area search represents a random encounter with no prior expectation on the presence or absence of a target. In open area search the expected number of encountdrs varies with the density of targets. The density of targets, in this analysis, varies with their distance from port in accordance with the base loss factor concept introduced in the transit section (i.e., as the distance from port increases, the total area in which the targets can operate also increases; hence, for a given force level, the target density will decrease).

The conclusions from the barrier case using passive search are applicable to open area search. However, active sonar is not very useful in open area search since the target is not constrained to cross a barrier. Since the target would passively counterdetect the searcher beyond the searcher's capability to detect, a high speed submarine could always evade the searcher.

For sprint-drift or flying-drift search the number of encounters per hour increases with the virtual speed and target density.

For both the barrier and open area search the optimum continuous search speed is in the lo speed range (10-20 knots) and higher search speed results in reduced effectiveness for each searching platform. However, vehicles in this lowest speed range are typically long endurance vehicles and are capable of sustained operations.

Thus, in the case of acoustic search for submarines, increased vehicle speed (and the implied advanced vehicles) may improve search effectiveness, but other improvements such as reduction or elimination of drift time and increased endurance would be necessary in order to fully realize these benefits.

E. PURSUIT

The classic problem of pursuit is in some form a function common to all forms of warfare. Any deployed naval vehicle is a potential participant in one role or the other in pursuit.

Wherever a vehicle has timely notice of the location of a pursuer and is free to maneuver, it can create a situation wherein the pursuer requires a speed advantage for success. The greater this speed advantage, the earlier capture occurs and the shorter distance the pursuee travels before capture. Thus, there is a clear case for increased speed in the pursuit function.

There are two basic tactics available to the pursuer:

1. The pursuit curve, wherein the pursuer continuously heads directly for the target and continuously alters course to do so.

2. The "steady bearing" tactic, wherein the pursuer calculates a future intercept point and heads for this point at the speed necessary for an intercept.

The pursuit curve resulting from the first tactic always results in a stern chase.

There are a myriad of modified pursuit paths generated by specifics of other parameters. One such is the case where the pursuer has a high speed weapon and "capture" occurs when he reaches weapon launch range. He then may modify his path to either follow a pursuit curve to the nearest point from which he could launch his weapon or take a steady course (lead angle) which minimizes the distance to a weapon launch point.

An important case is one where the pursuer lacks continuous information on target location. In this case, he pursues a datum and attempts to trap the target within the path which his sensor sweeps through this datum.

In all cases, there is a clear increase in utility with increases in speed ratios. Again, however, there are trade-offs with other parameters, such as detection ranges, frequency of up-date, weapon speeds, and weapon range. These are discussed in some detail in Section VI.

Important observations from this analysis include the following:

1. Pursuer-to-pursuee speed ratios of less than about 1.5 can result in very long tail chases. However, speed ratios above about 3:1 produce very small incremental gains. Table II-8 summarizes the inferences of the above for naval vehicles in potential pursuit scenarios. Note that the speed of the pursuer indicates the appropriate type of pursuit vehicle. Thus, pursuit of alerted high speed submarines by displacement ships will not be very effective even if the problem of acoustic sensor degradation can be overcome.

Table II-8. Appropriate Pursuit Vehicles For Given Pursuee Speed Ranges

Pursuit Vehicle Speed	Pursuit Vehicle Type	Pursuee Speed Range
15-35	Displacement	5-23
35-60	Hydrofoil	12-40
60-100	SES-ACV	20-67
100-200	LTA-WIG	33-133
> 200	Aircraft	> 67

2. The trade-off between pursuer's speed advantage and his weapon range (when pursuit culminates in attack) is of interest from two points of view. The first is that long weapon ranges can make pursuit effective at very low speed advantages. The second is that as the time available for capture (attack) becomes short, the trade off begins to favor greater weapon range rather than increased speed.

The analysis in Section VI addresses a case wherein initial separation is 200 nm and the pursuee's maximum speed is 25 knots. Table II-9 indicates results for two capture times (8 hours and 2 hours).

Table II-9. Illustrative Pursuer Speed-Weapon Trade-Offs

(Initial Separation = 200 nm, pursuee speed = 25 knots)

Maximum Pursuit Speed (kts)	Required Weapon Range (nm) To Attack In: 8 Hours	2 Hours
25	80	160
35	0	135
50	--	110
75	--	55
100	--	0

In the perspective of advanced naval vehicle development, increased speed increases effectiveness in the pursuit mission. However, there are clear trade offs with other vehicle parameters, depending on the ultimate purpose of the pursuit, the capability of the pursuee, and the initial geometry of the problem.

F. ATTACK AND COUNTERATTACK

Attack is the result of a sequence of events beginning with detection of an enemy target. Several of the vehicle functions, which formed the focus of this study, are involved in this sequence, and thus, are related to attack. Attack also includes the use of weapons and, therefore, weapon ranges of both parties, the attacker and target (or counterattacker) must be considered. Preparation for target escape in the form of counterattack begins when the target is initially alerted to an approaching attacker. The actual counterattack weapon is launched when the distance between platforms is reduced to the initial target's weapon range.

There are four important variables for each platform (target and attacker) which impact on the outcome of attack and counterattack. Of course, speed of each platform is the primary one under consideration. The others are, for each platform, surveillance range (includes external sources) weapon range and weapon response time (measured from detection to weapon launch). Several cases, then, are relevant.

Case I. Attacker surveillance range and weapon range are both greater than the target's surveillance range. Once the attacker contacts the target, speed is irrelevant. The outcome is simple. Given detection, the attacker can always attack the target. The target never has the opportunity to counterattack or evade.

Case II Attacker weapon range is less than the target weapon range, and additionally,

(1) Case II-1. The target surveillance range lies between the attacker's surveillance range and attacker's weapon range. In this case when the attacker's speed is greater than the target speed, the outcome depends on the target's response time.

The engagement consists of the attacker detecting (or receiving knowledge of) the target and closing the range to the target; but the target counter detects the attacker before the attacker is in a position to launch his weapon. The target then turns away from the attacker and prepares to counterattack, an operation which takes some time. In the meantime the attacker continues to close the distance until it reaches weapon range. For simplicity of description, weapon flight times are considered to be zero.

When the distance-speed relations are such that the time to close this distance is less than the target response time, the attacker always attacks and the target does not.

When the time to close is equal to the target response time, the attacker may choose to break off the attack, in which case the target never has the opportunity to do so (i.e., neither attacks) or the attacker attacks and the target also attacks.

Lastly, when the time is greater than the target response time, the attacker should break off his "attack"; otherwise, the target may choose to counterattack or it may break off the attack.

Examples of required attacker speed advantages (to close and make the first weapon launch) for this case are indicated in Table II-10. (See following page.) Note that increased attacker weapon range is an alternative to increased attacker speed and may be preferred for some of the combinations indicated.

Table II-10. Required Attacker Speed Advantages For Nominal Target Weapon Response Times (Case II-1)

Difference Between Target Detection Range and Attacker Weapon Range (nm)	Required Attacker Speed Advantage (Knots)	
	Target Weapon Response Time	
	5 Min	10 Min
20	240	120
10	120	60
5	60	30
1	12	6

(2) Case II-2. The target speed is greater than the attacker speed. In this case, the attacker detects and, as before, the target counter detects before the attacker reaches its weapon range. At this point the target can turn away and open or maintain range in a "Mexican stand-off" or the target might choose to allow the range to close further (even helping it) and engage the attacker.

Case III. The attacker's surveillance range and weapon range are each greater that the target's corresponding parameters, and the target surveillance range is greater than the attacker's weapon range. If the attacker's speed is also greater than the target speed, the attacker always attacks and the target never has the opportunity to counterattack. If, lastly, the target's speed is greater than attacker's speed, the target will probably choose to avoid engagement.

In any of the above cases, when one player has the option to engage the other and, by so doing, allow a counterattack, it will choose to do so on the basis of factors other than those considered herein (e.g., relative worth of the two forces).

The details of the above cases are contained in Section VII. Also considered therein is the more complicated case wherein the target is escorted.

In summary, attack and counterattack are functions closely related to the other functions studied. There are many situations where a speed advantage can influence the outcome of attacker-counterattack scenarios. Other parameters such as weapons and surveillance systems are equally important, however, and vehicle design decisions should be made considering the balance and matching required among speed and the other important parameters.

G. MANEUVER AND AVOIDANCE

Maneuver is a tactic employed by a naval vehicle which is designed to alter favorably the potential outcome of any offensive or defensive engagement. In general, maneuvers relate to the other vehicle functions addressed in the study. Offensive and defensive maneuvers are considered. Offensive maneuvers are those tactics which strive to increase the probability of successful attack either by confining the enemy or by achieving a favorable launch position; defensive maneuvers attempt to achieve escape by avoiding attack or reducing the effectiveness of enemy weapons.

In the pursuit section, the analysis of the case wherein the pursuer had continuous information on the pursuee's location finds that the pursuee can accomplish little by maneuver unless he has a speed advantage. If the pursuee also has information on the pursuer's location, he can either prepare for attack or attempt to escape. The pursuee's relative maximum speed and weapon capability determine the pursuee's actions. When the pursuer has intermittent information and the pursuee has at least intermittent information, the pursuee can, even with inferior speed, maneuver to increase the pursuer's area of uncertainty during the period of "blind" pursuit, breaking off the pursuit, or gaining time for eventual escape. Of course, if the pursuee has a detection range on the pursuer greater than the pursuer's weapon range and an equal or greater speed, then the pursuee can always avoid attack. The complete set of cases is discussed in the section on counterattack, which also takes into consideration weapon range.

The maneuver of a transitor through an area can be speed dependent. In a barrier transit, wherein the area sensors are randomly dispersed throughout the area, the transitor can reduce the probability of detection simply by

(1) taking a minimum length path, d, through the area, and (2) choosing a speed, V, which minimizes a function,

$$\frac{Q(V)\cdot d}{V}$$

where Q(V) is the detection range of the area sensor, increasing with increasing V. Thus, it is important to the transitor to know how the enemy area sensor depends on his own speed.

There is a class of cases wherein an enemy detection system depends on periodic "glimpses" to detect a moving naval vehicle. If the system has a near unity probability of detection per glimpse, the vehicle speed has little effect on whether he is detected or not. For example, a satellite sensor with a large field of view, high resolution and unaffected by cloud coverage might be such a system. However, for systems with a single glimpse probability of less than one, the less time that the vehicle spends in the surveillance area, the smaller his probability of detection. Vehicle speed can, therefore, be extremely important in this case to reduce total exposure time.

In the section on attack, the engagement was considered completed when one of the combatants launched the first weapon. There remains to consider maneuvers to reduce the probability of a successful weapon attack after an enemy has launched his weapon. For example, if the "Red side" has superior detection capability and higher speed than Blue, but Blue has a greater weapon range, Red has the option to engage or not engage, but he must concern himself with Blue's ability to fire first. Red must balance the worth of his own vehicle and that of Blue and the probability of survival of each side. Said differently, Red must determine whether his expected return is greater than his expected loss. It should be emphasized that it is Red's superior speed and greater detection range that provides him the choice of engaging or not. Blue, even with a superior weapon range but inferior speed capability, has no such option.

Furthermore, with superior speed, Red might be able to dart across Blue's weapon path, getting inside of Blue's weapon's turning circle (but outside of its weapon's effect radius). These are some of the traditional arguments for superior speed.

Generally, avoidance will require either a greater speed capability or increased counter detection capability. If the opposing platform is a submarine armed with conventional torpedoes, then, depending on the speed and angle on the bow (target angle), the target may be able to outrun the torpedo.

Reasonable projected speeds for torpedoes lie in the 50-60 knot region; hence, any future vehicle with a speed range of 50-60 or greater should be relatively invulnerable to torpedo attack, again depending on the angle on the bow at the time of torpedo firing and a reasonable torpedo detecting system.

If the opposing platform is either a submarine or surface ship armed with long-range missiles, then counter detection capability becomes the dominant factor, and the benefit of speed is derived from the ability to keep out of weapon range once the attacker has been detected.

In the case where the attacker has a great speed advantage, such as a long-range aircraft armed with air to surface missiles, then little benefit can be derived from either speed or counter detection capability, since the slower platform can neither outmaneuver nor avoid the attacker. Under these conditions the role of escorts becomes important, and again, the escort must have a speed range on the order of the attacker, as shown in the table of pursuit speed requirements (Table II-8).

Simply stated, in any engagement situation the benefit derived from speed is a function of the opposing platform types together with weapon and counter detection capability.

H. POLITICAL IMPLICATIONS

There are political benefits accruing from greater speed capability of naval vehicles that result from perception in the national and international fora. These benefits are largely intangible and non-quantitative, but are nevertheless real.

There are several perceived capabilities that depend on speed which enhance deterrence at lower levels of violence. The 1958 Lebanon crisis serves as an appropriate example. The United States had made a commitment to President Chamoun to provide military assistance, including troops, if asked. The general consensus, before the fact, held that it would take about three days to render such assistance. Yet, when asked, the United States responded within 24 hours. The rapidity of response was due, in part to the forward deployment posture, but also in part to the speed capability of the ships and aircraft involved. Two additional days could have been the difference between a major war breaking out and containing the relatively small incident which had occurred.

Perception on the part of a potential adversary that US response could be rapid, because high-speed vehicles are involved, might be the difference between complete success in deterring adversary action and a situation wherein the US is embroiled as a result of being incapable of rapid movement of force. Similarly, the success of ballistic missiles in deterrence depends to some extent on the speed of weapon delivery.

There is a school of thought which holds that, in some future crisis, the first superpower navy on the scene may be the only one. This may come about as a result of the other superpower realizing that it cannot arrive first, evaluating the escalation risk that occurs with direct confrontation and being deterred form proceeding. One could argue that this was a factor in the recent US decision not to send naval forces to Angola.

In any event, timely arrival has value and, considering the US and Soviet overseas basing trends, US Navy vehicle speeds may take on added importance simply because of the adverse trend of relative distances to travel.

Speed of vehicles also impacts on a set of illegal actions on the high seas which will probably increase as a result of the restraints of international relations such as the 200 mile fishing rights jurisdiction. The rapidity with which the US can react to reported incursions will determine the extent to which US rights under such relations will be violated or honored.

The success of future piracy actions of small nations or terrorist groups, particularly involving the security of nuclear weapons, might also depend on the speed capability of naval vehicles. A 50-knot intelligence platform might have prevented the PUEBLO incident without the subsequent embarrassment, without the use of force, and without the necessity to rely on complex command, control and communications systems.

In addition to enhancing deterrence at lower levels, there are several international and national political impacts of speed of naval vehicles, primarily associated with the "numbers game." The superpower watchers among the major powers and Third Nations are persuaded to one degree or another by perceptions of statements such as, "the Soviet VICTOR-class submarine is the world's fastest." One finds such statements in authoritative works, speeches, etc., as evidence that the Soviets are to one degree or another more advanced than is the United States. (The Sputnik coup was a similar situation outside the realm of speed.)

Traditionally, the "world's fastest" anything is of some interest in creating good public relations ("31-knot Burke"), obtaining public recognition and suggesting, perhaps, more than that which speed in itself implies. Thus, one nation may desire to create the illusion in the international forum that because it has the fastest planes, it therefore has "air superiority," which may or may not be true; but the statement itself is enough to muddy the waters, create doubts and otherwise fuel the fires in US-Third World relationships.

In the national forum, as can be observed in pre-convention activity in both Parties, the numbers game is continually being played. Thus, one sees many statements based on numbers regarding who is superior in military, naval and air power. Speed, a number to which most people can relate, may be used as an argument for or against a particular side. The "World's Fastest X-Vehicle" could easily be pointed to as an accomplishment of an Administration or Congress; failure to achieve the "World's Fastest Y-Vehicle" could also be used as a criticism. While possibly unrelated to direct military capability, the intangible impact of speed in such political situations is nonetheless important.

There is still another area wherein speed of naval vehicles impacts in a non-military, political and very real way, resulting from the actual use of speed rather than perception of some vague notion of "the faster, the better."

The US almost always goes to the aid of disaster victims, particularly when the area is accessible from the sea. In very recent times, for example aid was provided to earthquake victims in Central America and in Italy. The US Navy has usually participated in such aid and the US obtains intangible benefits in the minds of its own citizens, those assisted, and uninvolved observers. The faster the help comes (or seems like it is coming, i.e., "a high speed naval and merchant force is proceeding..."), the greater the impact of those benefits, whatever they may be.

Lastly, there is the matter of technology transfer from the research and development of advanced naval vehicle concepts to the private sector. The benefits of such transfer is a two-way street. The private sector usually cannot afford the research dollars and, thus, benefits from the results of military research; the Navy might not have the constituency to support the advanced concepts into production, which is provided by, for instance, the need for such concepts in the private sector. In the aerospace industry, technology transfer of this kind has constantly occurred. Some examples are the first large jet passenger liners (707/B-52) and the wide-bodied air fleets (747/C-5A). In fact, this could be one reason why the B-1 without its technology transfer civilian counterpart (SST) is experiencing a great deal of trouble with delays and funding. The military incentive is present, but the private sector incentive is wanting.

Similarly, an SES for purely military purposes may find greater difficulty in obtaining Congressional support and approval without concurrent support of the appropriate private sector, e.g., US Merchant Marine.

In summary, there are several intangible benefits to be derived from speed which one finds difficult to demonstrate conclusively, but which are worth mentioning and providing case histories.

SECTION III. TRANSIT OPERATIONS

A. INTRODUCTION

This section investigates the utility of speed in transit operations. (A later section will treat the specific problem of speed in convoy operations, a special case of transit.) Speed affects transit in three ways.

The first way strongly affects force levels by changing the amount of non-productive time spent in getting to and from an assigned station. In this application, it is assumed that the mission of a vehicle is to transit from a base to a station some distance from base and perform some task such as barrier, search, data collection, etc. over some period of time after which the vehicle returns to its base, which need not be the base of origin. Thus, the total time in a cycle is the two way transit time plus the time spent on station. A given vehicle will generally be capable of a specific maximum endurance, set by stores, fuel, personnel, maintenance requirements or other limiting factors. For a given total endurance, the less time spent in transit, the more time can be spent on station and, therefore, the more utilization that can be realized from each vehicle. Thus, greater speed of transit can provide higher vehicle utilization rates and therefore lower force levels for a given total task.

The second investigation of the effect of speed on transit deals with the economic costs of transportation and impacts less on the strictly naval problem. This effect does, however, relate to advanced vehicles of all types. The principal tradeoff to be considered is economic and is related to the fact that there are costs associated with transportation which depend solely on and increase with time. These costs are: (1) the time dependent costs associated with operating the vehicle, and (2) the "interest" cost associated with the investment in the cargo. These time dependent costs increase with time and therefore are reduced by higher transit speeds. However, higher transit speeds also operate to increase costs because of propulsion and energy considerations. The more valuable the cargo, the higher the time dependent cost factors and therefore the greater the incentive for higher speed. One expects, therefore, to find different optimum speeds corresponding to cargos of different value. From experience, coal, with a relatively low value per ton, is transported at relatively low speeds while military cargo, at a higher value per ton is transported at higher speeds and high value materials such as jewelry and precious metals are transported at still higher speeds.

The third treatment of transit speed deals with the problem of a sustained logistic support operation in which a steady demand at the end point requires a "pipeline" of goods from the supply point. The required number of platforms, of a given type, to fill this sustained demand is determined by the speed-capacity product of the platform and its load-unload rate.

B. TRANSIT TO STATION

Analysis of the transit to station case makes use of the idea of "base loss factor," first introduced by one of the authors of this report in 1963 and used in the OPNAV Mid-Range Objectives publication (MRO-78) published in 1966. The base loss factor (BLF) is an "overhead" and generally defined as the number of vehicles necessary in the force level to maintain one fully utilized in some task. The general base loss factor takes into consideration time in shipyard overhaul, reliability, transit time, training time, and maintenance time. The derivation of the general BLF formula is given in the Appendix (Sect. A). For the purpose of this analysis, only the overhead associated with going to and from station is considered. In this case, the base loss factor reduces to:

$$BLF = \frac{T_E}{T_E - T_{Tr}} = \frac{\lambda}{\lambda - 1} .$$

where T_E = endurance time of the platform

$= T_{Tr} + T_{St}$

T_{Tr} = two way transit time

T_{St} = on station time

$$\lambda = \frac{T_E}{T_{Tr}} = \frac{V_{Tr}\, T_E}{D}$$

V_{Tr} = transit speed

D = two way transit distance

Figure III-1

Number of Out-of-Overhaul Platforms Required to Keep One On Station (BLF)
As Function of Speed, Endurance, and Transit Distance

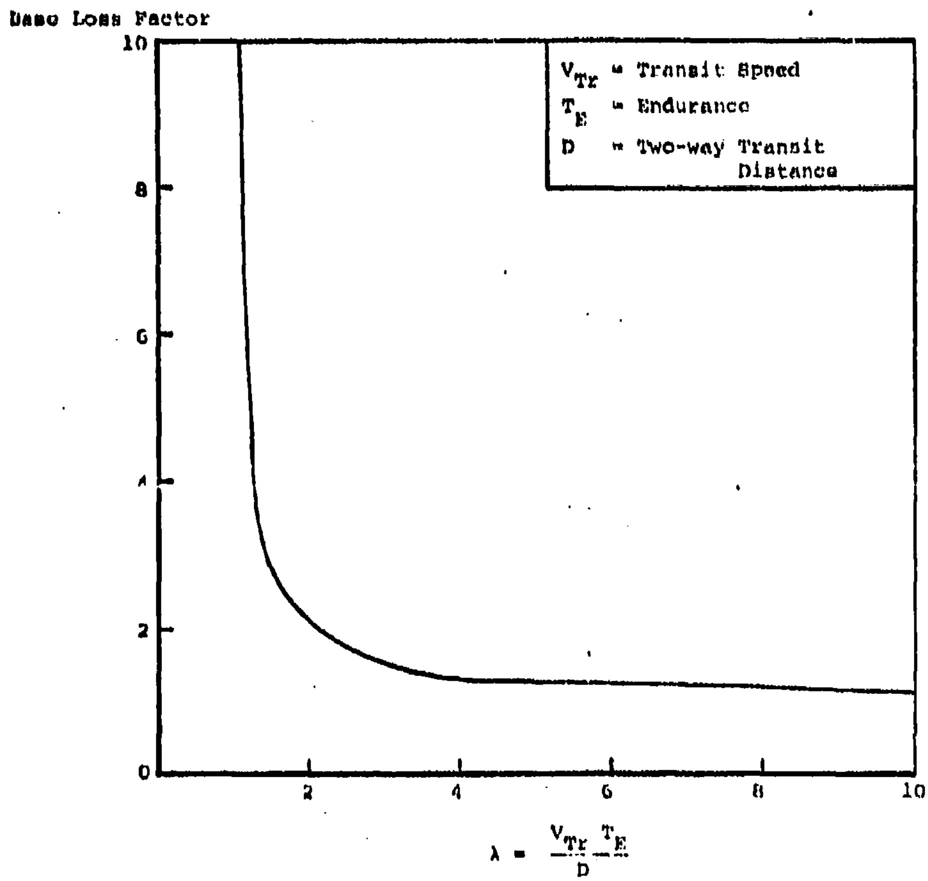


Figure III-1

Number of Out-of-Overhaul Platforms Required to Keep One On Station (BLF) As a Function of Speed, Endurance, and Transit Distance

Purpose

The purpose of this graph is to display the relationship of Base Loss Factor (BLF) to transit speed, endurance time, and two way transit distance.

Basis for Calculations

This is a plot of equation A-5.

The non-dimensional parameter λ is the ratio of the (transit speed)·(endurance time) product to the two way transit distance.

Principal Points

1. For a given vehicle endurance, T_E, and distance to station, D, λ is simply a measure of speed. The BLF falls off very rapidly between values of λ of 1 and 2.

2. The curve shows greatly diminishing marginal return (in reducing BLF) for values of λ beyond 3.

3. Recalling that the BLF is the number of vehicles in inventory (after accounting for overhaul, training maintenance and reliability) required to keep one on station, there is high payoff in reducing BLF. Because an increase in λ (i.e., speed for a given T_E and D) beyond current values could be costly, the cost of producing such reductions must be considered.

4. The effect of changes in λ through variation of T_E and D are discussed subsequently.

Figure III-2

Endurance Time Versus Transit Speed For
Various Constant Base Loss Factors (BLF)

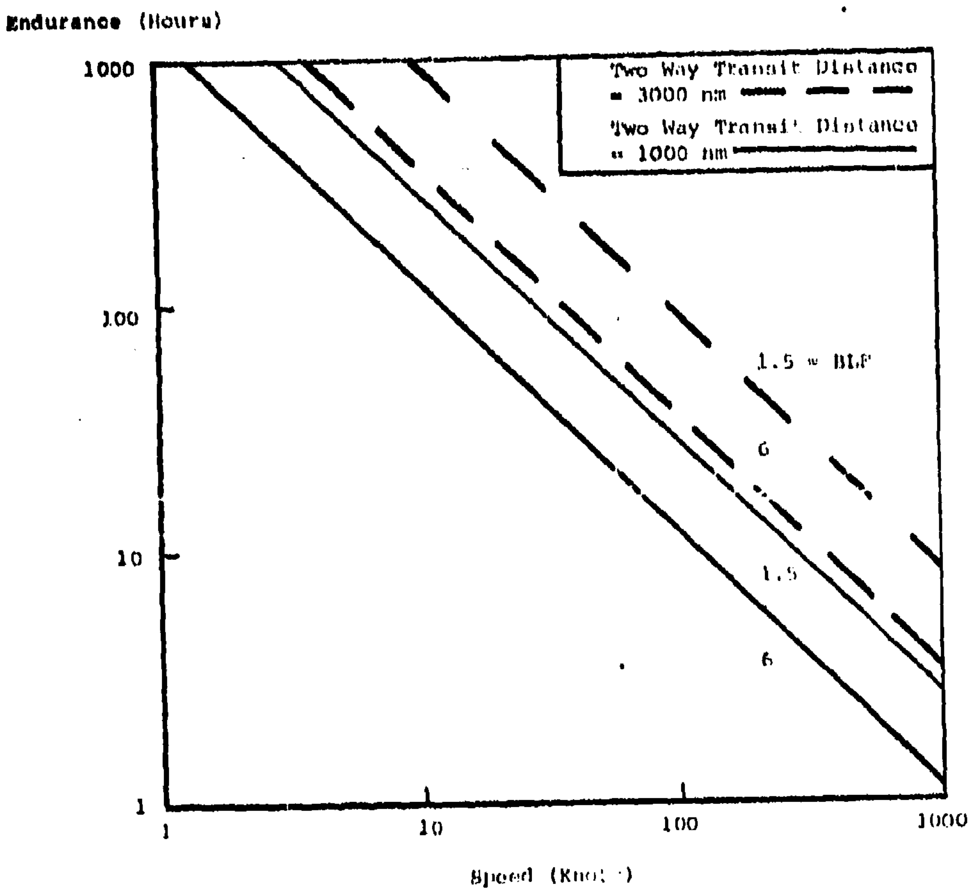


Figure III-2

Endurance Time Versus Transit Speed for Various Constant BLFs For a Given Two-way Distance to Station

__Purpose:__ To show the combinations of two principal vehicle design parameters, endurance time, and transit speed for a constant two-way distance to station (3000 nm) for various BLFs.

__Basis for the Calculation:__ A two-way distance to station of 3000 nm might be the round-trip distance to a mid-Atlantic operating area from an east coast operating base. Other typical mission distances are:

Mission Areas	Nominal Distance
Coastal	1000
Mid-Atlantic	3000
Trans-Atlantic	6000
Trans-Pacific (Hawaii)	7000
Trans-Pacific (West Coast)	8000

__Principal Points:__

1. The following table illustrates the endurances that would be required for various BLF's and transit speeds.

Transit Speed	BLFs	Endurance Required	
		1000 nm Two Way Distance	3000 nm Two Way Distance
10 - 20 knots	1.5	12.5-6.25 days	37.5-18.75 days
30 - 150 knots	1.5	4.2 - .8 days	12.5 - 2.5 days
200 knots	1.5	15 hours	45 hours
500 knots	1.5	6 hours	18 hours
10 - 20 knots	6.0	5 - 2.5 days	15 - 7.5 days
30 - 150 knots	6.0	1.7 - .3 days	5 - 1 days
200 knots	6.0	6 hours	18 hours
500 knots	6.0	2.4 hours	7.2 hours

2. Similarly constructed graphs can serve as nomograms for mission transit distance and required combinations of force levels and speed-endurance products.

C. TRANSIT TO DESTINATION

The cost of transportation is analyzed for a single platform transit from a point of origin to a destination. Loading and unloading rates at the end points are not considered in the single transit case, but will be treated in the next section on sustained logistic support operations. The cost for a single transit depends on:

1. Cost of the goods being transported since the dollar value of the goods could alternately be invested at some rate of interest during the time of transit.
2. Time dependent costs associated with operating the platform
3. Speed dependent cost related to energy consumption.

The value of the cargo at the origin is the number of tons of cargo times the value per ton of cargo. The value per ton of cargo can be expressed as the dollar value of the cargo or weighted dollar value when the cargo has a worth beyond the market value. The cargo value could be alternately invested during the time of transportation from the origin to the destination. The portion of the total transportation cost which is assigned to the cargo itself is the cargo value times the investment rate times the transit time.

This framework can be conceptually applied to military operations. In this case, cargo value would reflect military utility rather than cost or actual dollar value. The interest rate, I, would be a measure of urgency or critical nature of the delivery. Quantification would involve subjective judgments concerning the actual military worth of the cargo (as opposed to simple dollar costs) and the time dependency of this military worth in a dynamic conflict or crisis situation.

The transportation costs due to the particular platform used are divided into the platform operating costs (speed independent) and the energy consumption costs (speed dependent). The platform operating costs include depreciation of the platform and equipment, personnel costs, maintenance, port fees, overhaul and special costs due to the particular exercise. These operating costs can be added together and divided by the product of the lifetime operating hours of the platform and its cargo capacity to obtain an average platform operating cost per ton hour.* These costs were assumed to be independent of speed for this study. Some of these costs would become speed dependent if the platform utilization varied because of changes in speed.

The speed dependent costs were identified as being chiefly related to energy consumption. Energy consumption is a function of the propulsion system and the mode of transport.

The total cost of transportation is composed of the opportunity costs plus the various transportation costs. The transportation cost per ton mile is given by the expression:

$$\frac{\text{Transportation Cost}}{\text{Ton Mile}} = \frac{1}{V}\,[CI + C_o] + kV^{\alpha}$$

where:

C = cost of goods (dollars/ton)

I = investment rate (%/hour)

CI = opportunity costs (dollars/ton hour)

C_o = operating cost (dollars/ton hour)

---

*References for operating cost data include The Utility of High Performance Watercraft for Selected Missions of the United States Coast Guard(U), Project 721530, Center for Naval Analyses, November 1972.

k = proportionality constant relating speed to fuel consumption

V = speed of transit (knots)

α = proportionality constant relating fuel consumption to mode of transport

= 2 for area lift vehicles

= 3 for volume life (displacement) vehicles

kV^{α} = energy consumption cost/ton mile

Simplifying assumptions will be made about the sum CI + C_o. If C_o is 1 unit of cost per ton hour, the question arises as to how high the cost of the goods, C, can be before we need to consider the opportunity costs. An arbitrary, but reasonable, assumption might be to disregard CI unless it were at least 10% of C_o; that is,

$$\frac{CI}{C_o} = .1$$

or since

$$C_o = 1$$

$$C = \frac{.1}{I}$$

Let us suppose that I=20% per annum (=2.3 X 10^{-5} per hour); then the product of C times I be disregarded unless C is on the order of 4400 C_o dollars per ton. These simplifying assumptions are made in Figures III-3 and 4 which indicate the basic dependence of transportation cost on vehicle speed and the existence of optimum speeds. Figures III-5, 6 and 7 incorporate the CI product and indicate optimum speed and cargo value combinations for the indicated operating costs.

Table III-1 indicates current (November, 1974) cargo values of selected, critical raw materials.

Figure III-3

Transportation Cost Versus Speed
(Area Lift Vehicles)

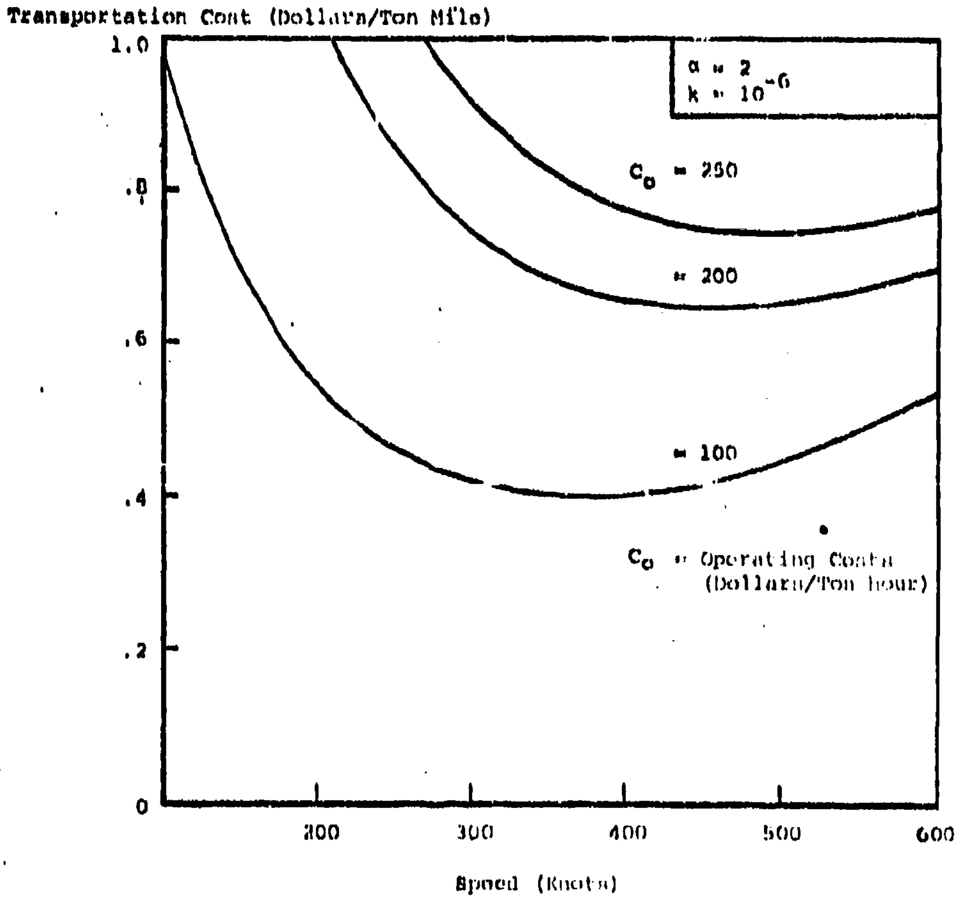


Figure III-3

Transportation cost versus speed of transit as a function of operating cost, and fixed fuel consumption proportional to the square of the transit speed.

Purpose:

This graph shows the relationship between transportation cost and speed of transit for a single area lift platform making one transit.

Basis for the Calculation:

This graph is an approximate plot of Equation A-10 assuming the CI product is small enough to be ignored. A fuel consumption proportional to the square of the transit speed was assumed. This relationship is valid in the speed range of this graph, which might typically display the transportation costs for flying platforms.

The selected operating costs (C_o) represent the various modes of transport. For example: A cost of $100/ton-hour may correspond to a medium size propeller aircraft and $250/ton-hour may correspond to a large jet aircraft.

Principal Points:

1. For a given operating cost, there is an optimum speed of transit which minimizes the transportation cost.

2. The optimum speed of transit and the corresponding minimum transportation cost increases with increasing operating cost.

3. Some specific examples are: A transit speed of 366 knots is optimum for an operating cost of $100/ton-hour. The minimum transportation cost which occurs at this speed is $0.403/ton mile. For an operating cost of $250/ton-hour the optimum speed of transit is 500 knots and the minimum transportation cost is $0.75/ton-mile.

Figure III-4

Transportation Cost Versus Speed
(Displacement Vehicles)

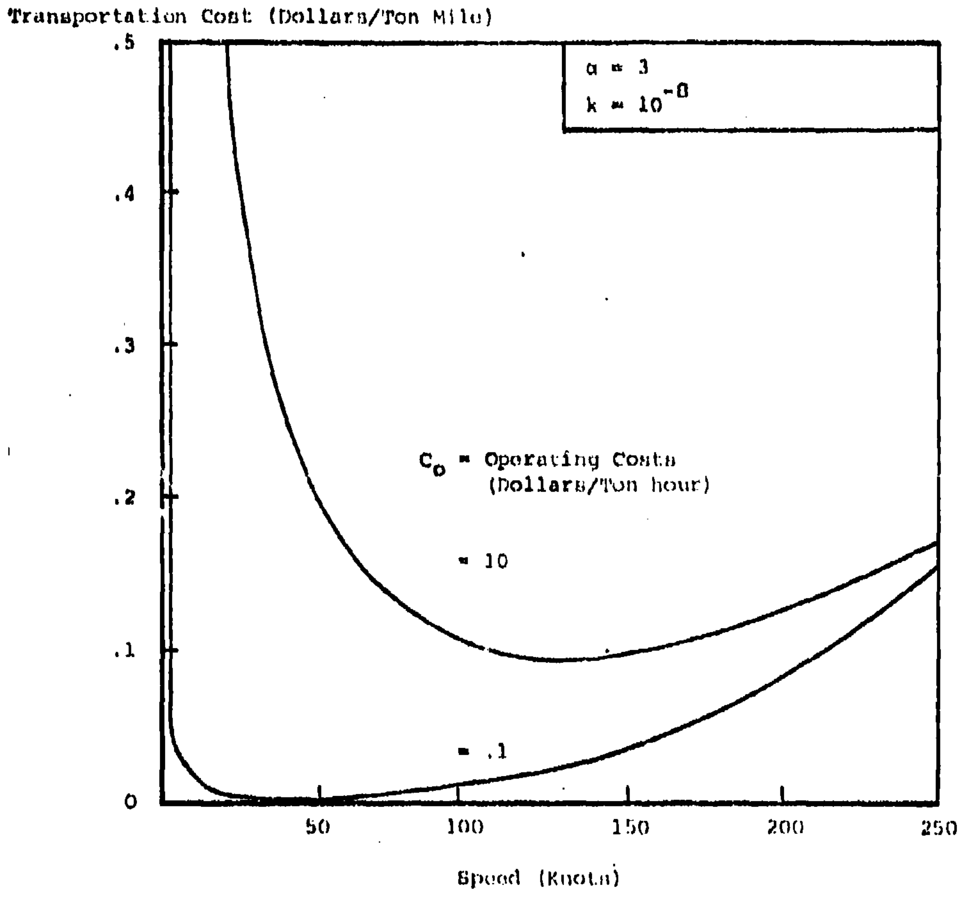


Figure III-4

Transportation Cost Versus Speed (Displacement Vehicles)

Purpose:

This graph shows the relationship between transportation cost and speed of transit for a single displacement platform (α=3) making one transit.

Basis for the Calculation:

The basis of this graph is similar to Figure III-3, except that in this graph a fuel consumption proportional to the cube of the transit speed is assumed. This relationship might typically display the transportation costs associated with volume lift (displacement) platforms.

The selected operating costs are representative of various existing modes of transport. For example: a cost of $0.1/ton-hour may correspond to a large cargo ship and $10/ton-hour may correspond to a smaller high speed surface platform.

Principal Points:

1. For a given operating cost, there is an optimum speed which minimizes the transportation cost.

2. The optimum speed of transit increases with operating cost and has a corresponding increase in transportation cost.

3. Some specific examples are:

For an operating cost of $0.1/ton-hour the optimum speed of transit is 42 knots and the minimum transportation cost is $.002/ton-mile.

For an operating cost of $10/ton-hour the optimum speed of transit is 164 knots and the minimum transportation cost is $.104/ton-mile.

Figure III-5

Cargo Value Versus Optimum Speed
(Moderate Speed, Displacement Vehicles)

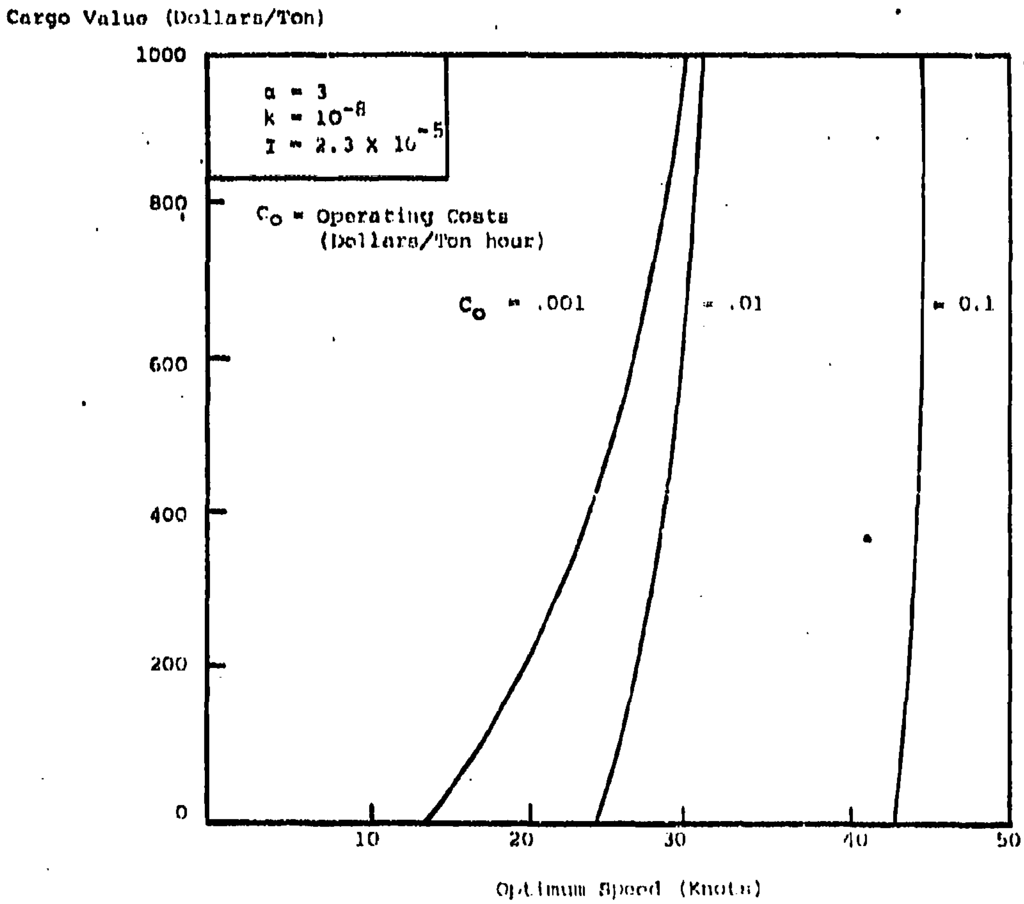


Figure III-5

Cargo Value Versus Optimum Speed
(Moderate Speed, Displacement Vehicles)

Purpose:

This graph shows the relationship between low to medium value cargo and the optimum speed of transporting the goods for representative operating costs of moderate speed displacement vehicles (n=3).

Basis for the Calculation:

The transportation cost equation (Equation A-10) was differentiated with respect to speed to determine the optimum speed of transit.

In this graph a fuel consumption proportional to the cube of the transit speed was assumed. This relationship is compatible with volume lift (displacement) platforms.

Operating costs of \$.001 to \$.1/ton-hour were chosen, and might typically represent surface transport ranging from low speed tug-in-tow to conventional cargo ships.

A fixed investment rate of 20%/year, which is equal to 2.3×10^{-5}%/hour, was chosen.

Principal Points:

1. For low operating costs (\$.001/ton-hour) the optimum speed of transit shows definite sensitivity to cargo value.

2. For typical operating costs of conventional cargo ships, the optimum speed of transit is relatively insensitive to cargo values over the indicated range.

3. This graph illustrates that the optimum speed of transit is directly related to cargo value in certain well-defined regions., i.e., cargo values in the low to medium range influence the optimum speed of platforms with very low operating cost.

Figure III-6

Cargo Value Versus Optimum Speed
for Various Operating Costs (Displacement Vehicles)

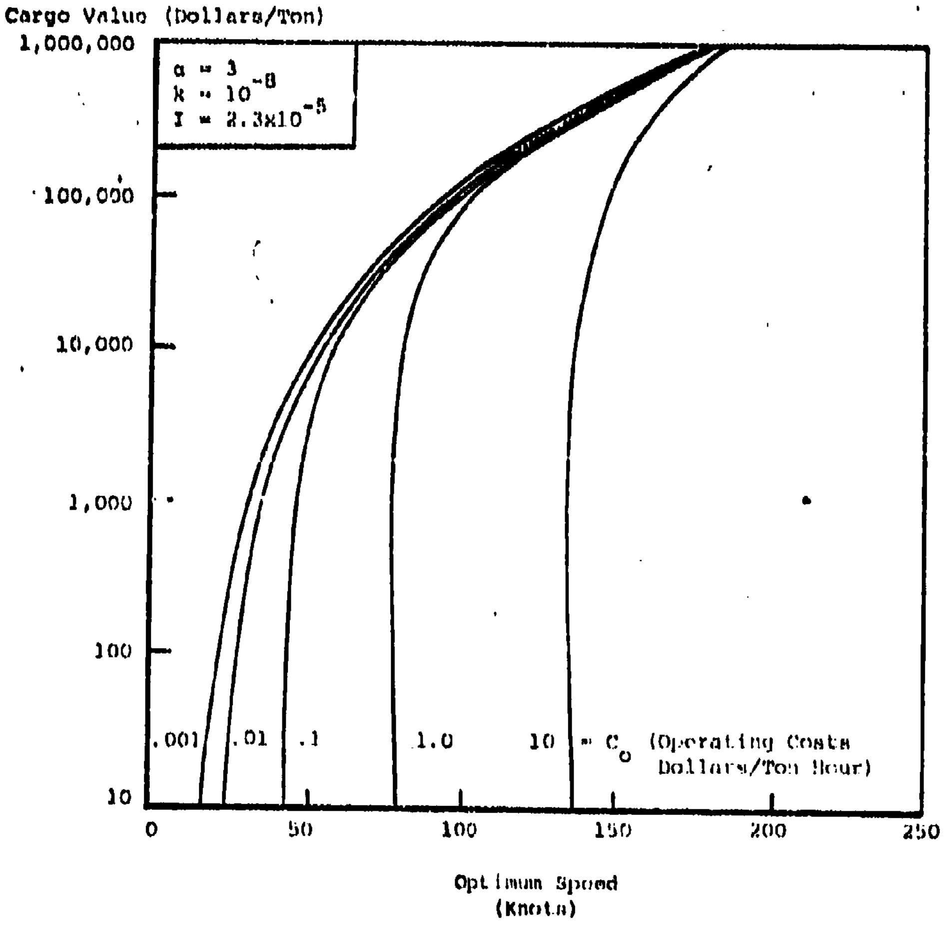


Figure III-6

Cargo Value Versus Optimum Speed for Various Operating Costs (Displacement Vehicles).

Purpose:

This graph shows (for displacement vehicles) the relationship between cargo values and the optimum speed of transporting the goods.

Basis for the Calculation:

The figure is a plot of Equation A-11 for displacement vehicles for a range of values of C_o.

This transportation cost equation was differentiated with respect to speed to determine the optimum speed of transit.

In this graph a fuel consumption proportional to the cube of the transit speed was assumed ($\alpha = 3$). This relationship is compatible with displacement (i.e., volume lift) vehicles.

A fixed investment rate of 20%/year was chosen. This is equal to 2.3×10^{-5}%/hour.

Principal Points:

1. Optimum transit speed is sensitive to discrete combinations of fixed operating costs and cargo values. Projected speed capabilities and operating costs of vehicles identify preferred transit missions (in terms of cargo values) for such vehicles.

2. A limiting speed of about 50 knots for displacement ships and typical operating costs of \$0.1/ton-hour, make them appropriate for cargo values up to the \$1,000-3,000/ton range.

3. If lighter than air (LTA) vehicles can achieve C_os of about \$1.0 to \$10/ton hour and speeds up to about 150 knots, they may be appropriate for cargo values up to about \$100,000/ton.

Figure III-?

Cargo Value Versus Optimum Speed
for Various Operating Costs (Area Lift Vehicles)

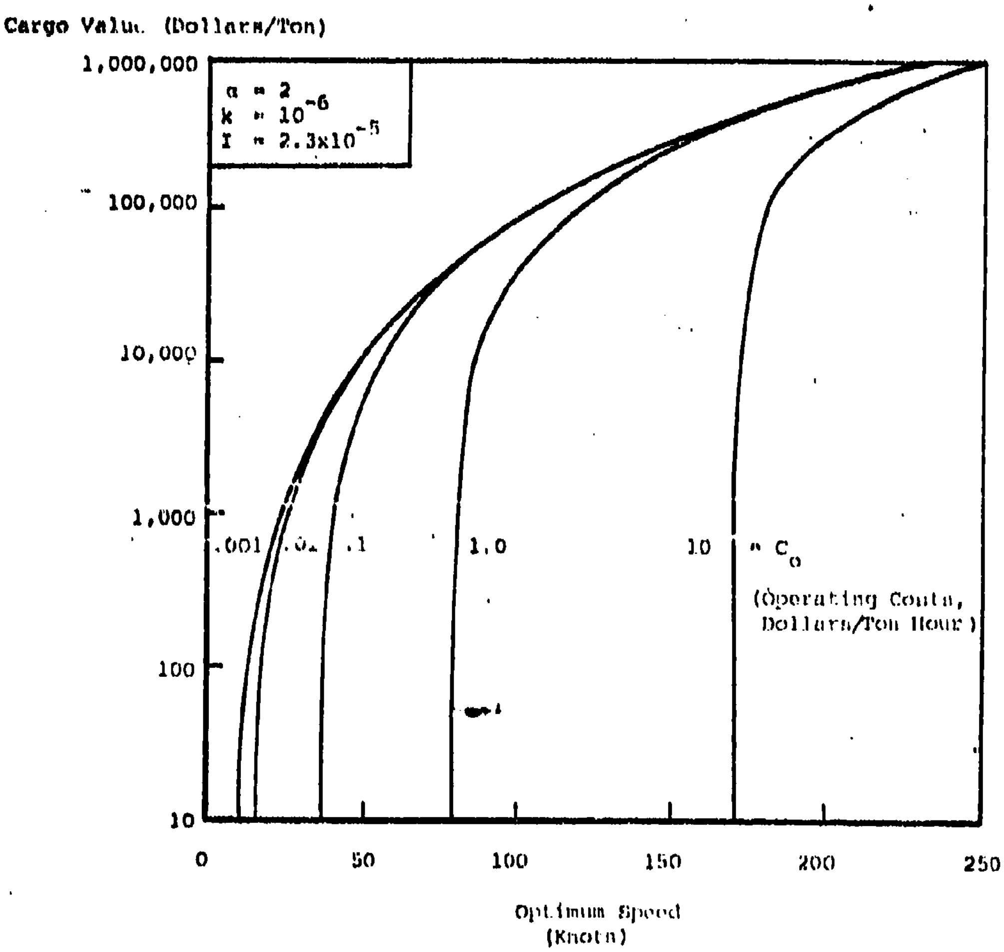


Figure III-7

Cargo Value Versus Optimum Speed for Various Operating Costs (Area Lift Vehicles).

Purpose:

This graph shows for area lift vehicles ($\alpha=2$) the relationship between cargo values and the optimum speed of transporting the goods.

Basis for the Calculation:

The figure is a plot of Equation A-11 for the indicated values of C_o. The curves are drawn for area lift vehicles ($c = 2$ and $k = 10^{-6}$).

Principal Points:

1. An overlay of Figures III-6 and III-7 indicates a close match at a C_o of \$1/ton hour and speeds of about 75-100 knots.

2. At cargo values above about \$100,000, area lift vehicles are preferable (optimum speeds exceed 100 knots for all operating costs).

Table III-1

Critical Raw Materials

Low Value Material	Cost/Ton (Dollars)
Iron Ore	11
Potash	34
Bauxite	40
Manganese Ore	79
Zircon	85
Medium Value Material	
Tin	215
Zinc	305
Lead	372
Asbestos	428
Titanium	503
Antimony	744
High Value Material	
Copper	1,180
Nickel	2,852
Columbium Tantalium	3,286
Cobalt	3,480
Tungsten	7,300
Silver	38,870

Reference: US Life Line, Imports of Essential Materials and the Impact of Waterborne Commerce on the Nation, OPNAV-OPD-P1, November 1974.

D. SUSTAINED LOGISTIC SUPPORT

The sustained logistics support problem is basically a pipeline of goods linking a supply point and a demand point, wherein a large amount of the material being transported is en route. This analysis deals solely with the number of platforms in the pipeline and at the end points. Transportation to and from the end points is not considered.

The number of platforms required to fill the pipeline is given by the expression

$$n = \frac{2}{t}\left(\frac{D}{V} + \frac{Q_p}{r}\right)$$

where,

- t = time interval between platforms (hours)
- D = one-way transit distance (nm)
- V = speed of transit (nm/hour)
- Q_p = payload capacity of the platform (tons)
- r = load-unload rate (tons/hour)

The demand rate at the end point is contained in t by the following relation

$$t = \frac{TQ_p}{Q}$$

where,

- T = total time of the operation
- Q = total amount of goods required
- Q_p = payload capacity of each platform

The number of platforms required to fill a specific pipeline demand is seen to be determined by the payload capacity, the load-unload rate, and the speed of the vehicle. Where the number of platforms is a critical consideration, increased speed can be important in reducing requirements, particularly for pipelines over long distances.

There are other factors which can influence the effectiveness of transit speed. The value of some types of perishable goods may drop off sharply after some critical handling and transit time. Air transit systems can deliver directly to inland locations and avoid the additional handling and transit costs of sea surface transit.

The choice of the mode of transit of goods may be influenced by many factors. Some of the more obvious are:

- The value of the goods being transported.
- Costs of delays, damage or loss in transit.
- Critical time factors for certain goods under certain circumstances (such as food, medical supplies, electronics equipment).
- Cases where only one form of delivery is available (e.g., Berlin Air Lift).

The above may apply to the "ad hoc" transit to Destination Problem as well as to the Sustained Logistics (Pipeline) Problem.

From the point of view of the effectiveness of vehicle speed in a pipeline, the principal variable of interest is the number of platforms required to sustain a given rate of delivery. Table III-2 provides a basis for the following figures which address this problem.

Table III-2. Number of Platforms Required to Fill a Pipeline for Fixed Two-Way Transit Distance of 6,000 nm and Unloading Rate of 60 Tons/Hour

( ) = Conceptual or Planned

Nominal Speed Range (knots)	Type	Speed (knots)	Payload (tons)	Number Required
15-35	cargo ship	20	4,000	12
Displacement Ships	cargo ship	33	20,000	5
35-60 Hydrofoil	PGH	40	15	1,145
60-100	(SES)	(50)	(1,300)	14
SES	(ACV)	(50)	(700)	23
ACV	ACV	50	20	689
	Airship	67	60	174
	(ACV)	(70)	(70)	144
	(Airship)	(70)	(110)	93
100-200	(WIG)	(195)	(150)	27
WIG	(WIG)	(200)	(65)	56
LTA	(WIG)	(200)	(870)	8
200-600	(WIG)	(215)	(220)	18
Fixed Wing Aircraft	(WIG)	(230)	(320)	13
	C130	300	23	103
	C5A	500	70	23

Figure III-8

Fraction of Platforms Required When Compared to the Base Case to Fill A Pipeline for Various Velocity-Capacity Relationships

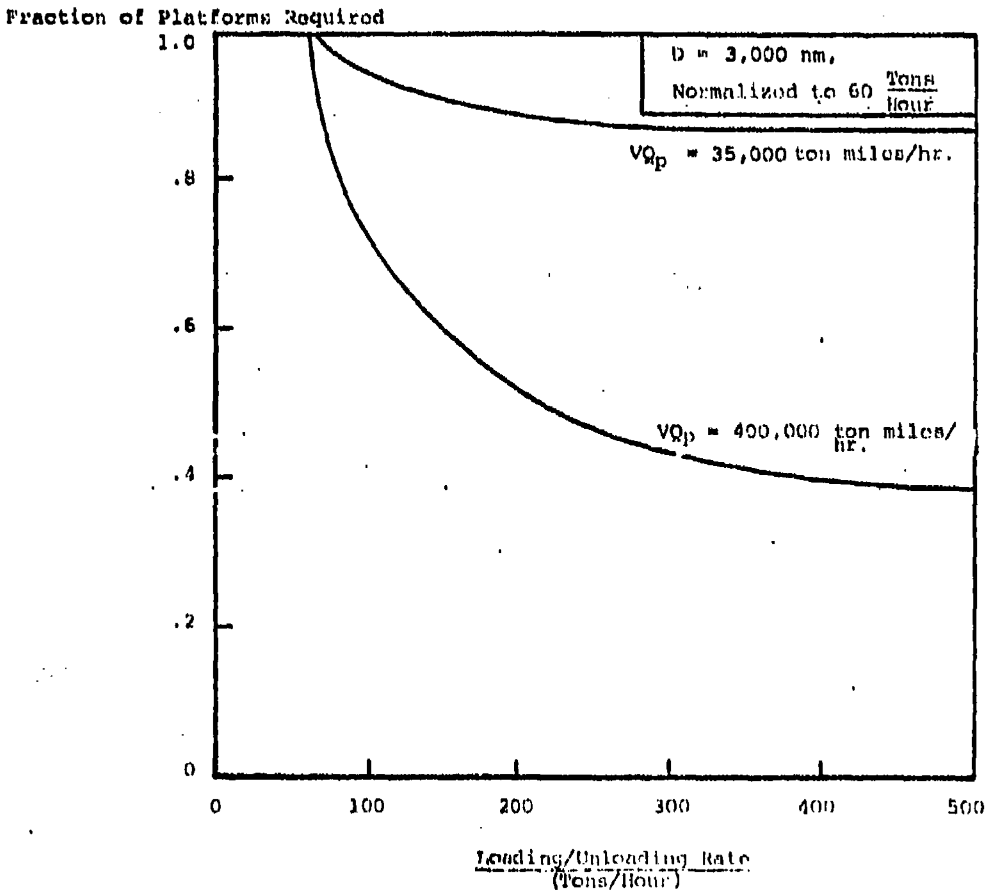


Figure III-8

Purpose

This graph shows the effect of unloading/loading rates on the fraction of platforms required (compared to the base case) to fill a pipeline for a given velocity-capacity product.

Basis of Calculations

For any loading/unloading rate, (r), the number of platforms (n) required to fill the pipeline is proportional to:

$$\frac{D}{VQp} + \frac{1}{r} \qquad \text{(text, page III-25)}$$

where, D = length of the pipeline (nm)

V = velocity of a platform (knots)

Qp = payload capacity of a platform (tons)

Selecting a nominal value of r (in this case = 60 tons/hr, which is about the rate for a C-5A aircraft) and normalizing n to a value of one for this rate, the relative number of platforms required for any rate r is:

$$\frac{\frac{D}{VQp} + \frac{1}{r}}{\frac{D}{VQp} + \frac{1}{60}}$$

The figure plots this ratio (fraction of platforms required) for values of r from 60 to 500 tons/hr. Curves are plotted for two platform speed capacity products:

- 35,000 ton miles/hr, which is typical of the C-5A (70 tons of cargo at 500 knots)

- 400,000 ton miles/hr, which approximates a standard merchant ship (20,000 tons of cargo at 20 knots)

Principal Points

1. The relative number of platforms for a fixed velocity-cargo capacity product decreases as the unloading/loading rate increases.

2. For each velocity-cargo capacity product, increasing the loading/unloading rate produces diminishing returns in reducing the required number of platforms.

E. SUMMARY AND CONCLUSIONS

The utility of speed in transit was investigated for three cases.

- Transit to station (base loss factor)
- Transit to destination
- Sustained logistics support

The analysis of transit to station made use of the base loss factor, which is generally defined as the number of platforms necessary to maintain one on station. The principal parameters in this case are: the two-way transit distance to station, transit speed, and the total endurance time.

It should be noted that this analysis focused on the impact of speed on the transit to and from station. The general base loss factor concept can be readily extended to include other parameters such as the impact of speed on time on station, maintenance time, training time, and time to overhaul.

The principal points in the transit to station are:

- Increasing speed of transit can reduce the base loss factor (BLF). Sharply diminishing returns set in at BLFs below about 1.5.
- The important consideration is the effect of increasing transit speed (V) the total endurance time (T). Thus, the VT product is the important measure.

The investigation of the transit to destination (economics of transportation) illuminates the utility of speed through the associated value of time in transit. The time dependent factors are: the hourly operating costs of the platform and the inventory value of the goods while in transit. These time dependent costs increase with time and, hence, are reduced by higher transit speeds. However, higher transit speeds increase costs due to propulsion and energy considerations. The fundamental trade-off, then, is between the time dependent costs and the energy costs.

The principal points in the economics of transportation are:

- An optimum vehicle for transporting cargo of a given value can be defined by a combination of the time dependent costs of operating the vehicle (per ton of cargo capacity) and the vehicle speed.
- In general, for a given time dependent operating cost, the optimum transit speed is insensitive to cargo value up to a critical value. Above this value, optimum transit speed increases monotonically with cargo value. These critical cargo values increase with increasing time dependent operating costs.
- Transit of military cargo involves military worth which can far exceed simple dollar values and which may be highly time dependent. The analysis provides a basic framework but subjective judgments are necessary.

The third case of the utility of speed in transit investigated a sustained logistics support operation. This operation was considered as a pipeline of goods, wherein a large amount of the material being transported is en route. In this case, the principal measure of effectiveness is the number of platforms required and the critical parameters are: the transit speed, the payload capacity of the platform, and the load-unload rates.

The principal point in the sustained logistics support operation is that:

- The number of platforms required to sustain the operation is strongly dependent on the speed-payload product of a platform and the loading/

unloading rates. For each speed-payload product, the required number of platforms is reduced by increasing the loading/unloading rate. However, there are rates beyond which, diminishing returns are evident. For example, for a speed payload product of 35,000, the number of platforms required at an unloading rate of 200 tons/hour is 13% less than at the nominal 60 tons/hour. At higher rates there is no further appreciable gain. For a speed payload product of 400,000 the number of platforms required is 60% fewer at a rate of 400 tons/hour and continues to show slight gains at even higher rates.

SECTION IV. CONVOY OPERATIONS

A. INTRODUCTION

The purpose of this chapter is to determine the relationship between the more important variables in convoy operations and the ratios of speeds of the various forces which are involved in convoy operations. To focus on the speed of forces involved, some simplifications have been made which will be described where applicable.

Studies over the last ten to fifteen years which have examined the problem of convoy operations have generally limited the convoy units to present and near term ship propulsion technology such that only small ranges of variations in speeds of convoy ships have been considered. This has also generally resulted in essentially fixed relationships among convoy speeds, attacker speeds and attacker weapon speeds. Thus, the studies have been characterized by complex computer simulations to determine, usually over an entire campaign of several months, the effects of varying other parameters, such as number and spacing of ships in the convoy, number of attackers, kinds of weapons and sensors, etc. In the studies reviewed (e.g., SEAMIX I and II) the attacker (the enemy) was characterized by a submarine armed with torpedoes. In those studies it has been assumed that the use of missiles is not warranted against convoy ships. Thus, all of the pertinent speed variables have been confined to very small ranges of variation and the utility of higher speeds is not readily discernible. These assumptions will have to be changed in future large scale examinations of convoy operations.

This chapter draws on the more basic classic analysis of the convoy operations problem. We consider convoy ships, escorts and attackers. The attackers are generally thought of as enemy submarines and, therefore, one may think in terms of a maximum of a few tens of knots with respect to attacker speeds. The methodology, however, is general enough to extend to attackers which are enemy advanced naval vehicles. Ratios of convoy ship speed to attacker speed of 0 to 5 are considered and "micro-tactics" are not considered. For example, the analysis only keeps track of the convoy "center"; distances, times and track angles are measured from this point rather than, for example, the convoy ships nearest the attacker.

The objective of the enemy attacker in every case of the analysis is to detect, approach, attack and sink convoy ships (i.e., the convoy center). The primary parameters associated with the attacker are the detection range, the approach speed, and the weapon speed and weapon range. The actual kill by the attacker, which depends on overall weapon effectiveness, is not relevant to the focus of the study.

The principal parameter of the convoy is its speed. The speed is used to reduce threat arcs and threat areas. The option of rerouting and evasion is implicit for some combinations of convoy speeds and other key parameters. This is indicated, but not quantitatively treated. The convoy speed range at which independent sailing becomes an alternative is qualitatively treated in the final subsection (after the necessary investigations of interactions among convoy speed, escort speed, and attacker speed).

The objective of the escort in protecting the convoy is detection and counter-attack of the attacker at a range sufficient to prosecute an attack against the attacker before he can effectively launch his weapons. The principal escort parameters considered in the analysis are speed, sprint speed and relative force levels as a function of convoy speeds and attacker speeds, and other attacker capabilities (weapon speed and weapon range).

Past studies have often concluded that a convoy which could travel at about 15 knots above the maximum speed of an enemy submarine would be relatively invulnerable to attack by submarines. This conclusion is a direct result of the fact that the speed of the submarine weapon (torpedo) has been of the same order as the (fast) convoy speed, and the fact that the detection range of the convoy by the submarine is of the same order as the maximum torpedo run. The higher speed of missiles, particularly when used in connection with external data from aircraft, satellite or other surveillance, renders this conclusion invalid.

The analysis of this chapter deals with three interactions:

- Attacker against convoy ship
- Escort against an attacker.
- Escort speed (sprint and drift) requirements generated by high convoy speeds

These results are then collected for brief discussions of the influence of the various speed ratios on how one might employ high speed escort type ships and on the question of convoys versus independent sailings. The appropriate equations and derivations are collected in the Appendix (Sect. B), but are not needed to understand the results of the analysis, which are displayed in graphical form.

B. CONVOY SPEED

The concept of operations envisages a convoy steering a steady course at a constant speed and the analysis begins with detection of the convoy (i.e., the convoy center) by the enemy attacker. Convoy speed is treated in two general categories: convoy speed greater than attacker speed and convoy speed less than attacker speed.

Case I. Convoy Speed Greater than Attacker Speed

We define an area of threat to the convoy (convoy threat area) as that instantaneous area from which an attacker with the requisite combination of detection range, attacker speed, weapon speed and weapon range can detect and subsequently attack the center of the convoy. Using this area of threat as the significant parameter facilitates the subsequent development of other measures (such as screen length, number of escorts required) as a function of the relative speeds required.

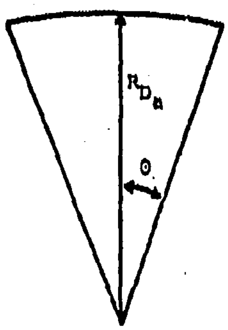
For a given range at which the attacker can detect the convoy, the maximum size and the shape of this area will vary with the realtionships among the achievable values of the various parameters. This is illustrated in Figure IV-1 for the three subcases indicated. In all cases the convoy proceeds at its best speed (to minimize the possible threat area) and the boundaries of the areas represent the resultant maximum limits of the threat area which the attacker can generate with his maximum speed, weapon speed, and weapon range combined with optimal approach tactics.

In case Ia it is assumed that the maximum speed of the attacker's weapon is equal to his maximum speed (alternatively, the weapon has zero range and the attacker must intersect the convoy center). Thus, the only important parameters are the convoy speed (V_C) to attacker speed (V_A) ratio and the "track angle" of the convoy. That is, the angle measured between the projected course of the

Figure IV-1

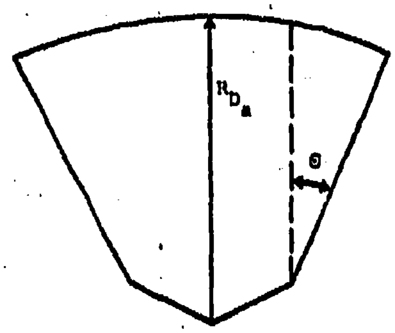
Area of Threat to a Convoy for a Given Attacker Detection Range as a Function of the Convoy/Attacker Speed Ratio, the Convoy/Attacker Weapon Speed Ratio, and the Attacker Weapon Range

<u>Case I</u> $V_C > V_A$



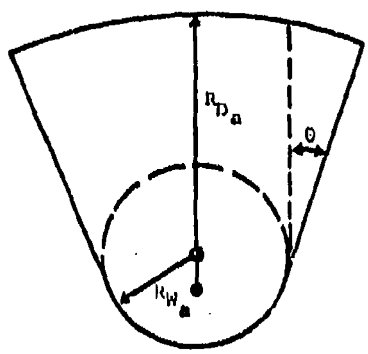
<u>Case Ia</u>

$V_{W_a} = V_A$ (or $R_{W_a} = 0$)



<u>Case Ib</u>

$V_C > V_{W_a} > V_A$



<u>Case Ic</u>

$V_{W_a} > V_C > V_A$

Where: R_{D_a} = Detection Range of Attacker

R_{W_a} = Weapon Range of Attacker

V_C = Speed of Convoy

V_A = Speed of Attacker

V_{W_a} = Speed of Attacker's Weapon

convoy and the relative bearing of the attacker from the convoy center (this angle is sometimes called "target angle" or "angle-on-the-bow" and is measured up to 180° right or left of the convoy's projected course). In the figure, the specific angle θ indicates (for a given V_C/V_A ratio) the maximum value of this angle which can result in an intercept. The line which intersects the projected course of the convoy at the convoy center to form the angle θ is the limiting line of approach of the attacker for an intercept. Thus, the area is completely determined by specifying an R_{D_a} and either a V_C/V_A ratio or the resultant angle, $\theta = \sin^{-1} (\frac{V_A}{V_C})$.

The resultant Convoy Threat Area is plotted in Figure IV-2 as a function of V_C/V_A ratios of 1 to 5.

The area is normalized to a circular threat area whose radius is the detection range of the attacker.

It should be noted that throughout this discussion the convoy threat area is an area of potential threat to the convoy. The area exists whether or not the convoy has knowledge of an attacker's presence in the area. Note that, given such knowledge, the higher the convoy to attacker speed ratio the more likely that the convoy will be able to successfully evade the attacker.

The specific geometry of the Convoy Threat Areas in Cases Ib and Ic in Figure IV-1 results from maintaining the same range at which the attacker can detect the convoy (R_{D_a}) and the same V_C/V_A ratio (thus the same θ).

Case Ia is where the range of the attacker's weapon is zero, and the attacker must intercept the convoy; Ib is the intermediate case where the value of V_{W_a} lies between that of V_C and V_A and thus the resultant convoy threat area lies between that of Case Ia and Ic. Case Ic is where the speed of the attacker's weapon is greater than the speed of the convoy and greater than the attacker's speed, i.e., $V_{W_a} > V_C > V_A$.

In Case Ic, the instantaneous area is the sum of the threat area relative to the convoy center generated by a weapon with a given range and weapon to convoy speed ratio (represented by the offset circle of radius R_{W_a} and the projection of its diameter along the convoy's projected track out to the detection range arc) and the original attackers convoy threat area from Case Ia.*

The resultant areas as a function of V_C/V_A ration (from 1 to 5) are plotted in Figure IV-3 for selected ratios of the attacker's weapon range R_{W_a} to the detection range R_{D_a}. The example illustrates a case where $V_{W_a}/V_A = 6$ (thus, $V_{W_a} > V_C$ across the entire plot). Again, the convoy threat area is normalized to a value of one for a threat area that is a circle of radius R_{D_a}.

Note that, as expected, a V_{W_a}/V_C ratio greater than one generates larger threat areas for any attacker weapon range greater than zero and that increasing the weapon range to values of the same order as the detection range dramatically increases this area. In this era of submarine and surface ship launched SSM threats, this region is probably the more realistic one in which to investigate the utility of speed for a convoy.

Case II. Attacker Speed Greater than Convoy Speed

This case is of current interest in that it probably best represents the current convoy and threat situation.** The precise geometry of the convoy threat

*The area is developed by sequential application of the relative motion between the weapons and the convoy, over the distance the weapon can travel, and the original attacker to convoy relative motion. Calculations shown in the Appendix.

**With, of course, modifications induced by limits on attacker's speed by other factors, such as detection of a submarine attacker's radiated noise by escorts or surveillance systems.

area is, again, dependent on the relationships among all of the pertinent parameters. However, in a practical sense in any situation where the convoy has a long distance to travel to its destination and the attacker has more than a marginal speed advantage, the attacker, having detected the convoy, can overtake it. Further, the attacker, given enough weapon speed and weapon range, can launch the weapon from some distance astern (as in case Ic where $V_{W_a} > V_C$). Thus, his required distance to close can be very small. In a practical sense, the threat area can be considered to be a circle of radius R_D with its center on the convoy center.* Note that this is the maximum threat area which can be generated, except in the case of external intelligence and larger attacker weapon ranges. In this case, the convoy threat area is a circle whose radius is the weapon range.

An important consideration derived from the effects of convoy, attacker and attacker weapon speeds on the size and shape of instantaneous threat areas is that of the implications of convoy escort requirements.

Escort requirements for a convoy can be viewed as fulfilled by the product of the capabilities of each escort times the number of escorts. Required escort capabilities as a function of speed ratios are discussed in the next section. However, the required number of escorts of a <u>given capability</u> is a function of the basic V_C/V_A ratio. This is indicated by the geometry in Figure IV-1.

The maximum requirement exists in Case II where $V_A > V_C$ and threats can be located anywhere on the perimeter of the circle. In Case I escort protection

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*The actual area is the area <u>common</u> to the R_D circle about the convoy center and the area from which an attacker astern could close to the offset weapon range circle (as in Ic) in the time available (before the convoy completes its transit or before the weapon reaches its extreme range).

is required only across an arc between the limiting lines of approach.*

This is illustrated in Figure IV-4 which indicates that relative number of escorts required as a function of V_C/V_A. The plot is normalized to a value of 1.0 for Case II where the full perimeter of the circle must be covered. Note the discontinuity near $V_C = V_A$, which is due to the shift from a full circle to a semicircle as V_C becomes greater than V_A. Note also the increase in requirements when $R_{W_a} > 0$ and $V_{W_a} > V_A$ (as in Cases Ib and Ic).

* The required radius of the escort arc is a function of escort to attacker speed ratios and the other parameters (i.e., escort quality).

Figure IV-2

Normalized Threat Area Versus
Convoy to Attacker Speed Ratio

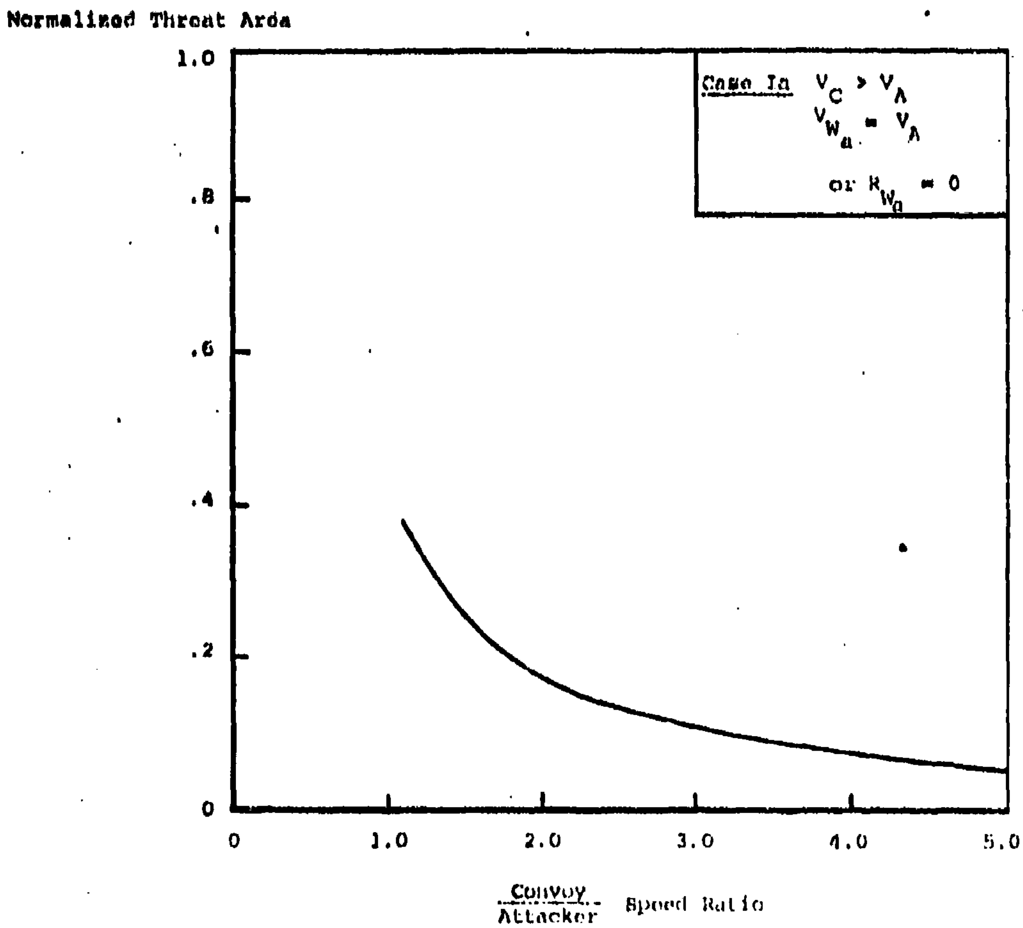


Figure IV-2

Normalized Threat Area Versus Convoy to Attacker Speed Ratio.

__Purpose__

This figure shows the relationship between normalized threat area and convoy to attacker speed ratio for the case when the attacker weapon range is zero, or equivalently, when the weapon speed is equal to the attacker speed.

__Basis for Calculation__

This graph is a plot of equation B-4.

The threat area at an instant of time is a function of convoy speed, attacker speed, attacker radius of detection, and attacker weapon range. The threat area represents the area from which an attacker can close the convoy. When the weapon range is zero, the attacker must intercept the convoy.

The threat area is normalized to the case of a circle centered at the convoy center and radius equal to the attacker's radius of detection.

In the figure:

V_C = convoy speed

V_A = attacker's speed

V_{W_a} = attacker's weapon speed

R_{W_a} = range of attacker's weapon

Principal Points

1. For a given attacker speed and radius of detection, the threat area decreases with increasing convoy speed.

2. If the convoy has external information on potential threats, the convoy can maneuver to achieve the least potential threat.

3. Increasing the convoy to attacker speed ratio from 1.1 to three reduces the normalized threat area from about .35 to about .10. Further increasing the speed ratio from three to five results in a much smaller reduction (.10 to .05).

Figure IV-3

Normalized Threat Area as a Function of Convoy to Attacker Speed Ratio and Attacker Weapon Range

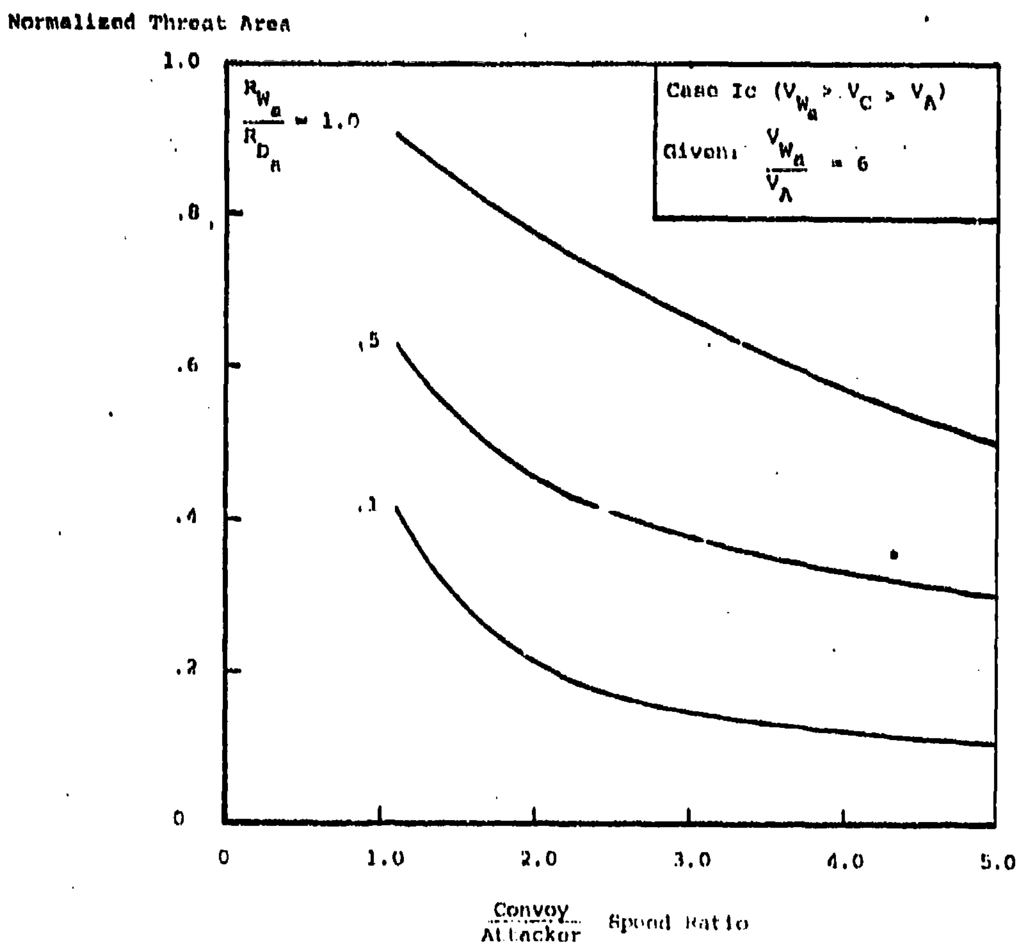


Figure IV-3

Normalized Threat Area as a Function of Convoy to Attacker Speed Ratio and Attacker Weapon Range

Purpose

This figure shows the relationship between normalized threat area and attacker weapon range when the attacker's weapon speed is greater than the convoy speed and convoy speed is greater than attacker speed (i.e., $V_{W_a} > V_C > V_A$).

Basis for Calculation

This graph is a plot of equation B-9a.

In this figure the threat area is a function of convoy speed, attacker speed, attacker detection range and attacker weapon range.

In the figure:

V_{W_a} = attacker's weapon speed

V_A = attacker's speed

Principal Points

1. For a given attacker weapon speed and weapon range, the convoy can reduce the threat area by increasing the convoy to attacker speed ratio.

2. As the attacker's weapon range is increased, the convoy must achieve higher convoy to attacker speed ratios to reduce the threat area.

3. The severe problem presented to modern convoy operations against high speed weapons is depicted by this figure. Let us suppose that a convoy had, to begin with, a speed advantage of two to one (a

difficult feat in itself) and the ratio of weapon range to detection range of the attacker is one-half, with a resultant normalized threat area of about .48. A doubling of the attacker's weapon range would necessitate an increase in the convoy speed advantage to about 5 to 1 to maintain the same threat area. More generally, it appears that the attacker has a higher leverage in creating threat area by increasing weapon range than the convoy has in reducing threat area by increasing speed.

Figure IV-4

Normalized Number of Escorts Required Versus Convoy to Attacker Speed Ratio

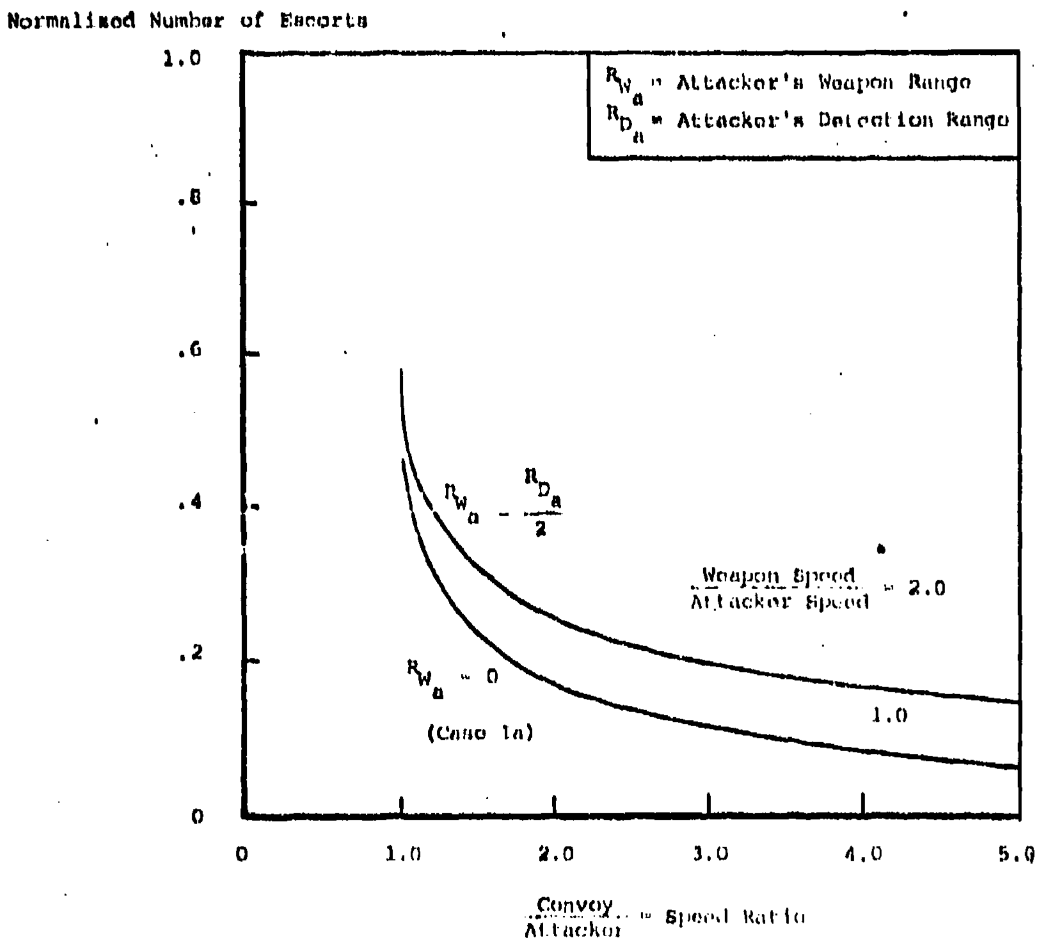


Figure IV-4

Normalized Number of Escorts Required Versus Convoy to Attacker Speed Ratio

Purpose

This figure shows escort requirements as a function of convoy to attacker speed ratios greater than one for:

- Case Ia where the attacker weapon speed is equal to the attacker speed ($V_{W_a} = V_A$) or attacker's weapon range (R_{W_a}) is zero.
- The specific case where $V_{W_a} = 2V_A$ and $R_{W_a} = \frac{R_{D_a}}{2}$.

Basis for Calculation

The specific number of escorts required depends on the required radius of the escort coverage arc from the convoy center. This is a function of the relative capabilities of the escort and the attacker (Subsection C).

The normalized number of escorts (of any given capability against a given attacker) is the ratio of the required angular coverage to that in Case II, where the attacker's speed exceeds the convoy speed and full circular coverage is required.

Principal Points

1. At very small convoy speed advantages the threat arc (and the resulting normalized escort requirement) is very sensitive to the speed ratio and insensitive to the attacker's weapon parameters.

2. Increasing the convoy to attacker speed ratio decreases escort require-

ments. At ratios of about 3:1 the marginal returns from further increasing convoy speed are small.

3. The attacker can counter the convoy's speed advantage (and increase escort requirements for a given speed ratio) by increasing his weapon range and weapon speed.

4. Case II, $\frac{V_C}{V_A} < 1$, is not illustrated, since the normalized threat arc in this case is unity providing the attacker can close from the rear before the convoy can complete its transit.

C. ESCORT SPEED REQUIREMENTS

There are two important escort speed ratios: escort speed to attacker speed (V_E/V_A) and escort speed to convoy speed (V_E/V_C). The first is required to insure timely closing and counterattacking a detected threat (before he can launch his weapons). The second is to insure maintaining this detection capability over the assigned area relative to the convoy.*

1. Escort to Attacker Speed Ratio

The base case for escort requirements is taken from Case II ($V_A > V_C$) where the entire perimeter of the threat circle must be covered by the escorts. There are values for the area of the threat circle wherein evasion by the convoy is not an option; these values are determined by the attacker's weapon range and detection range.

The purpose of the escort is to detect the threat, close and consummate an attack before the attacker can launch his weapon. Thus, the parameters for escort quality are the V_E/V_A ratio, and the maximum range of the escort's weapon.

Figure VI-5 plots the number of escorts required as a function of V_E/V_A for the indicated ratios of the escort weapon range and detection distance. The figure determines the escort requirements to counter the attacker before he comes within weapon range to the convoy center.

For an intercept to take place, the detection distance must be greater than the attacker's weapon range. The distance over which intercept can occur is the difference between the detection distance and the attacker's weapon range. Hence, increasing the detection distance gives the escort more distance (and time) to intercept the attacker.

*Note that when $V_E > V_A$, and the geometry is otherwise favorable, a timely escort detection of a threat can be followed by successful convoy evasion of the threat.

2. Escort Sprint Speed Requirements

The purpose of the escort is to close and consummate an attack before the attacker can launch his weapons. The attacker could be detected by either the escort or some other system, in which case the escort acts as a pouncer who is vectored to the datum by the searching system once a contact has been established, and consummates the attack. In this case, the escort may use sprint speed to provide timely prosecution against attackers around a convoy.

An escort using continuous acoustic search to sanitize an area around the convoy is limited to slow search speeds. Hence, in order to escort convoys with a speed of advance greater than about 15-20 knots, the escort must use sprint-drift tactics (defined and discussed in Section II, pp II-14-16).

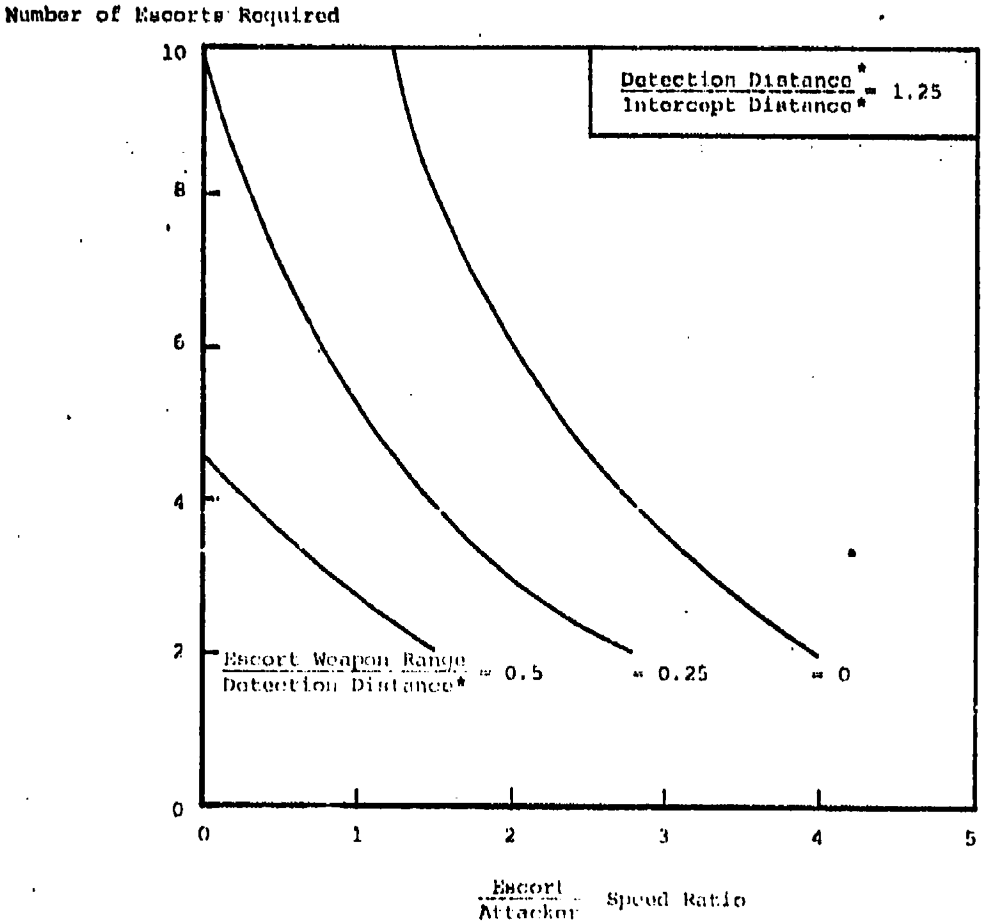
To provide the desired acoustic coverage around the threat area, the escort must maintain a speed of advance equal to or greater than the convoy speed of advance. The escort's speed of advance capability is determined by the combination of his sprint speed and his virtual speed. Virtual speed is the ratio of detection range while drifting (which is a determinant of the sprint distance) and the drift time required for each search period. Thus, to maintain the required speed of advance (equal to the convoy speed) the escort must achieve the proper combin tion of sprint speed and virtual speed.

Figure IV-6 indicates required escort sprint speeds as a function of convoy speeds for selected virtual speeds. The accompanying information sheet discusses the advantage (in reduced escort sprint speed requirements) of a tactic which employs two leap-frogging sprint-drift escorts for each escort station.

In addition to the implied trade-off of escort sprint speeds with escort force levels, it should be noted that the leap-frogging tactic may provide a means to overcome technological barriers (combinations of limiting sprint speeds, maximum detection ranges and minimum drift times) preventing sprint-drift escort protection of very high speed convoys.

Figure IV-5

Number of Escorts Required to Provide Timely Prosecution Around the Entire Circumference of a Threat Circle Versus Escort to Attacker Speed Ratio



* Measured from the center of the convoy.

Figure IV-5

Number of Escorts Required to Provide Timely Prosecution Around the Entire Circumference of a Threat Circle Versus Escort to Attacker Speed Ratio.

Purpose

The purpose of this graph is to show the number of escorts required to provide timely prosecution around the entire circumference of a threat circle as defined in Case II, versus escort to attacker speed ratio for various detection distances and weapon ranges.

Basis for the Calculation

This graph is a plot of equation B-15.

This is a case to illuminate the escort versus attacker problem. In this case, the speed of the convoy is much less than the attacker's speed, hence, maneuvering by the convoy to avoid attack is not considered.

In this calculation, the attacker detects the convoy and approaches toward the center of the convoy with constant course and speed (V_A). The attacker is detected at a detection distance (R_{D_c}) from the convoy and R_{D_c} is greater than the attacker's weapon range. The detection could be made by the escort or other systems (such as satellites) in which case the escorts act as pouncers. The time the escort has to intercept the attacker is

$$t = \frac{R_{D_c} - R_I}{V_A}$$

where R_I is some distance greater than the attacker's weapon range measured from the center of the convoy.

The sector angle which can be covered by a single escort is a function of: escort speed, time (t), and escort weapon range. The number of escorts required is determined from the sector coverage of a single escort.

Principal Points

1. For a given detection to intercept distance ratio, the number of escorts required can be reduced by either increasing the escort to attacker speed ratio, or by increasing the escort's weapon range. For example, the number of escorts required in the case where the escort to attacker speed ratio is unity and the escort weapon range is .25 times the convoy force detection range is about 5.2. Increasing the escort to attacker speed ratio to 2.1 reduces the requirement to about 2.8 escorts. The same reduction can be achieved by doubling the escort weapon range.

Figure IV-6

Escort Sprint Speed Required for a Given Virtual Speed as a Function of the Convoy Speed of Advance

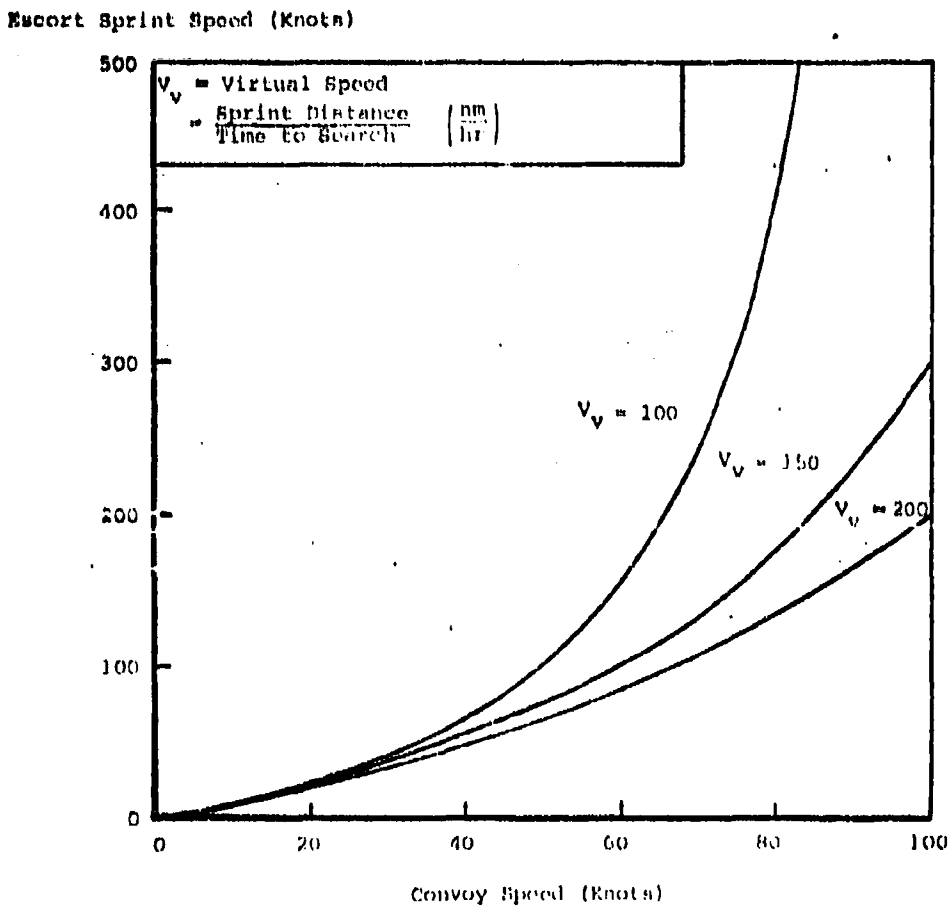


Figure IV-6

Escort Sprint Speed Required for a Given Virtual Speed as a Function of the Convoy Speed of Advance.

__Purpose__

The purpose of this graph is to show the escort sprint speed and virtual speed (V_v) required to escort a convoy with a given speed of advance.

__Basis for Calculation__

This graph is a plot of equation B-20.

The escort must maintain a speed of advance equal to or greater than the convoy speed of advance.

The escort's speed of advance capability is determined by his sprint speed and the percentage of the time he spends drifting. The percentage of time drifting (i.e., searching) is determined by the required time for each search (t_d). The frequency of search is governed by his sprint distance, which is a dependent function of the detection range (R_{D_e}).

Virtual speed is defined as sprint distance divided by time to search. Sprint distance is the distance between listening periods. In the case of a single escort for the assumed search coverage (see Appendix, Section B), sprint distance equals the detection range.

The minimum escort sprint speed requirement is determined by the escort's required overall speed of advance (convoy speed) and the best achievable trade-off of increasing the sensors' detection range (R_{D_e}) or the number of escorts assigned to each sprint-drift coverage area or by decreasing the drift time required to complete a search.

Principle Points

1. The virtual speed of the escort has the dimensions of velocity and represents the limiting value of the convoy speed of advance that the escort can satisfy at any sprint speed.

2. For any given convoy speed, as the virtual speed of the escort is increased, the sprint speed requirements are decreased. This implies a trade-off between virtual speed and sprint speed, i.e., if either the detection range can be increased or the required drift time decreased then less sprint speed capability will be required to maintain the given convoy speed of advance.

3. For a fixed time to search and a fixed detection range, the virtual speed can be increased by increasing the number of escorts and using them in a leapfrog geometry. For example, R_{D_e} = 30 nm and T_D = .3 hrs,

$\frac{R_{D_e}}{T_D}$ = 100 and to maintain a convoy speed of 60 knots, for a single sprint-drift escort,

V_V = 100 and the required sprint speed is 150 knots (which far exceeds the current estimate at which the sensor can be towed while sprinting).

For two leap-frogging escorts,

V_V = 200 and the required sprint speed for each escort is 85 knots (which may be a feasible towing speed).

D. INDEPENDENT SAILINGS

The previous discussions on convoy speeds and escort requirements opens the question of independent sailing versus convoys. There are realms where one or the other is the obvious choice.

Independent sailing is preferred when the convoy to attacker speed ratio is high and the attacker's weapon speed and range are such that the threat area remains narrow and the added benefit of escorts is marginal, compared to the price to achieve the requisite speed, detection range, weapon range, search rate or the desired combinations. The benefit of escorts can be zero as in the case of the high speed independent ships (e.g., Queen Mary) used in World War II.

Convoys may be the proper choice whenever the convoy speed is less than the attacker speed, or when the convoy speed is less than than the attacker's weapon speed and escorts possess the requisite speed, detection range and weapon range.

E. SUMMARY AND CONCLUSIONS

This section investigated the relationship between the ratio of speeds of the various forces involved and the other important variables in convoy operations. The forces considered were convoy ships, escorts and attackers.

In convoy operations the attackers are generally thought of as enemy submarines, with speeds of a maximum of a few tens of knots. The methodology presented in this analysis is general enough to extend to attackers which are enemy advanced vehicles. Ratios of convoy to attacker speeds of zero to five were considered and "micro-tactics" were not considered.

1. Attacker Against Convoy Ship

The effect of convoy speed was treated in two categories: convoy speed greater than or equal to attacker speed, and convoy speed less than attacker speed.

The principal points in attacker against convoy ship are:

a. Increasing the convoy to attacker speed ratio reduces the threat area, but this effect is modified by the values of other parameters (i.e., speed and range of the attacker's weapon).

b. Increasing the convoy to attacker speed ratio also operates to reduce the required number of escorts of a given capability, again, with modifications induced by the values of the other parameters.

c. For convoy speed less than attacker speed, the attacker, given enough time, can always overtake the convoy.

2. Escort Against Attacker

In the analysis of escort versus attacker, two important escort speed ratios emerge: escort speed to attacker speed, and escort speed to convoy speed. The first ratio is required to insure timely closing and counter-attacking the detected threat. The second is to insure maintaining this detection capability over the assigned area relative to the convoy.

The principal points in escort against attacker are:

a. Increasing the convoy to attacker speed ratio reduces the number of escorts required by narrowing the front to be covered; increasing the escort to attacker speed ratio increases the sector coverage of this front and, hence, further reduces the number of escorts required.

b. The sector coverage of the escorts can also be increased by increasing escort quality (i.e., by increasing the effective range of the escort's weapons and increasing the requisite range of detection to the attacker).

c. For convoy speeds greater than the limiting speed of continuous acoustic search, the escort must use sprint-drift tactics.

d. An escort using sprint-drift tactics must maintain a speed of advance equal to or greater than the convoy speed of advance. The parameter which determines the escort's sprint speed requirements is the virtual speed, which is a function of the sensor's acoustic detection range and search time, i.e., drift time.

e. Multiple sprint-drift escorts employing leap-frog tactics can relax constraints on maximum escort speeds of advance.

3. Independent Sailings

The question of independent sailing was considered qualitatively based on the results of the previous analysis on convoy against attacker and escort against attacker.

The principal points involved in choosing convoys or independent sailings are:

If the pipeline is composed of high speed ships and the attacker's capabilities are limited (e.g., submarines with torpedoes only) such that this convoy speed can produce small and narrow threat areas, independent sailing may be the proper choice. If such "convoy" speeds are also essentially beyond the speed capability of effective escort, independent sailing is a clear choice. If, however, the enemy threat (surveillance, speed, weapon range) is relatively insensitive to convoy speed (e.g., aircraft, missiles) and escorts can provide effective protection, convoying may be the proper choice.

The general conclusion of this section on convoy operations is that relative speeds and speed ratios are not sufficient, in themselves, to determine adequate measures of effectiveness. Other modifying parameters, such as detection range and weapon effectiveness, can often compensate for speed deficiencies.

SECTION V. SEARCH OPERATIONS

A. INTRODUCTION

This section addresses the general search problem, identifies those situations where search vehicle speed influences the effectiveness of the search and indicates the general nature of the potential payoff, if any, resulting from increased platform speed.

The basic problem is to quantify the effect of speed of the searching vehicle on a measure of search effectiveness, such as search rates, probability of detection, or number of detections per unit time.

Clearly, for the class of sensors whose detection range is not sensitive to search platform speed, increasing search speed capability will increase the achievable search rate (area searched per unit time). There is always the question of whether or not the increase is worth the effort. When the detection range is very long (e.g., air search radars) the benefit of increasing the platform speed may not be very important. Conversely, in the case of a short range system such as a magnetic anomaly detection (MAD) system, effective search speed is the principal determinant of search rate.*

Acoustic searches differ importantly in that the detection range of a sonar is degraded by a complex combination of factors (primarily noise). One of those factors is the flow noise around the sensor housing. This noise increases with search speed. Thus, in the speed range where flow noise is a major factor, the detection range varies inversely as the speed of the search vehicle. Since the other dimension of the search rate is directly proportional to the search speed, the existence of an optimum search speed is implied.

* There are, of course, limits insofar as the overall search effectiveness of a system involves factors such as integration time for a detection, classification, etc.

This analysis addresses the utility of speed in the case of a single search vehicle, employing an acoustic sensor and conducting random searches.

Search with prior information, multiple sensors and other sensors such as radar or MAD, are considered in the sections on attack and counterattack, convoy and pursuit, wherein the searcher (upon detection) uses speed for some other function, such as localizing and attacking the target.

There are two important factors which tend to bound the speed range of interest for acoustic search. For surface or near surface platforms, flow noises at speeds in excess of about 30 knots reach a level at which the detection range is for all practical purposes, zero. Herculean design efforts appear to be necessary to produce any increase in this limiting speed.

At very low speeds, the combination of prevailing background noise in the sea and the machinery noise components of self noise dominates the problem. Thus, the theoretical detection ranges which might be achieved in a noiseless environment do not occur in the real world. In general, detection ranges are limited by the environment to a constant value until searcher speed reaches about 10-15 knots, and then decrease with increasing speed, reaching the zero value at about 30 knots.

Thus, the search speed of interest, for the foreseeable future, lies between 10-15 knots and about 30 knots. This suggests that the projected speed capabilities of most of the advanced naval vehicle concepts (with the possible exception of SWATH ships) gain little or no support from the search function.*

We address two general search operations: Barrier Search and Open Area Search:

The barrier operation represents a well defined area to be searched with a high expectation that a target may attempt to transit the barrier. The barrier

* This is not entirely true since, in the analysis of sprint-drift or flying-drift search, we find a clear case for high sprinting (or flying) speeds between search periods.

is taken to be positioned across normal submarine transit lanes, such as the G.I.U.K gap. A barrier front of 250 nm per barrier unit is used.

The open area search represents a random encount with no prior expectations of the presence or absence of a target in the search area. The effectiveness of open area search is dependent on the density of targets, i.e., the number of targets per square nautical mile. This target density is correlated with the target system base loss factor concept introduced in the section on transit. As the target distance from port increases, the number of platforms required to keep one on station will also increase. In addition, the total area in which the targets operate will also increase with distance from port; hence, the target density will decrease with distance for a given target force level.

The search techniques addressed in this analysis are:

- Continuous active and passive search
- Sprint-drift search
- Flying-drift search

Initially an idealized environment (with no background noise) is assumed. This, therefore, results in indications of optimum speeds which are lower than one's intuition or experience would indicate. Applying a mean level of background noise has the effect of clipping off the detection ranges at lower speeds. Thus, one can expect to find realistic optimum search speeds between about 10-15 knots and about 20 knots. It is important to note that the levels of effectiveness at those speeds are less than those for the idealized case.

The idealized case was chosen for graphical display because it illustrates the methodology while at the same time avoiding the vagaries of geography, seasons, time of day, and weather which are not the principal areas under investigation.

B. BARRIER SEARCH

The purpose of this portion of the analysis is to investigate the impact of search speed on the probability of detecting a target attempting to transit a barrier.

A single searcher conducts a random search in a barrier with front equal to 250 nm per barrier unit.

The methodology and results are extendable to barriers of any length; in general, absolute values of probabilities of detection will change but optimum speeds derived herein (in the idealized case) do not change.

In the case of continuous search, the detection range (sweep width) decreases with increasing speed due to self noise considerations. Self noise is composed of background noise, machinery noise, and flow noise. Of these components, flow noise is directly dependent on speed; hence, for purposes of analysis, the other components were considered to be constant and attention was focused on flow noise.

Flow noise directly affects sensors using broad band detection. By improving the design of sonar domes and utilizing narrow band signal processing, the effect of flow noise on detection capability can be reduced.

With broad band detection, the benefit derived from increased speed is offset by degradation of sensor capability with self noises.

In either case (narrow or broad band) since there is a component of search rate which increases with speed and another which decreases as speed is increased, an optimum search speed is implied.

In the case of sprint-drift search, the detection range is not degraded by search speed since the searcher listens only during the drift portion. However, the speed of advance is directly affected by the detection range and drifting time. Using passive sensors, such as towed arrays, about five minutes are required for the array to settle down; and the average processing time is about fifteen minutes. Hence, a drift time of 0.3 hr is used.* It is generally accepted that the next generation of towed arrays (IOC 1980) will be towable at speeds up to 80 knots. Therefore, throughout this analysis, it is assumed that no time is required to deploy and retrieve the array when sprint speeds of 80 knots or less are used. In the case of flying drift where the array cannot be towed while flying, a total drift time of 1.5 hours is assumed. This allows an additional 1.2 hours to account for the time to deploy and retrieve the array.

The following figures develop a general quantification of the utility of vehicle speed in conducting a barrier search. The discussion sheets which accompany the figures illuminate the principal points of each graph. Figure V-1 addresses the idealized case. Subsequent figures assume a combination of background and self noise such that the detection range is constant over a searcher speed range from zero to ten knots.

It is important to note that, in general, the assumed detection ranges are optimistic for present systems. They are viewed as the maximum performance levels which foreseeable technology may produce.

* "Analysis of Passive Ranging Tactics Using a Towed Array," TRW Report, 13 September 1972.

Figure V-1

Degradation of Passive Detection Range
Due to Flow Noise Versus Speed

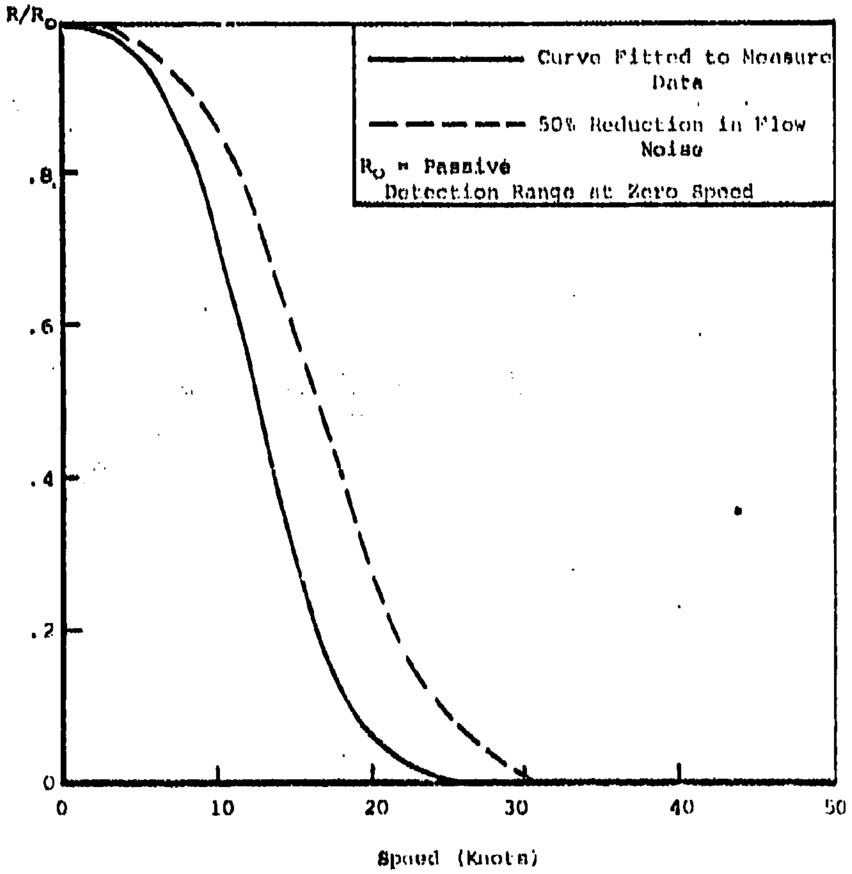


Figure V-1

Degradation of Passive Detection Range Due to Flow Noise Versus Speed.

Purpose

The purpose of this graph is to show the impact of flow noise as a function of speed on the passive detection range of a hull-mounted sonar.

Basis for the Calculation

This graph is a plot of equation C-1. R_o is the detection range at zero speed for an idealized case, wherein the effects of background noise and internal self noise on R_o are assumed to be zero.

The measured data is taken from R.J. Urick Principles of Underwater Sound for Engineers, which gives a value for the increase in flow noise of 1.8 db/knot in the speed range 10-20 knots. The fitted curve is in good agreement with measured data in this speed range.

The dashed curve represents the improvement in detection range which could be expected if a 50% reduction in flow noise were obtained.

Principal Points

1. The detection range for hull-mounted sonar decreases with the cube of the speed in the given speed range.

2. Reduction in flow noise by improved design or coating should result in increased detection range and decreased sensitivity to speed.

Figure V-2

Probability of Active Detection of a Transiting Submarine Versus Search Speed for Continuous Search

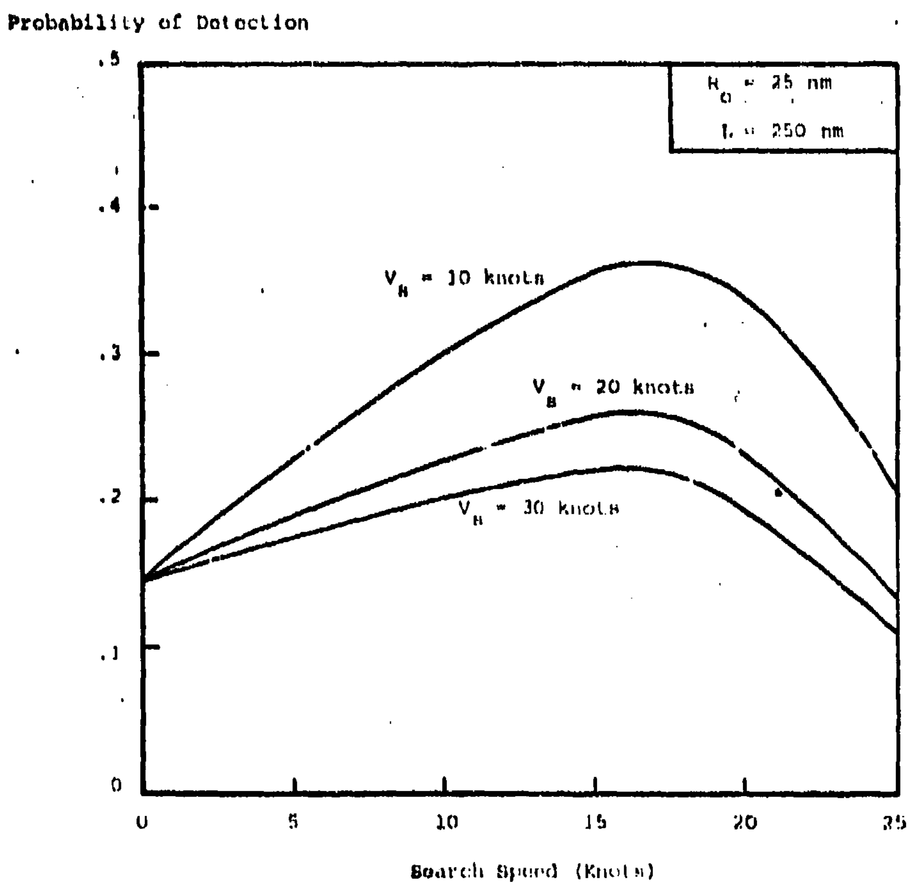


Figure V-2

Probability of Active Detection of a Transiting Submarine Versus Search Speed for Continuous Search.

Purpose

The purpose of this graph is to display the probability of detecting a submarine transiting a barrier using continuous active search for various transit speeds.

Basis for the Calculation

In the speed range $0 \leq V \leq 10$, the range of detection, R, is approximately constant ($= R_o$, the maximum range of detection). In this special case equation C-6 simplifies to

$$P_D = 1 - e^{-\frac{R_o}{L}\left(\frac{2V}{V_s} + \frac{\pi}{2}\right)}$$

For $V \geq 10$ the range of detection decreases with increasing speed as in equation C-1. Thus, equation C-6 becomes

$$P_D = 1 - e^{-\left[\frac{R_o}{L} e^{-a(V-10)^3}\left(\frac{2V}{V_s} + \frac{\pi}{2}\right)\right]}$$

A value of 25nm is used for R_o, which corresponds to a hull mounted sonar under ideal acoustic conditions, i.e., low sea state and backgound noise.* The value used for R_o is an optimistic choice for the maximum detection range. However, different choices of R_o would not significantly change the shape of the curves.

It was assumed that the target speed, V_s, had negligible effect on the active search detection range; that is, we ignore possible returns from target wake.

Principle Points

1. For continuing active search, the probability of detection decreases with increasing target speed due to the shorter time of transit through the barrier for higher speeds.

2. For the assumed conditions, the curve displays an optimum search speed of about 15-18 knots.

3. At higher speeds, the probability of detection decreases, since increasing flow noise decreases the figure of merit of the sonar. Thus, it appears that high speed advanced naval vehicles have limited application in continuous active search.

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*CYCLOPS, Volume V, IX, Center for Naval Analyses, Study #47, 1967. (SECRET)

Figure V-3

Probability of Passive Detection of a Transiting Submarine Versus Search Speed for Continuous Search

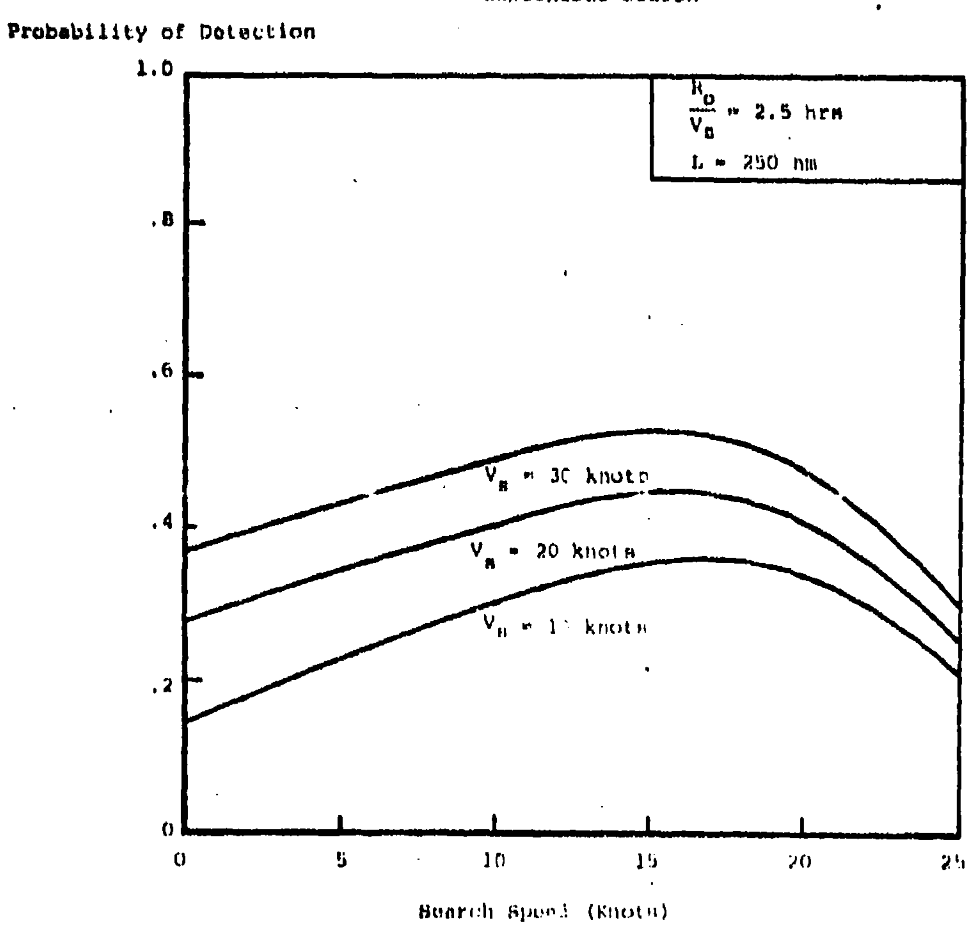

Figure V-3

Probability of Passive Detection of a Transiting Submarine Versus Search Speed for Continuous Search.

Purpose

The purpose of this graph is to display the probability of detecting a submarine transiting a barrier using continuous passive search.

Basis for the Calculation

This graph is a plot of equation C-6. In equation C-6 the dependency of the probability of detection on target speed occurs as a ratio, $\frac{R_o}{V_s}$, i.e., the ratio of the detection range at zero search speed to the target speed. It can be shown* that R_o increases approximately linearly with target speed. The SEAMIX Study provides the following relationships.

Target Speed (knots)	Detection Range (nm)
10	25
20	50
30	75

The ratio for this computation is 2.5 hours.

Principal Points

1. The probability of detection is independent of the target speed, so long as the ratio $\frac{R_o}{V_s}$ is a constant. The ratio for this computation is 2.5 (hours).

2. The optimum search speed occurs in the range 15-18 knots.

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*SEAMIX I, CNO, Systems Analysis Division (OP-96), April 1972. (SECRET)

Figure V-4

Probability of Passive Detection of a Transiting Submarine Versus Search Speed for Sprint-Drift Search

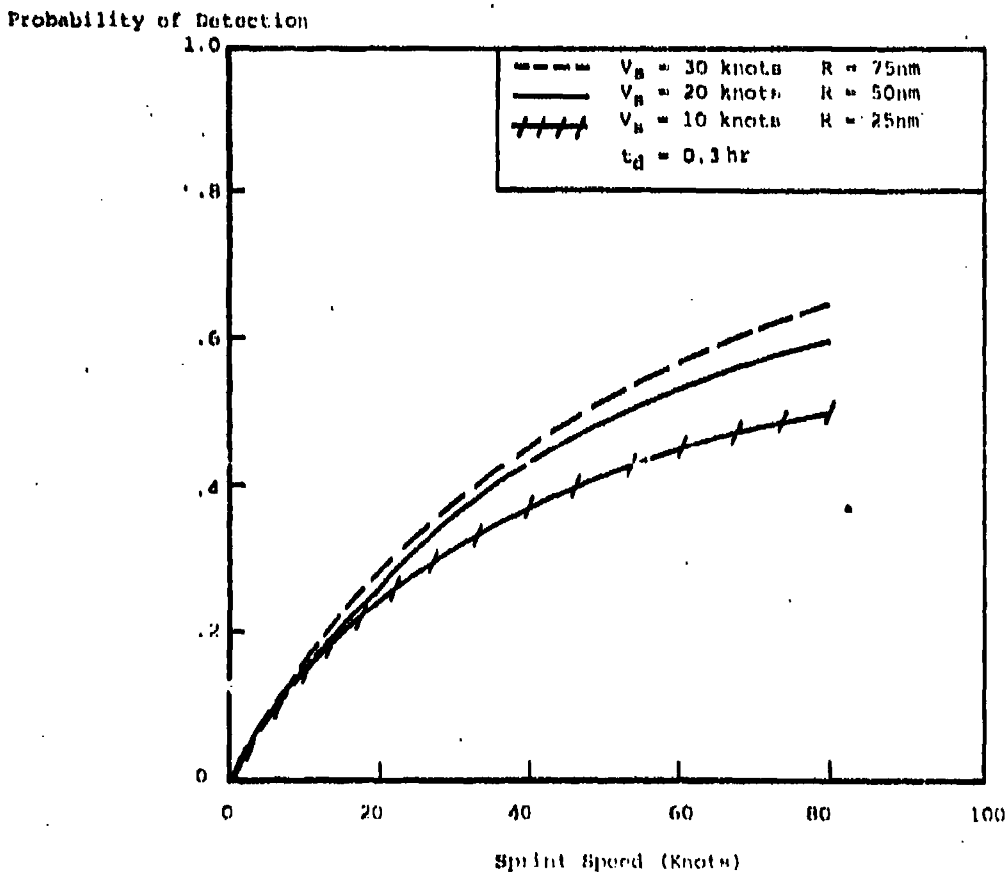


Figure V-4

Probability of Passive Detection of a Transiting Submarine Versus Sprint Speed for Sprint-Drift Search.

Purpose

The purpose of this graph is to display the probability of detecting a transiting submarine using sprint-drift tactics for various target speeds and corresponding detection ranges.

Basis for the Calculations

This graph is a plot of equation C-11, where R is the detection range and increases with target speed due to increased radiated noise according to the following:

Target Speed (knots)	Detection Range (nm)
10	25
20	50
30	75

The drift time, t_d, is taken to be 0.3 hr since it requires five minutes for the array to settle down and an average of fifteen minutes is required for processing.

It is generally accepted that the next generation of towed arrays (IOC 1980) will be towable at speeds up to 80 knots, hence, no time is required to deploy and retrieve the array at search speeds of 80 knots or less.

Principal Points

1. In this case the probability of detection increases with sprint speed and target speed.

2. For a given detection range, the probability of detection displays diminishing returns as sprint speed increases, however, this speed is beyond the maximum towing speed at which the array can survive (about 80 knots).

Figure V-5

Probability of Passive Detection of a Transiting Submarine Versus Flying Speed for Flying-Drift Search

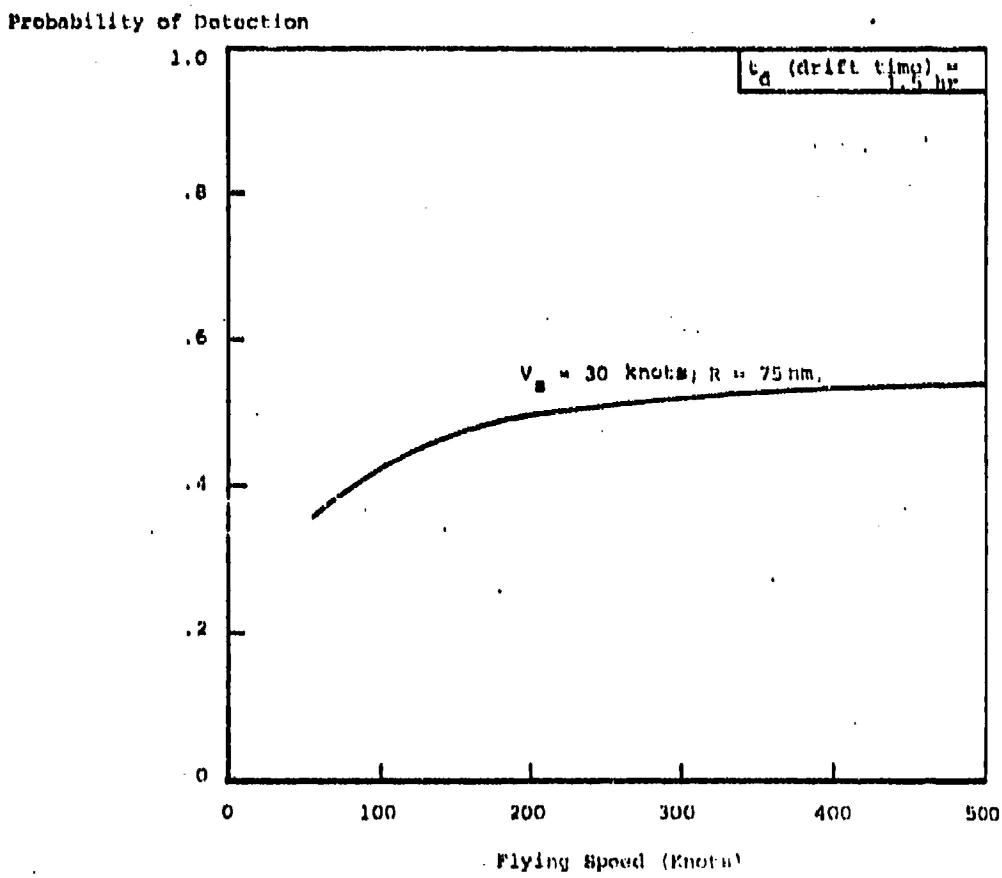


Figure V-5

Probability of Passive Detection of a Transiting Submarine Versus Sprint Speed for Flying-Drift Search.

Purpose

The purpose of this graph is to display the probability of detecting a submarine attempting to transit a barrier using flying-drift tactics.

Basis for the Calculations

This graph is a plot of equation C-11.

The calculation was made using a single value for target speed, V_s, and detection range, R, to illustrate the difference between flying-drift and sprint-drift.

A total drift time, td, of 1.5 hrs was used which includes time to deploy and retrieve the array; the actual listening time is still 15 minutes as in the sprint drift case. In the flying-drift case, the array cannot be towed while flying; hence, it is necessary to include the time to deploy and retrieve.

Principal Points

1. The probability of detection increases monotonically with speed until about 200 knots, after which the probability of detection is relatively insensitive to speed.

2. The probability of detection for flying-drift is consistently lower than sprint drift, due primarily to the increased drift time which decreases the speed of advance. The impact of detection range and drift time on speed of advance is further illuminated in the following figures.

Figure V-6

Comparison of Probability of Detection Versus
Speed For Various Barrier Search Tactics

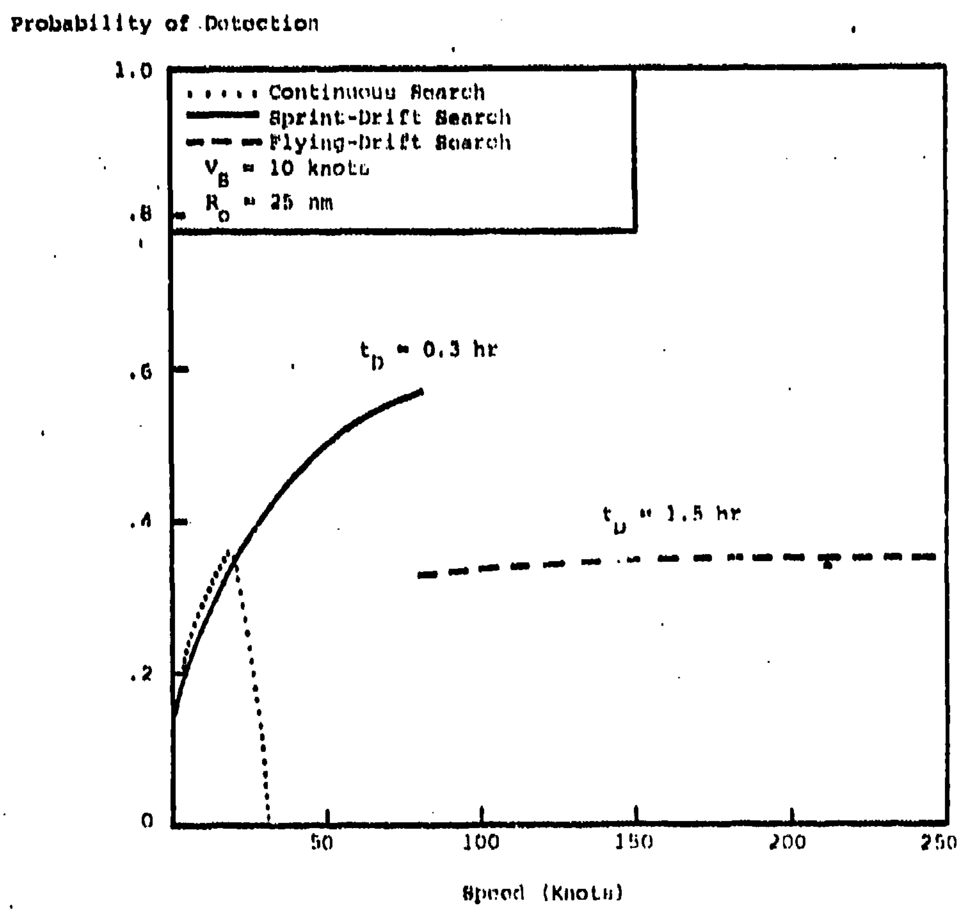


Figure V-6

Comparison of Probability of Detection Versus Speed for Various Barrier Search Tactics.

Purpose

The purpose of this graph is to display the probability of passively detecting a transiting submarine using various search tactics for a given target speed and detection range.

Basis for the Calculation

This graph is a plot of equation C-6 for the continuous case and equation C-11 for the sprint-drift and flying-drift case.

The submarine speed is 10 knots which is an approximate optimum speed of a submarine transiting a passive acoustic barrier. This results in a searcher's maximum detection range of about 25 nm (assuming ideal acoustic conditions).

For the sprint-drift case a drift time of 0.3 hr is used.

At the present level of technology, the amount of stress the towed sensor can withstand limits the sprint speed in sprint-drift search to under 80 knots.

For the flying-drift case, a drift time of 1.5 hr is used to account for array deployment and retrieval.

The speed is the respective speed for each tactic, i.e., continuous, sprint and flying.

Principal Points

1. For speeds less than 20 knots, sprint-drift search and continuous search yield approximately the same probability of detection. In the speed range from 20 to 30 knots (still in the realm of conventional naval vessels) sprint-drift search dramatically improves the probability of detection. For speeds greater than 30 knots, self-noise makes continuous search ineffectual, but does not hinder sprint-drift search.

2. The probability of detection increases monotonically with sprint speed.

3. The probability of detection for flying-drift search is relatively insensitive to speed in the range considered for a drift time of 1.5 hr.

4. By decreasing the drift time, a significant improvement in probability of detection is obtained for flying-drift search.

Figure V-7

Speed of Advance Versus Sprint Speed for Various Drift Times

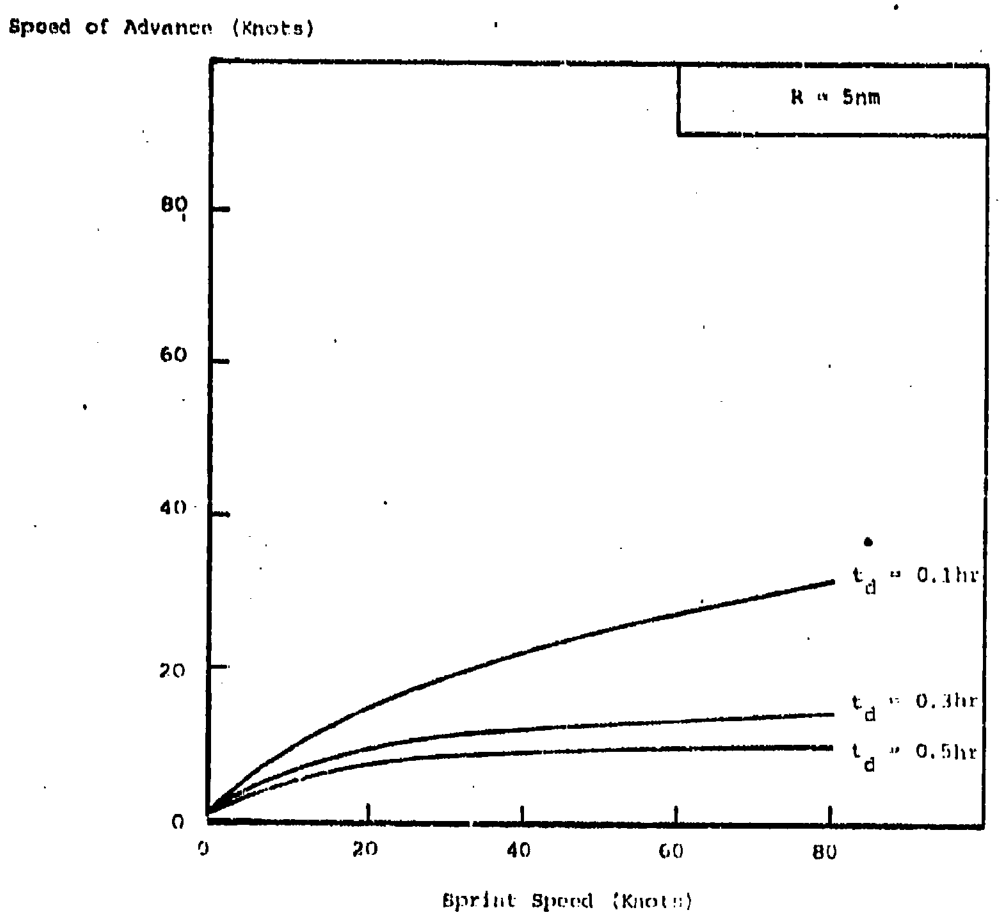


Figure V-7

Speed of Advance Versus Sprint Speed for Various Drift Times.

Purpose

The purpose of this graph is to show how the speed of advance varies with sprint speed and drift time for fixed detection range.

Basis for the Calculation

This graph is a plot of equation C-8.

Principal Points

1. For relatively short detection range (5 nm) and drift times of 0.5-0.3 hours there is a diminishing return in speed of advance once a speed of about 30 knots is reached.

2. If the drift time can be reduced to 0.1 hr, improvement in speed of advance can be obtained.

Figure V-8

Sweep Rate Versus Sprint Speed
for Various Drift Times

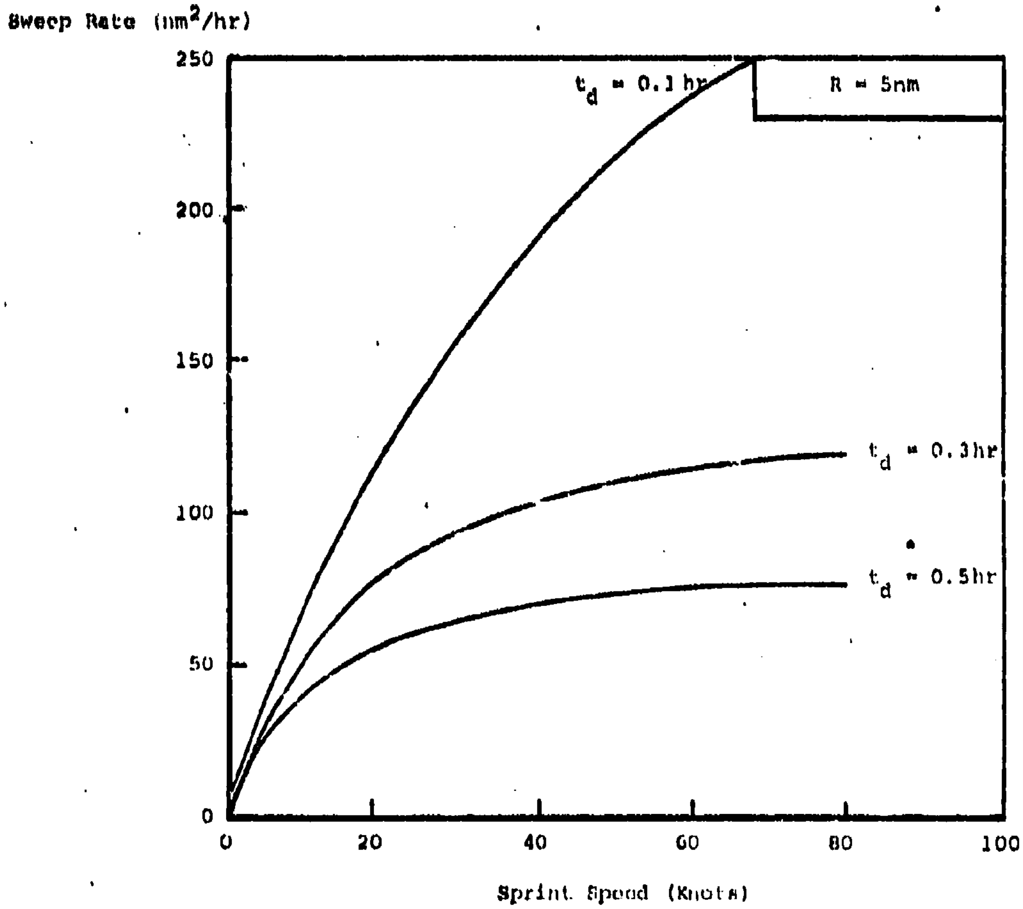


Figure V-8

Sweep Rate Versus Sprint Speed for Various Drift Times

Purpose

The purpose of this graph is to show how the sweep rate varies with sprint speed and drift time for fixed detection range.

Basis for the Calculation

This graph is a plot of equation C-9.

Principal Points

1. This graph shows diminishing return in sweep rate for drift times of 0.5-0.3 hours which correlates with the speed of advance in the previous figure.

2. By reducing the drift time to 0.1 hr, significant improvement in sweep rate can be obtained.

3. For the modest but frequently realistic detection range assumed, unless the current drift time of 0.3 hr can be reduced, the penalty in increased fuel consumption and reduced endurance time at speeds greater than 40 knots would probably far exceed the benefits.

Figure V-9

Speed of Advance Versus Sprint Speed
for Various Detection Ranges and Fixed Drift Time

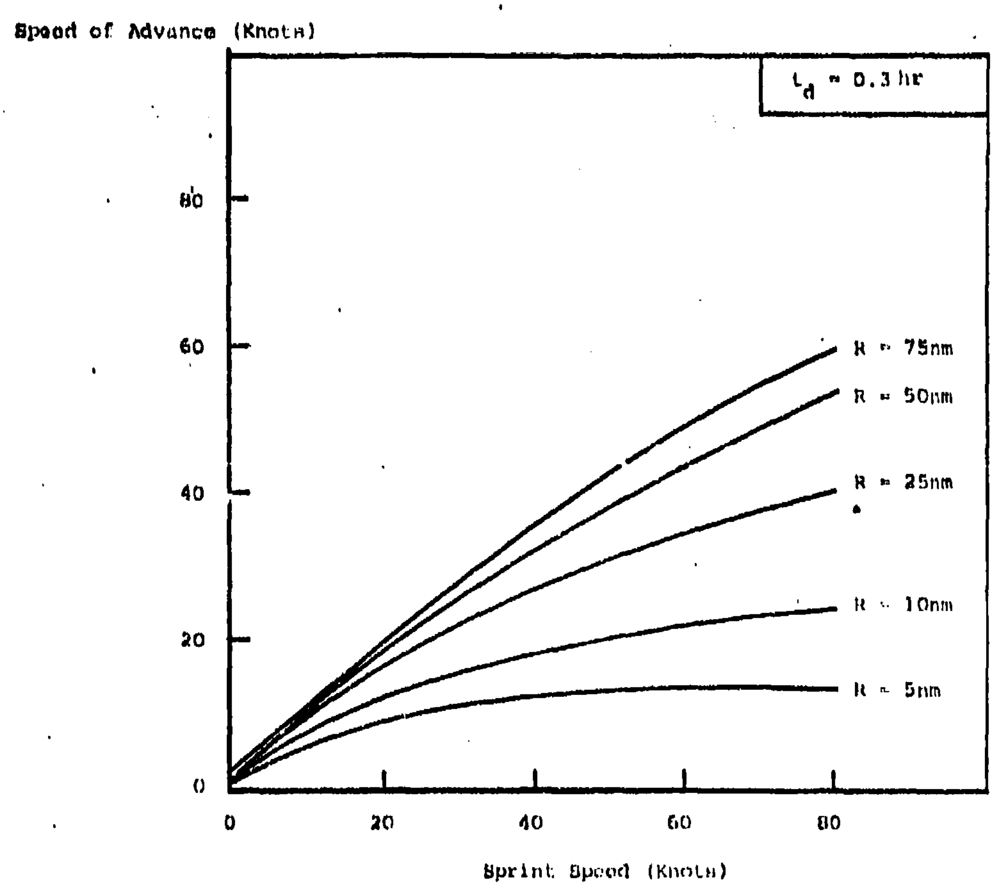


Figure V-9

Speed of Advance Versus Sprint Speed for Various Detection Ranges and Fixed Drift Time.

Purpose

The purpose of this graph is to show how the speed of advance varies with detection range for fixed drift time.

Basis of Calculation

This graph is a plot of equation C-8.

Principal Points

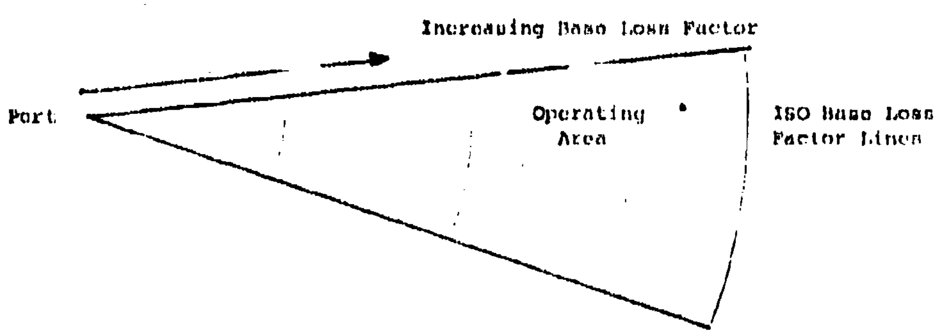
1. There is rapidly diminishing return in speed of advance as a function of sprint speed at detection ranges of <25 nm.

2. The preceeding figures (6 and 7) imply a definite tradeoff between detection range, drift time, and sprint speed.

C. OPEN AREA SEARCH

The purpose of this portion of the analysis is to investigate the impact of search speed on the expected number of targets to be encountered in an open area search. The expected number is dependent on: the search speed, the target speed and direction, detection range, and the density of targets.

The density of targets varies with their distance from port in accordance with the base loss factor concept introduced in the section on transit. As the distance from port increases, the number of target platforms required to keep one on station increases and the total area in which the targets operate also increases. Hence, for a given force level, the target density will decrease with distance from port. This concept is illustrated below.



The search sensors and techniques used in the open area search are identical with those used in the barrier search.

The following figures graphically display the utility of speed in conducting an open area search against uniformly distributed targets. The sheets which accompany each figure illuminate the principal points of each graph.

Figure V-10

Expected Number of Targets Detected Per Hour
Versus Search Speed for Continuous Active Sonar Search

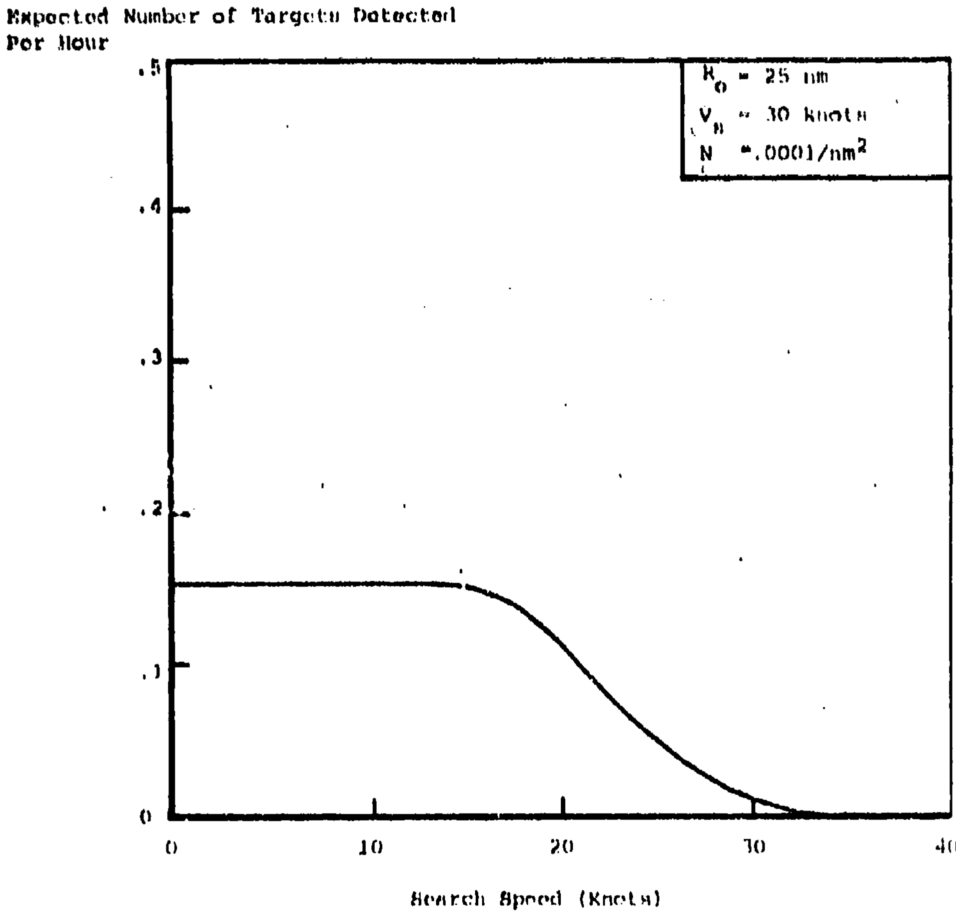


Figure V-10

Expected Number of Targets Detected Per Hour Versus Search Speed for Continuous Active Sonar Search

Purpose

The purpose of this graph is to show the expected number of targets detected in an open area search as a function of search speed and fixed target density.

Basis for the Calculation

This graph is a plot of equation C-12.

R_o = detection range at zero search speed = 25 nm

V_s = target speed = 30 knots

N = target density (number/nm^2) = 0.0001

As in Figure V-2, the speed range has been divided into two parts, $0 \le V \le 10$ and $V \ge 10$, where R, the range of detection, is R_o and $R_o e^{-\alpha(V-10)^3}$ respectively. Equation C-12 is then

$$N_o = (V + V_s) \frac{4N}{\pi} R_o \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{4VV_s}{(V + V_s)^2} \sin^2 \psi}\, d\psi, \quad 0 \le V \le 10$$

$$= (V + V_s) \frac{4N}{\pi} R_o e^{-\alpha(V-10)^3} \int_0^{\frac{\pi}{2}} \sqrt{1 - \frac{4VV_s}{(V + V_s)^2} \sin^2 \psi}\, d\Psi, \quad V \ge 10$$

Principal Points

1. A continuous open area search using active sonar results in few target encounters even with high target density and is limited to slow search speed.

2. The number of detections per unit time increases very slightly over the speed range of 0-15 knots and then decreases until it is essentially zero at about 30-35 knots. The flat portion at lower speeds results from the combination of two opposite effects of increased speed:

a. Since the detection range is assumed constant over most of this speed range, increasing speed increases the area searched per unit time. This operates to increase detections.

b. The dynamics of an increasing searcher speed and assumed constant target speeds (in random directions) results in fewer timely entries of targets into the searchers sweep path per unit time. This operates to decrease the number of detections.

3. Above 10 knots, the detection radius decreases with increasing speed and the area swept per unit time levels off and then decreases down to a value of zero at about 30-35 knots.

4. Thus, for the assumed conditions, the range of optimum search speeds is about 0-15 knots.

Figure V-11

Expected Number of Targets Detected Per Hour Versus Sprint Speed for Sprint-Drift Search

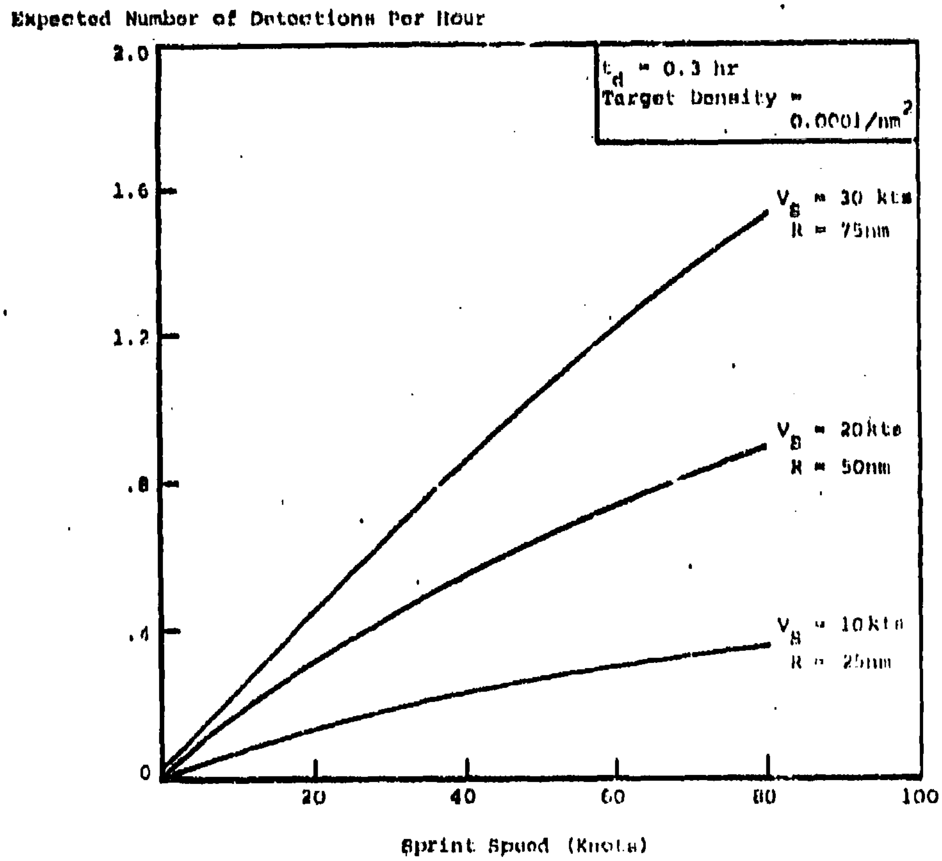


Figure V-11

Expected Number of Targets Detected Per Hour Versus Sprint Speed for Sprint-Drift Search.

Purpose

The purpose of this graph is to show the expected number of targets detected in an open area search using sprint-drift search and high target density.

Basis for the Calculation

This graph is a plot of equation C-14.

The graph is a first order approximation for the number of targets detected per hour and illustrates the impact of speed when a sprint-drift search tactic is employed. The following assumptions were used in equation C-14.

R is the detection range and increases with target speed due to increased radiated noise according to the following:

Target Speed (knots)	Detection Range (nm)
10	25
20	50
30	75

The drift time, t_d, is taken to be 0.3 hr since it requires five minutes for the array to settle down and an average of fifteen minutes for processing. Targets that had been detected in previous search periods were not differentiated from new detections and could be counted more than once. The sprint distance was assumed to be equal to the detection range R and the sprint drift cycle was assumed to begin in the sprint phase. Thus, the number of detections at zero speed was zero since the searcher would require infinite time to move a sprint distance.

It is generally accepted that the next generation of towed arrays (TOC 1980) will be towable at speeds up to 80 knots.

Principal Points

1. The expected number of detections increase with increasing sprint speed and detection range.

2. For slow target speed and reduced detection range, the number of detections display diminishing returns with increasing search speed.

3. Sprint-drift tactics show significant improvement over continuous search.

Figure V-12

Expected Number of Targets Detected Per Hour Versus Sprint Speed for Sprint-Drift Search

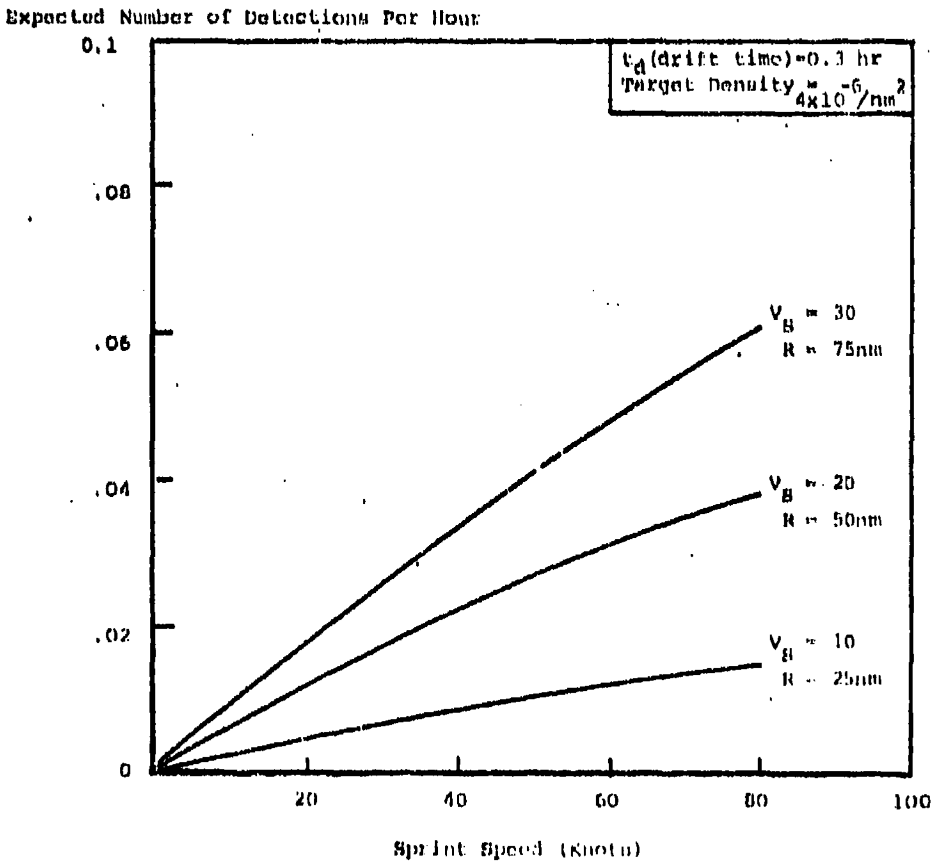


Figure V-12

Expected Number of Targets Detected Per Hour Versus Sprint Speed for Sprint-Drift Search.

Purpose

The purpose of this graph is to show the expected number of targets detected in an open area search as a function of sprint speed and low target density.

Basis for the Calculation

This graph is a plot of equation C-14.

The basis of calculation is the same as in Figure V-11.

Note that the vertical scale has been changed from the previous figure by a factor of 25.

Principal Points

1. The expected number of detections per hour is linearly dependent on the target density. For example: Decreasing the target density by a factor of 25, results in a twenty-five fold decrease in detections per hour.

Figure V-13

Expected Number of Targets Detected Per Hour Versus Flying Speed For Flying-Drift Search

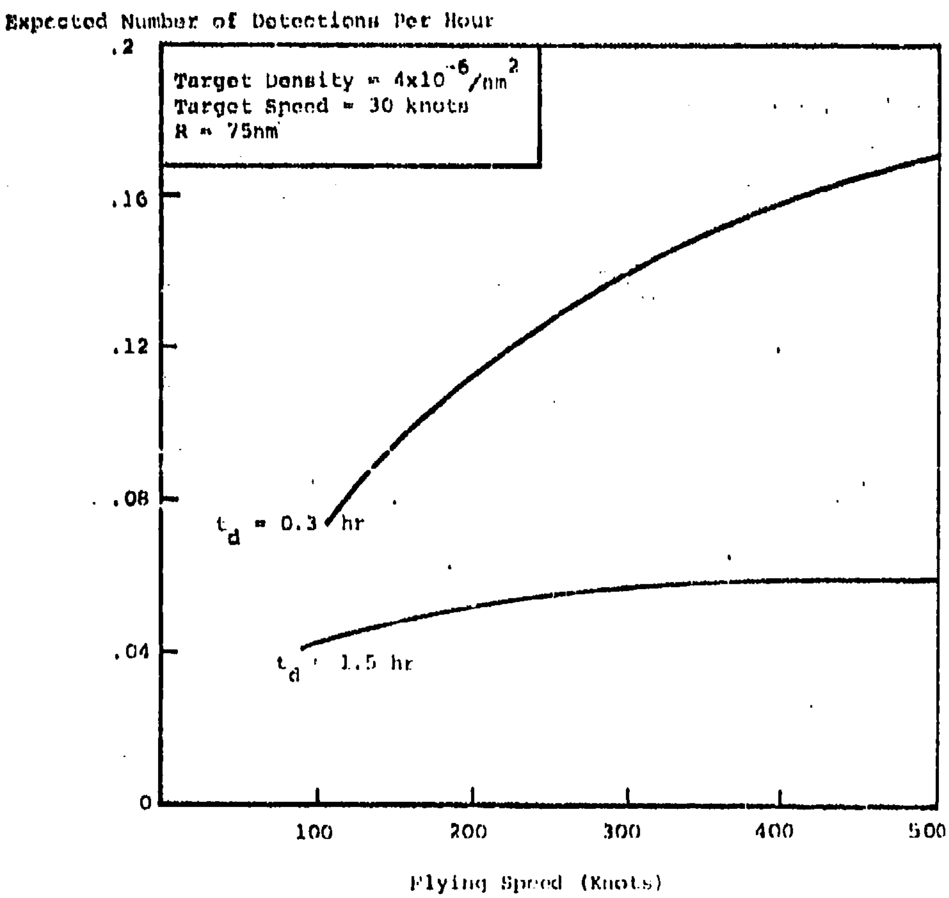


Figure V-13

Expected Number of Targets Detected Per Hour Versus Flying Speed for Flying-Drift Search.

<u>Purpose</u>

The purpose of this graph is to show the expected number of targets detected in an open area search using flying-drift search for low target density and various drift times.

<u>Basis for Calculation</u>

This graph is a plot of equation C-14.

A drift time of 1.5 hour is used to account for deployment and retrieval of the array.

A drift time of 0.3 hr, as used in sprint drift, is also shown to demonstrate the sensitivity to drift time.

<u>Principal Points</u>

1. For drift times of 1.5 hour there is a diminishing return in the expected number of detections per hour with increasing flying speed.

2. By reducing the drift time to 0.3 hr there is a significant increase in the expected number of detections per hour which increases monotonically with flying speed.

D. SUMMARY AND CONCLUSIONS

The utility of speed in conducting search operations for submarine targets was investigated for two cases:

- Barrier search
- Open-Area search.

The search techniques employed in both cases were:

- Continuous active and passive search
- Sprint-drift search
- Flying-drift search

The barrier search represented a well defined area to be searched with a high expectation that a target may attempt to transit the barrier. The principal parameters in the barrier case are: search speed, target speed, detection range, drift time and barrier dimensions.

The principal points in the barrier search are:

- Continuous active search is limited to slow search speed due to increased flow noise with increasing search speed.
- For continuous active or passive search there is an optimum search speed in the range of about 15-18 knots.
- The critical parameter in using either sprint-drift or flying-drift tactics is the speed of advance since this directly affects the sweep rate.
- The speed of advance is directly affected by the detection range and the drift time, i.e., for a given sprint speed, the speed of advance increases with increasing detection range and decreased listening time.

• The required drift time is the sum of settling time and processing time; in the case of flying-drift search, it also includes the time required to deploy and retrieve the array.

The open area search represented a random encounter with no prior expectation of the presence or absence of a target. The principal parameters in the open area search are: search speed, target speed and detection range, drift time, and target density.

The principal points in the open area search are:

• The expected number of encounters per hour varies linearly with the target density.

• The density of targets vary with their distance from port in accordance with the base loss factor concept introduced in the section on transit. As the distance from port increases, the number of platforms required to keep one on station increases. In addition, the total area in which the targets operate also increases. Hence, for a given force level, the target density will decrease with distance from port.

• The same general conclusions in the barrier case apply equally to the open area case.

Advances in technology which would provide across the board improvements for all cases are:

• Reduction in flow noise due to improved design or coatings on hull mounted sensors would increase search speed for continuous search.

• Reduction in drift time requirements would result in increased speed of advance and, hence, sweep rate for sprint-drift or flying-drift search.

• There is a tradeoff between detection range and speed of advance. As the detection range is increased, the speed of advance increases for a given sprint speed. On the other hand, increased sprint speed results in higher fuel consumption and reduced endurance time. This tradeoff could also be extended to include cost considerations.

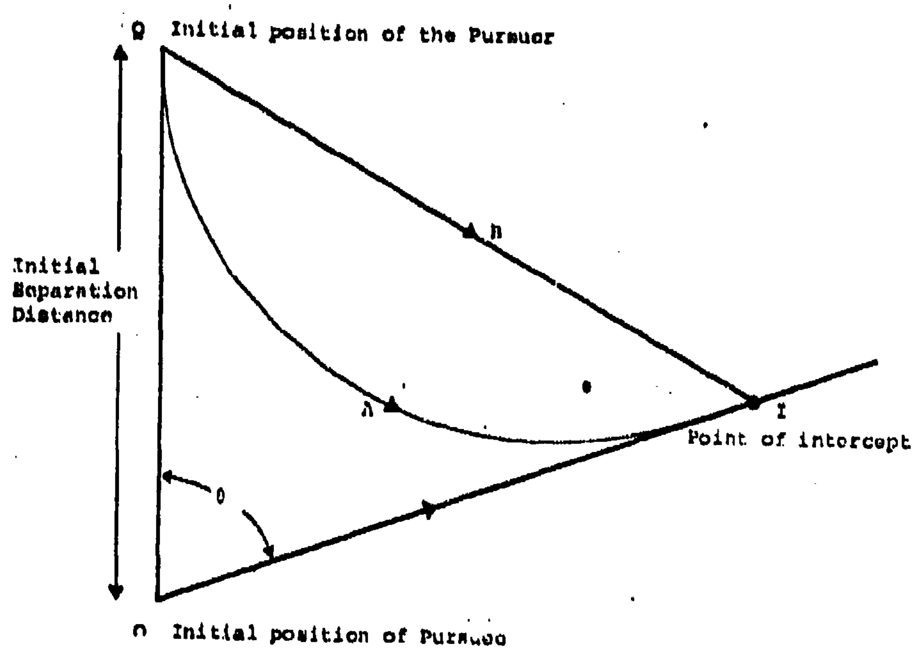
SECTION VI. PURSUIT

A. INTRODUCTION

The subject of pursuit has long been one of much study, since it is an essential ingredient of warfare between platforms or people. Its roots lie in the antiquity of the hunt. Much scholarly attention has also been given to the subject of pursuit due to its aspect of relative motion which, while simple enough to describe, gives rise to a set of mathematically interesting differential equations (see, for example, Introduction to Nonlinear Differential and Integral Equations, by Harold T. Davis, Northwestern University, September 1960, which, in the introduction to Chapter 5, attributes the origin of the curve of pursuit problem to Leonardo da Vinci in the 15th century).

The applications of interest in this basic study of pursuit by naval platforms involve fairly elementary consideration. While they have probably been examined and described many times previously, we have found it easier to derive them than to find the set of references dealing with the pertinent specific applications.

The basic calculations whose results are described later in this section are based on the following geometry:



The pursued vehicle (hereafter "pursuee") is at point O, where he is initially detected by the pursuer at point Q (alternatively the pursuer receives equivalent information from an external source) and the pursuit begins.

The direction of movement of the pursuee is along the path OI. The intersection of OQ and OI forms the initial track angle, θ. The detection range (more generally, initial separation distance) will be considered to be unity so that separation distances throughout the pursuit period can be treated as multiples and fractions of this distance for the first few basic calculation.

The pursuer has basically two pure tactics, indicated by paths A and B from Q to I (the intercept point) in the diagram.*

A. The "pursuit curve", which is the pursuit path which results from the pursuer continuously heading directly for the pursuee and continuously changing his course to do so.

B. The "steady bearing" tactic, which consists of making the necessary observations and calculations to predict a point of intercept I and heading directly for it. (At the appropriate speed this constant heading results in a steady bearing on the pursuee which is maintained until intercept)

Tactic A, which always results in a stern chase, is typified by a homing weapon or a pursuit vehicle whose speed is high compared to that of the pursuee.

The angle θ is an important parameter since the larger θ is, the greater the speed necessary for successful intercept in a given time. Time to complete the intercept is an important consideration whenever the specific mission dictates.

The third parameter employed in the following analysis is the distance that the pursuee travels from initiation of the pursuit until intercept (i.e. OI in the diagram). This distance, sometimes known as "capture distance", is used as a measure in the basic analysis. It is plotted in the first few graphs as a function of the pursuer to pursuee speed ratio. It is significant in

* A myriad of mixed tactics, governed by specifics of other parameters, generate alternative paths which lie between A and B.

that, coupled with a knowledge of the pursuee's speed, it is equatable to the time to intercept. The measure of effectiveness of a naval platform in a pursuit mission might be specified in terms of either a time to intercept or a capture distance or both.

The following analysis of the utility of speed in pursuit addresses two general cases. The first is the basic case where the pursuer continuously tracks the pursuee. The second introduces the problem of intermittent tracking and thus addresses the potential importance of speed in reducing the impact of uncertainties as to the pursuee's location and actions.

B. PURSUIT WITH CONTINUOUS TRACKING

A general indication of the utility of speed in a pursuit mission can be obtained by investigation of the effects of increased pursuer speed on the distance the pursuee moves before intercept is accomplished (i.e., capture distance). This distance, however, is also a function of the initial track angle θ and the separation distance at the start of pursuit.

Figure VI-1 provides such a basis for the "pursuit course" (tactic A in the basic diagram). Generality is achieved by expressing the pursuer speed in terms of a ratio of pursuer to pursuee speed and by expressing capture distance in units of the distance between vehicles at the start of the pursuit. The initial track angle (θ) is parameterized from 0° to 180°.

As the figure indicates (from the point of view of designing speed capability into a naval vehicle for the purpose of missions involving pursuit), the speed range of interest lies between about 1.5 times the potential pursuee's speed and about 2.5 - 3.0 times his speed. Ratios less than 1.5 result in long stern chases for all but small θ's. Ratios greater than about 3.0 would appear to produce small marginal returns and indicate resort to other means (such as improved surveillance, increased weapon ranges, force levels, etc., as the specific mission dictates.)

This indication also holds for the "steady bearing" tactic as shown in Figure VI-2, which compares the pursuit course curve for θ = 90° from Figure VI-1 with that for a pursuit maintaining a steady bearing. Note, however, the difference in effectiveness for the same speed capabilities within this region. For example, with the steady bearing tactic a pursuer to pursuee speed ratio of 1.5 produces intercept before the target has traveled as far as the separation at the start of the pursuit. That is, a capture distance of less than 1.0. A pursuit course with the same speed ratio would result in a capture distance of about 1.2.

Thus, as one might expect, the effect of platform speed on pursuit mission capability is sensitive to the pursuit tactics. Additional important sensitivities emerge when one considers other parameters.

An example is illustrated in Figure VI-3, which shows the effect of defining an intercept as reaching a point from which the target could be attacked by the pursuer's weapon and examining the effects of maximum weapon range on the pursuit capability-speed ratio function.

Note that in this figure the ordinate is actual capture distance for a specified initial detection distance of 20 nm. These dimensions suggest a specific example where the pursuer is a convoy escort who has detected (at 20 nm) a submarine attempting a torpedo attack on the convoy. For a required capture distance of less than 10 nm (which may be considered as the distance the submarine must travel before he can effectively fire torpedoes), an escort weapon range of 10 nm will permit timely counterattacks with an escort to submarine speed ratio of about 1.7. A zero range escort weapon, such as depth charges, would require a speed ratio of about 2.5.

Note that capture distance serves as a measure of effectiveness of the utility of speed in this particular pursuit mission. A naval platform might be directed to pursue and intercept some other platform (or force) before it reaches some point; a unit in a barrier may be required to make detections and intercepts within a bounded area, etc. Note also that specifying a target speed makes capture distance equatable to time over which pursuit takes place.

$$\frac{\text{Capture Distance}}{\text{Target Speed}} = \text{Pursuit Time}$$

Pursuit time so defined provides an equally convenient performance parameter for investigation of speed and weapon range trade-offs in the pursuit mission. We illustrate with an assumed scenario in which an advanced naval vehicle is assigned a mission to intercept and attack (or pose a deterring threat to) a surface force proceeding on a steady course at 25 knots on some unspecified mission. The initial separation is 200 nm and the target course is perpendicular to the initial bearing (θ = 90°).

Figure VI-4 indicates the nature of the trade-off for a potential pursuer in this scenario.

The nominal 50 - 60 nm range of the Harpoon surface-to-surface missile provides a convenient reference for comparisons. A displacement hull in current inventory would require about eight hours (at 30 knots) to reach a position within Harpoon range of the target. An advanced platform capable of about 50 knots (and carrying the same weapon) could do so in less than four hours. Alternatively, equipping the current hull with a 110 nm missile would also complete the purruit phase in about 4 hours.

More significant perhaps is the indication that the trade-off tends to become more favorable to weapon range improvement as the pursuit time requirements become more demanding (i.e., pursuit time decreases). A two hour requirement for a Harpoon equipped platform dictates pursuit speeds of about 75 knots. This requirement is also met with a 50 knot platform and a 110 nm missile.

While this example is specific, note that by proper scaling some generalization is possible. By analogy, similar inferences can be drawn about sensor range versus platform speed where the mission is to achieve and maintain a trailing position on the pursuee and the weapon range is analogous to trail maintenance range of this sensor.

Figure VI-1

Capture Distance Versus
Pursuer to Pursuee Speed Ratio for Various Initial
Track Angles

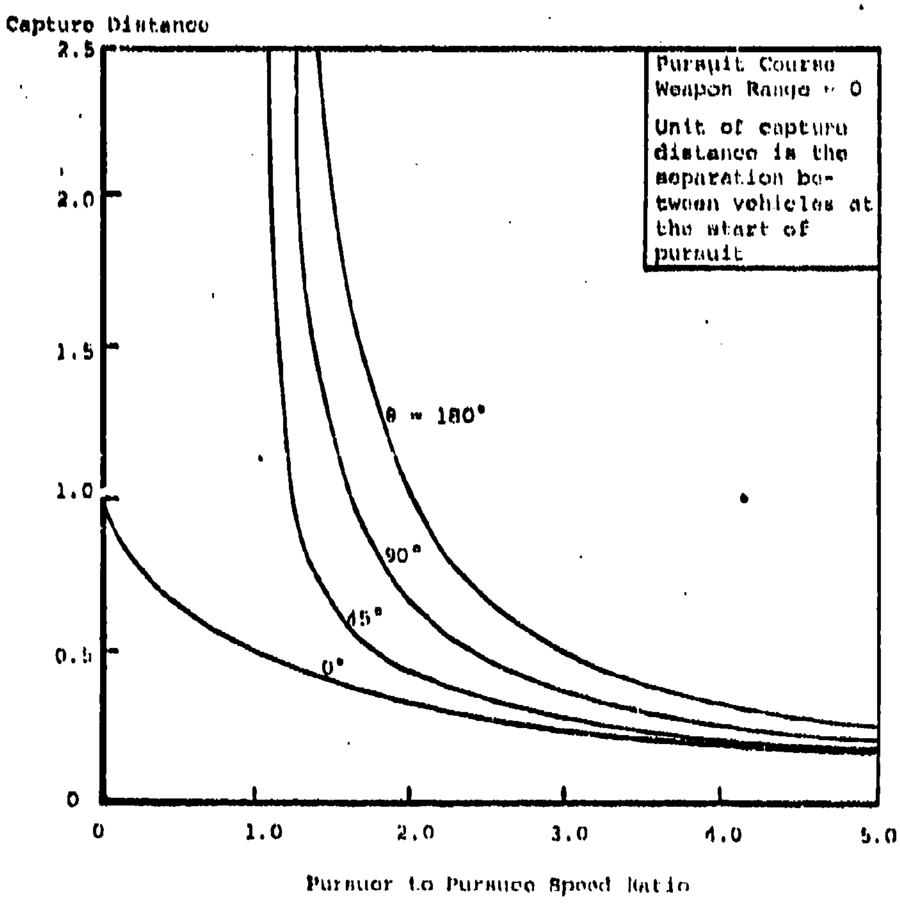


Figure VI-1

Capture Distance Versus Pursuer To Pursuee Speed Ratio for Various Initial Track Angles

Purpose

The purpose of this graph is to show how capture distance varies with pursuer to pursuee speed ratios for various initial track angles. The pursuer employs the pursuit course tactic.

Basis for the Calculation

These curves are a plot of equation D-15.

For this calculation, the pursuee maintains a constant course and speed and does not maneuver during the pursuit.

The capture distance displayed on the ordinate is expressed as a multiple of the initial separation distance at the time pursuit begins, i.e., a capture distance of 0.5 means the pursuee travels a distance equal to one-half the initial separation distance before capture occurs.

Principle Points

1. For a given capture distance, speed ratio requirements become more stringent as θ (the angle between pursuer's course and initial line of sight) increases from 0° to 180°.

2. For all angles, there are diminishing returns as the speed ratio increases.

Figure VI-2

Comparison of Capture Distances for Pursuit Course and Constant Bearing Intercept

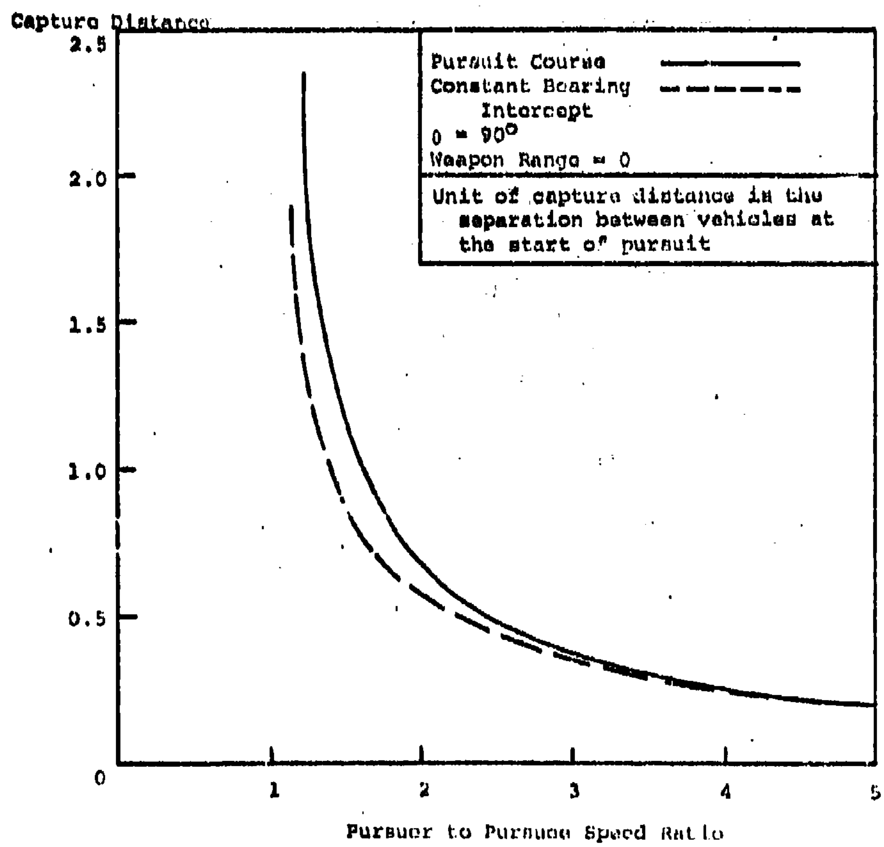


Figure VI-2

Comparison of Capture Distances for Pursuit Course and Constant Bearing Intercept.

Purpose

The purpose of this graph is to display the difference in the capture distance function for the two basic pursuer tactics (pursuit course and steady bearing intercept).

Basis for the Calculation

The pursuit curve is a plot of equation D-15 and the constant bearing curve is a plot of equation D-23.

The capture distance is as defined in Figure 1, i.e. it is a multiple of the initial separation distance at the time pursuit begins.

The pursuee does not maneuver during pursuit.

Principal Points

1. A capability to follow a steady bearing tactic (which may imply greater demands on sensors or external data links) results in reduced speed requirements for the same capture distance. This difference is greatest at a speed ratio of about 1.5.

2. Alternatively (and perhaps more significantly) in this same range the steady bearing tactic greatly reduces capture distance for any given speed ratio.

Figure VI-3

Actual Capture Distance Versus Pursuer to Pursuee Speed Ratio for Various Pursuer Weapon Ranges

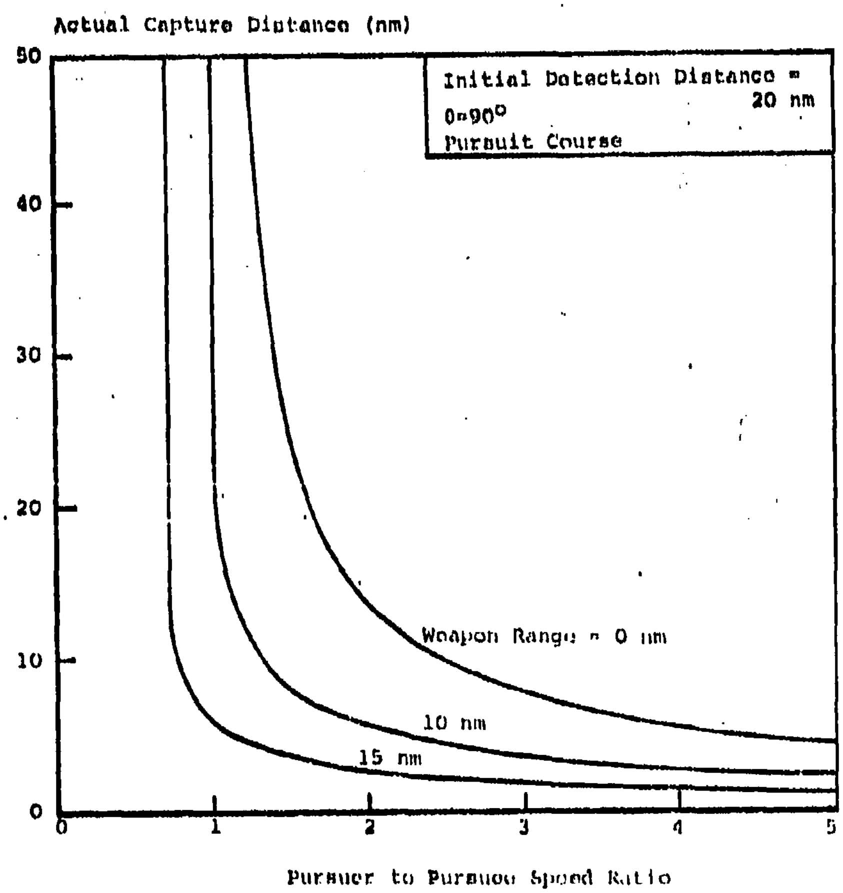


Figure VI-3

Actual Capture Distance Versus Pursuer to Pursuee Speed Ratio for Various Pursuer Weapon Ranges

Purpose

The purpose of this graph is to show the interrelationship between pursuer to pursuee speed ratios and capture distance for various weapon ranges in the pursuit problem.

Basis for the Calculation

This graph is a plot of equation D-19.

The pursuer employs the pursuit course tactic. Capture occurs when the distance between pursuer and pursuee equals the pursuer's weapon range; the actual firing of the weapon is not considered (i.e., the flight time of the weapon is taken to be zero, the weapon velocity is taken to be infinite).

Principal Points

1. For weapon ranges less than half the initial separation distance, the Capture Distance versus Pursuer to Pursuee Speed Ratio curves are asymptotic at 1. If the weapon range is greater than half the initial separation distance, however, the asymptote is shifted to the left, e.g., the asymptote is around .7 for a weapon range of 15 nm. Thus, if the weapon range is greater than half the initial separation distance, it is possible for the pursuer to capture the pursuee even though he has a lesser speed.

2. In the case shown, in the region of high speed ratios an increase in weapon range allows for a larger reduction in required speed ratios. For example: a speed ratio of 4 is necessary to obtain a 5-mile capture distance with zero

weapon range; a 10-mile weapon range reduces the requirement to about 2, and a 15-mile weapon range reduces it to 1.1. The effect diminishes rapidly at speed ration below 1.5. A similar effect is noted for the constant bearing tactic.

Figure VI-4

Pursuer Weapon Range Versus Pursuer to Pursuee Speed Ratio For Given Time to Intercept Pursuee

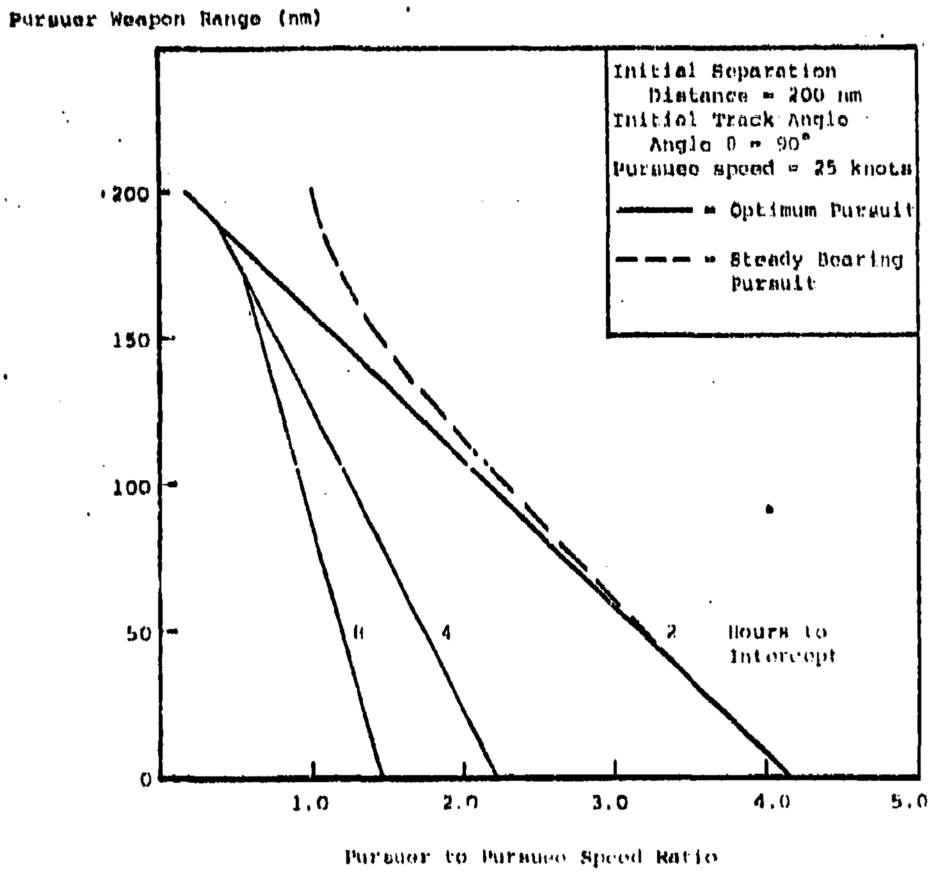


Figure VI-4

Pursuer Weapon Range Versus Pursuer to Pursuee Speed Ratio for Given Time to Intercept Pursuee

Purpose

This figure illustrates the possible pursuer trade-offs between his weapon range and pursuit speed when the pursuer must close the pursuee within a given time.

Basis for Calculation

In the case illustrated, the optimum pursuit path (solid lines) is one which lies between the pure pursuit tactic and the pure steady bearing tactic. This path consists of taking and maintaining a lead angle which minimizes the speed ratio required to come within weapon range of the pursuee within the prescribed time period. Thus, this pursuer tactic maintains a steady course but not a steady bearing.

For a zero weapon range capability the distance which the pursuer must travel in the specified time is the hypotenuse of a right triangle of which one side is the initial separation distance (D) and the other is the product of this specified time and the pursuee's speed. The range of the pursuer's weapon subtracts directly from this requirement. So that:

$$V_p t = \sqrt{D^2 + (V_{p'} t)^2} - R_W$$

where

V_p = Pursuer's required speed (knots)

$V_{p'}$ = Pursuee's speed (in this case 25 knots)

t = Time to intercept (hours)

D = Initial separation distance (in this case 400 nm)

R_W = Range of pursuer's weapon (nm)

The dashed line for the two hour requirement plots the same information where the pursuer uses the pure steady bearing tactic, in which, by definition (for the assumed 90^0 track angle) the minimum pursuer to pursuee speed ratio is ≥ 1.

Note that the optimum tactic converges to the steady bearing tactic as weapon range approaches zero. Note also that the optimum tactic converges with the initial stages of the pure pursuit tactic as weapon range approaches the initial separation distance (as the intersections of the solid lines indicate, as R_W approaches D, smaller lead angles produce earlier intercepts at lower pursuer speed.)

Principal Points

1. If time to intercept is not critical, i.e., times on the order of 8 hours are acceptable, then small increases in speed ratio are equivalent to large changes in weapon range. For example, increasing the speed ratio from .9 to 1.2 is equivalent to reducing the weapon range requirements from 100 nm to 50 nm.

2. The trade-off becomes less favorable to higher platform speeds when time to intercept is short. A two hour requirement with a 50 nm weapon requires a pursuer to pursuee speed ratio of 3.1. A 100 nm weapon meets the same requirement with a speed ratio of 2.2.

C. PURSUIT WITH INTERMITTENT INFORMATION

The previous subsection has addressed the case wherein the pursuer has access to constant information with respect to the pursuee's location. However, pursuee information can be intermittent in nature. An example of such a case is a sonobuoy field located in the open ocean with the capability to relay pursuee location data to an information processing center. After interpretation of the information, the center passes the information to a platform on alert and vectors it toward identified coordinates. A surface ship or submarine transiting through the field would be detected by one or more buoys. Unless the sensor radii overlap, gaps in information occur. If a series of buoys is triggered by the intruding platform, coordinate information would be processed and relayed to the pursuit vehicle. For each piece of information made available, the uncertainty of pursuee area location is reduced to a value commensurate with the information processing time, sensor system accuracy and the speed of the target. The following relationship exemplifies the above discussion:

$$P_D = f\left(W_S,\ A,\ \frac{1}{V_p},\ \frac{1}{V_{pe}},\ \frac{1}{D},\ \frac{1}{T_R}\right)$$

where

P_D = probability of detection by the pursuer

W_S = swath width of field-of-view of the pursuer's onboard sensor

A = location accuracy of the sonobuoy detection

V_p = velocity of pursuer

V_{pe} = velocity of pursuee

D = initial separation distance (at the time of information receipt)

T_B = interpretation time (time required by processing center to receive, interpret and relay information to pursuit platform)

The area of pursuee uncertainty (A), assuming perfect initial sonobuoy location, is a circle of radius V_p, t where:

t = time from sonobuoy detection until pursuer receives another update or completes his search.

$$t = \frac{d}{V_p} + T_B$$

d = distance pursuer travels before a new update or until completing the search.

In the following analysis T_B was assumed to be zero.

As the magnitude of A is increased, the probability of the pursuit platform detecting the pursuee on a first pass is reduced. In other words, the pursuit phase becomes less likely to evolve directly into attack. An interim search will be required. Thus, an increase in pursuee speed acts to decrease P_D, and an increase in pursuer speed does the opposite. It then remains to be determined if V_p and $V_{p'}$ impact upon other terms in the proportionality.

The accuracy parameter, Λ, is a function of the information derived from the sonobuoy system. Velocities probably will not influence this parameter since it is inherent to sensor technology, rather than pursuee characteristics. However, as shown in Section C, SEARCH, sensor swath width, W_s, is a function of V_p, for an acoustic sensor. Additionally, an increase in $V_{p'}$ could result in more frequent updates by the sonobuoy field.

Provided that a command, control and communication (C^3) system exists which permits the relay of updated information in near real-time, the value of D, the distance from pursuer to pursuee, is periodically reduced. Thus, additional intelligence has much the same impact as increased pursuer speed.

The following sequence of two figures and discussion shows some inter-related effects of these detection systems parameters and the relative velocities.

Figure VI-5

Impact of Swath Width and Speed Ratios on the Probability of Detection

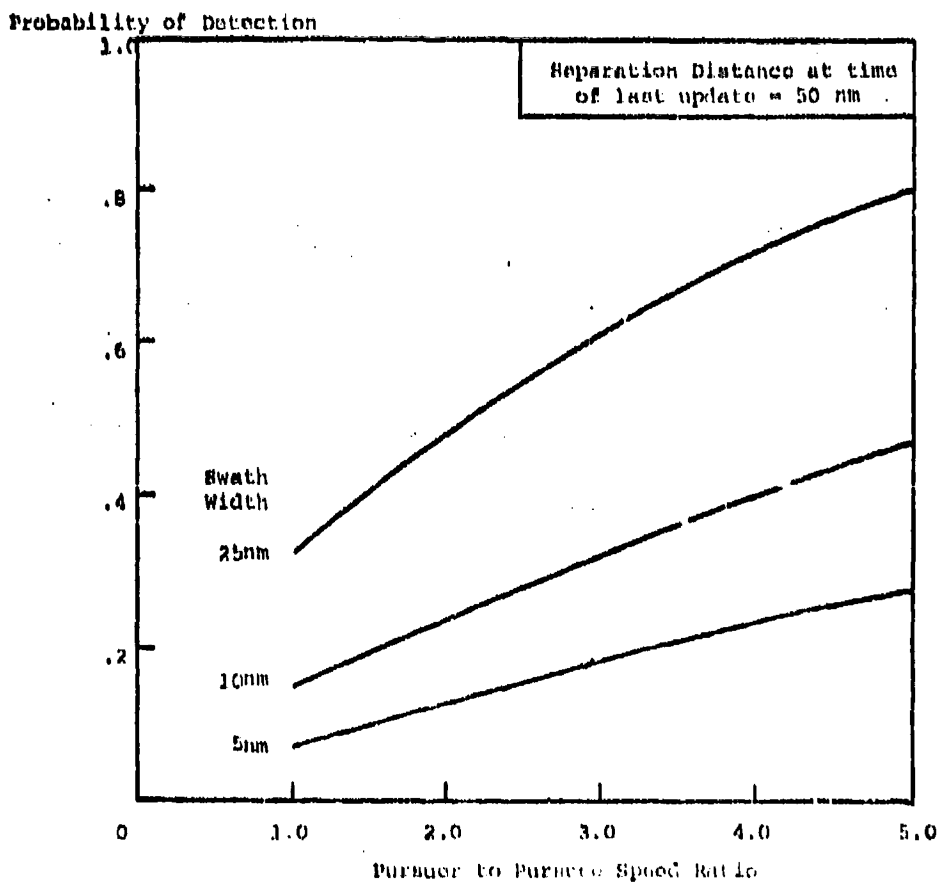


Figure VI-5

Impact of Swath Width and Speed Ratio on the Probability of Detection

Purpose

This figure shows the trade-off between the detection range capability of a pursuer's on-board sensor and increased pursuer speed.

Basis for the Calculation

This is a plot of equation B-33.

The pursuer receives intermittent information on the location of the pursuee and closes the last known position. As he does so, the area of uncertainty grows as a function of the speed of the pursuee and the time required for the pursuer to reach this position (this time, in turn, increases with the initial separation distance and decreases with the pursuer's speed).

This simple case assumes a sensor system for the pursuer which has a constant swath width. The probability of detection within this swath is one. Outside, it is zero (i.e., a "Cookie-Cutter"). The pursuer cuts a swath through the area of uncertainty, and in doing so passes through the last known position of the pursuee. Pursuit terminates when the pursuer completes a swath.

The area of uncertainty grows from the instant of the last update until the completion of the first pass. Therefore, the probability of detection varies directly with pursuer's speed and sensor swath width and inversely with pursuee's speed and the initial separation distance.

Principal Points

Large incremental increases can be noted for the first pass probability of detection by the pursuer as the sensor swath width is increased. However, an increased search speed is interchangeable in effect. For example, a speed ratio of 3.0 in combination with a 10 nm swath width results in the same probability of detection as a 25 nm swath width and a velocity ratio of about one.

Of particular interest is the relative slopes of the three example curves shown. At wider swath widths, any positive increment of pursuer to pursuee speed ratio produces a greater increase in detection probability than the same speed increment at narrower swath speeds. This illustrates the interdependence between the utility of speed and other important parameters.

Figure VI-6

Interraction of Parameters of Intermittent Information Model

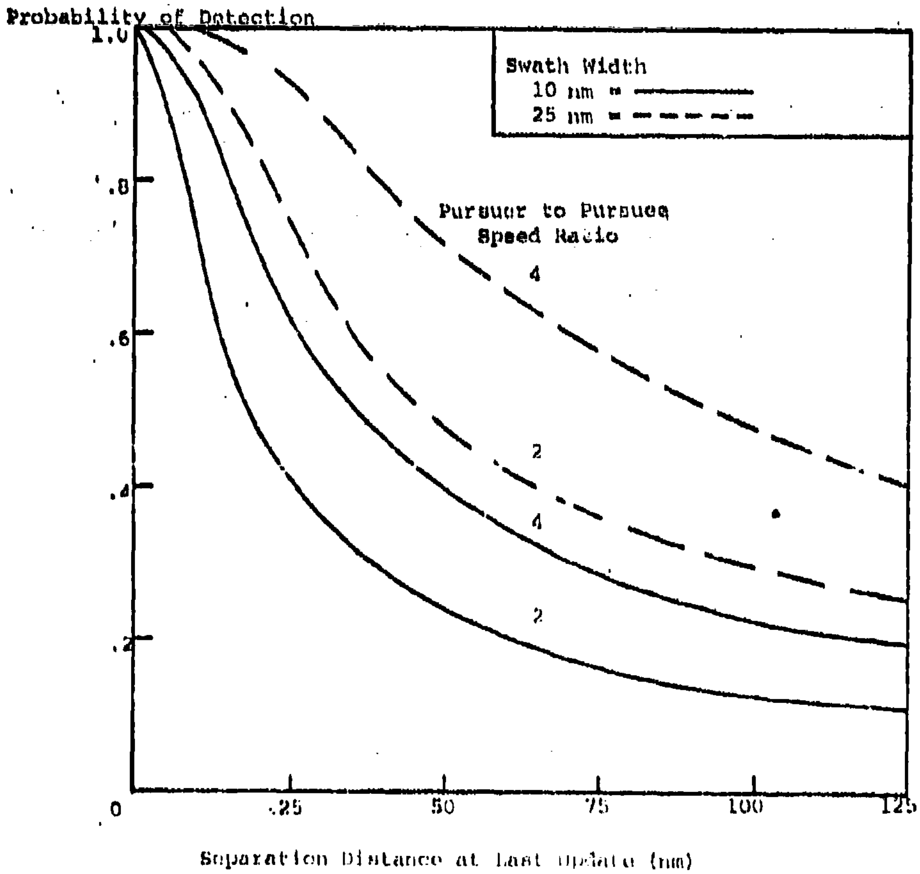


Figure VI-6

Interaction of Parameters in the Intermittent Information Model

Purpose

This figure dispalys the effect of changing the timeliness of information available to the pursuer as a function of sensor swath width and speed ratios. Timeliness of information refers to the number of updates during a pursuit or effectively the distance from pursuer to pursuee at the time of last update.

Basis for the Calculation

This is a plot of equation D-33.

The calculations have the same basis as those in Figure VI-5. This figure highlights the detection probability as a function of separation distance at last update.

Principal Points

1. The impact of reducing the interval between updates is depicted by the curves of Figure VI-6. For the conditions of a 10 nm swath width and a speed ratio of 4, a reduction in separation distance from 100 nm to 50 nm increases the probability of detection from 0.24 to 0.40. Hence improved speed, swath width and information level combine to increase the detection probabilities. Certain minimum requirements appear necessary for each of the three parameters.

D. SPRINT-DRIFT PURSUIT

An additional example of pursuit with intermittent information is that of a pursuer who must use sprint-drift tactics to close a pursuee. An example is a high speed ASW ship pursuing a high speed submarine. Sprint-drift tactics become necessary when the sensor is acoustic and the overall speeds exceed the maximum speed at which the sensor is effective.

The pursuer always sprints to the last known position of the submarine. The justification for this is that the submarine may select any course after he has been detected, and therefore it does not benefit the pursuer to anticipate the submarine's new course.

The time between adjacent drift-listen periods decreases as the pursuer gets closer to his quarry and a limit of convergence is reached when the ground gained while sprinting between drift periods equals that lost while actually listening. This is due to the fact that the submarine always travels a limiting distance equal to the product of his speed and the pursuer drift-listen time; the limit of convergence is the time to sprint this distance plus the drift listen time.

Using these two basic inputs, an expression can be derived which enables the separation distance to be determined by an iterative process for each successive period, and from this a separation distance history can be plotted.

A specific example has been calculated and is shown as Figure VI-7. Appendix D contains a discussion of the basic iterative process.

Figure VI-7

Closing Distance Versus Elapsed Time for Various Target Speeds When Pursuer Uses Sprint-Drift Tactics

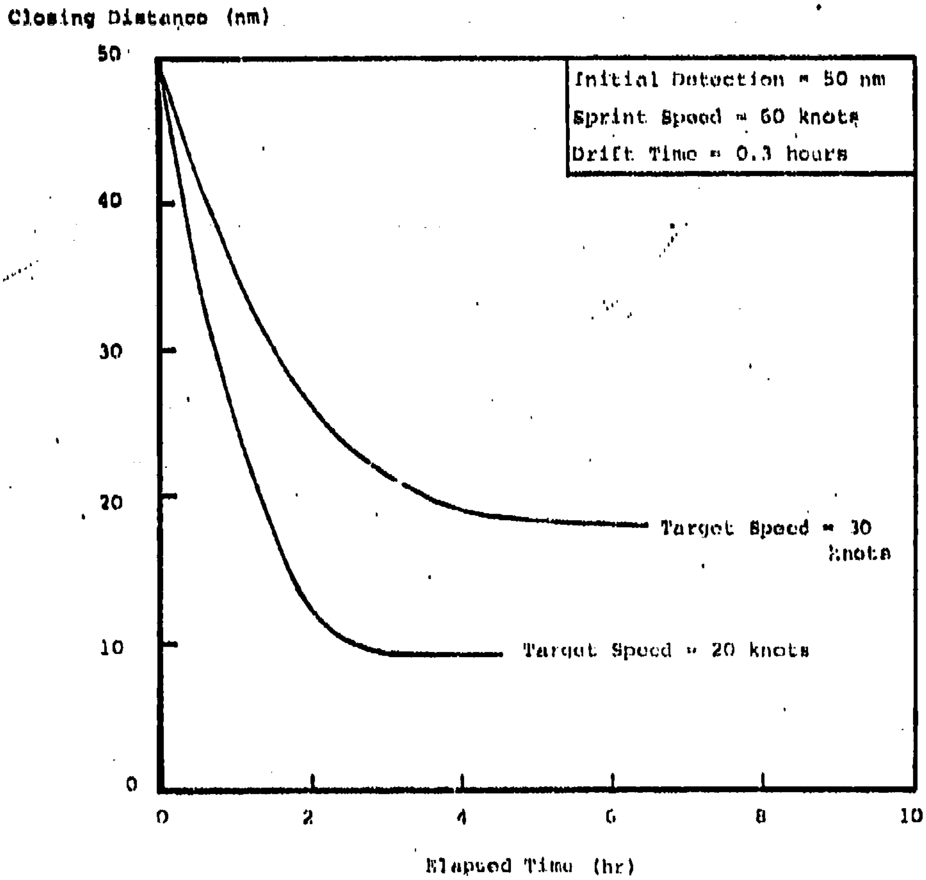


Figure VI-7

Closing Distance Versus Elapsed Time for Various Target Speeds When Pursuer Uses Sprint-Drift Tactics

Purpose

The purpose of this graph is to show the effect of intermittent information (in the form of a sprint-drift pursuit) on closing a target.

Basis for the Calculation

The methodology for calculating the curves displayed on this graph is discussed in Appendix D on pages D-10 and D-11. Basically, it is an iterative process wherein each value of closing distance is dependent on the previous elapsed time and target speed.

At some initial time, t_0, the pursuer detects a target at an initial distance, R_0, which can be equal to or less than his detection range. He then sprints to this datum at a given sprint speed, V_p. During the sprint and drift interval, the target has moved a distance R_1 which is equal to the product of his speed (V_{p_t}) and the elapsed time, t. The pursuer now sprints a distance R_1 to the new datum, and the process is repeated until the pursuer reaches his limiting closing distance, where $R_n - R_{n-1}$ approaches zero.

This process can be viewed as a modified form of pursuit since the pursuer proceeds to the point of the last known position of the target as opposed to heading toward the actual target position as in the case of pure pursuit.

Principal Points

1. For a given detection capability and sprint speed, there is a limiting distance to which the pursuer can close the target. This distance is dependent on the target speed, i.e. the limiting distance increases with increasing target speed.

This implies that the pursuer must have a weapon range equal to or greater than his limiting distance, or a secondary sensor which allows continuous close-in pursuit.

E. SUMMARY AND CONCLUSIONS

There are two basic pursuit tactics:

- The "pursuit curve" wherein the pursuer always heads directly for the target and at some point before capture ends in a stern chase.

- The "steady bearing" wherein the pursuer computes an intercept lead angle, follows this path and captures at a predicted point.

Given accurate prediction, the steady bearing tactic is more efficient but both require pursuer to pursuee speed ratios of about 1.5 or more. The marginal return for speed ratios greater than 3.0 is small.

The pursuer can substitute increased weapon range for a higher pursuit speed ratio when the object of pursuit is attack. The trade-off becomes more favorable to increased weapon range as time available to capture is reduced.

When the pursuer has intermittent information, the area of uncertainty of the pursuee's location grows as the product of the pursuee speed and the time since the last look. Thus, there is a trade-off between increasing the pursuer's speed and increasing his swath width of detection. There is also a much greater marginal gain from increasing both speed and swath width.

In the sprint-drift form of intermittent pursuit, there is a minimum assured range to the pursuee which a pursuer can achieve. This is due to the fact that the pursuee can move in any direction during the sprint period of the pursuer. In order to capture, the pursuer must possess either a secondary sensor which operates during sprint or a weapon range greater than this minimum assured range.

SECTION VII. ATTACK AND COUNTERATTACK

A. GENERAL

This section addresses the impact of speed on the potential outcome of engaging naval platforms.

Attack is a result of a sequence of events beginning with detection of an enemy target. Following detection, the target is pursued by an alerted platform until their separation distance has been reduced to an estimated or measured magnitude. If the initial target location error and the interval between updating of target position information were sufficient to cause uncertainty in final target location, a search would have to be executed at the termination of pursuit. The search would continue until the target had been redetected or the pursuit vehicle had reached its limit of endurance. When search is required, the attack phase is assumed to be initiated at the instant of secondary detection. Otherwise, attack is assumed to begin when the distance between platforms is equivalent to the range of the pursuer's on board weapons.

Preparation for target escape in the form of counterattack begins when the target is initially alerted to an approaching platform. The actual counterattack, of course, cannot begin until the distance between platforms has been reduced to the initial target's weapon range.

Another form of escape is avoidance by employing a speed advantage with respect to a pursuer or by means of using speed to maneuver. A maneuver might be used either to confuse the enemy platform or to avoid a launched weapon. Escape by maneuver and avoidance is addressed in the "Maneuver and Avoidance" section.

In its most simple form, the tactic of attack/counterattack may be viewed in terms of two competing platforms, each possessing an on-board surveillance system or communication access to a remote system. Inherent to each platform is a weapon system specified by a maximum range, a lethal radius of the warhead, a maximum G-force (acceleration) which the weapon can sustain, and a minimum weapon system response time. Response time includes the minimum time interval required for all events between detection and weapon launch, i.e., interpretation of information, updates of target position and weapon set-up and firing. The travel time of the weapon from firing to detonation might also be considered. The possibility of maneuvers to avoid a launched weapon is considered in the section on maneuvers. Thus, in this section, the measure of effectiveness used is the relative positioning of the competing platforms such that a weapon can be fired by at least one of them and contain the other within its maximum range. The first platform to accomplish this advantage is assumed to have won the encounter. No attempt is made to assess weapon effects (which are not germane to this analysis).

B. ATTACK AGAINST AN UNESCORTED TARGET

The interaction under consideration is between two opposing platforms each supported by its own surveillance system, internal or external. Either one of the systems exceeds the other with respect to range or they are equal in capability. The platform with the inferior detection system is initially considered as the target which later might attempt a counterattack. To facilitate the discussion, the initial attacker is referred to as Red and the initial target is called Blue. It is assumed that the area of operation is large when compared to the surveillance ranges of both Red and Blue. Thus, the benefits of greater detection capability can be fully utilized. After detection of Blue, Red might decide to prepare to attack or to avoid engagement. Such a decision will be affected by the relative weapon capabilities and speed ratios of the platforms. Thus, the proper balance of platform speed, weapon radius and detection range can provide a commander the choice of engaging or not engaging.

A decision tree can be constructed for the potential attacker based upon his best estimates of enemy capability. The parameters considered are shown in Table VII-1.

Table VII-1

Attack/Counterattack System Parameters

	Red	Blue
Surveillance Range	R_{S_1}	R_{S_2}
Weapon Range	R_{W_1}	R_{W_2}
Platform Velocity After Target Detection	V_1	V_2
Weapon Response Time Measured from Target Detection to Weapon Launch	T_{W_1}	T_{W_2}

Tables VII-2a and VII-2b list the outcomes of encounters under the conditions indicated. Table VII-2a includes the cases where Blue has the greater weapon range; Table VII-2b, those where Red has the weapon range advantage. In both tables, P_A is the probability of Red firing a potentially destructive weapon at Blue prior to or simultaneously with a counterfiring by the target. The term P_B is similarly defined for counterattack by Blue. Note that even though Blue may not have detected the Red platform, it does not necessarily mean that he is completely helpless. Under some circumstances, it might be possible to observe the course of a launched weapon and carry out avoidance maneuvers prior to detonation.

The simplest case occurs when Blue's surveillance range is less than both the surveillance range and weapon range of Red. Thus, for the conditions

$$R_{S_1} > R_{S_2} \quad \text{and} \quad R_{W_1} > R_{W_2}$$

it follows that,

$$P_A = 1 \qquad (1)$$

Table VII-2a

Conflict Conditions and Deterministic Results
(Blue Weapon Range is Greater)

General Conditions: $R_{S_1} > R_{S_2} \geq R_{W_2} \geq R_{W_1}$

Case 1 - Special Conditions:

$$V_1 > V_2$$

$$\text{Red Weapon Flight Time} + \frac{R_{S_2} - R_{W_1}}{V_1 - V_2} < T_{W_2}$$

Results: $P_A = 1$; $P_B = 0$

Case 2 - Special Conditions:

$$V_1 > V_2$$

$$\text{Red Weapon Flight Time} + \frac{R_{S_2} - R_{W_1}}{V_1 - V_2} = T_{W_2}$$

Results: $P_A = P_B = 1$, or $P_A = P_B = 0$

Case 3 - Special Conditions:

$$V_1 > V_2$$

$$\frac{R_{S_2} - R_{W_1}}{V_1 - V_2} > T_{W_2}$$

Results: $P_A = 0$; $P_B = 1$, 0

Case 4 - Special Conditions:

$$V_1 \leq V_2$$

Results: $P_A = P_B = 0$,

or $P_A = P_B = 1$

Table VII-2b

Conflict Conditions and Deterministic Results
(Red Weapon Range Is Greater)

General Conditions: $R_{S_1} > R_{S_2} > R_{W_1} > R_{W_2}$

Case 5 - Special Conditions:

$$V_1 > V_2$$

Results: $P_A = 1$ and $P_B = 0$

Case 6 - Special Conditions:

$$V_1 \leq V_2$$

Results: $P_A = 0$ and $P_B = 1$, 0

More interesting cases evolve when the weapon range of Red is less than the surveillance range of Blue. When this occurs, the conditions in Tables VII-2a and VII-2b may apply and both parties enter into the decision process.

The discussion of Table VII-2a begins with Case 1. As the general conditions indicate, the potential attacker is either at a weapon range disadvantage, or, at best, equality (i.e., $R_{W_1} \leq R_{W_2}$). However, the attacker is capable of a greater platform speed. It is assumed for this analysis that the detection range capability of each system is greater than or equal to its weapon range. In other words, even if a weapon could travel beyond the maximum detection range of the system, it would not be launched because of a lack of target information.

After relative detection ranges, weapon ranges and speeds have been defined, the final parameter to be considered is the target weapon response time. Since the initial attacker is at a weapon range disadvantage, he must rely upon speed in order to carry out a successful attack. Red must position himself within the circle of maximum enemy weapon range in order to commence firing. The time available to accomplish such a position is defined in Table VII-2a, Case 1, to be:

$$\frac{R_{S_2} - R_{W_1}}{V_1 - V_2} \qquad (2)$$

The distance depicted in the numerator of the above terms is the difference between the maximum detection range of Blue and the weapon range of Red. The denominator is the velocity difference of the platforms. This simple form holds only after both platforms have detected. Prior to a Blue counterdetection, Red will be closing on Blue using a pursuit or constant bearing course, and the relative velocity is more complex. These tactics are discussed in the Pursuit section. However, after Red is counterdetected, it is assumed that Blue chooses a course directly away from Red. Subsequent to this maneuver, the relative velocity simplifies to the denominator shown in equation (2).

Avoidance maneuvers to reduce weapon accuracy would again generate an angular component in the relative velocity expression. However, different conditions exist. Red has fired. Discussions of this situation is contained in the maneuver and avoidance section.

In Case 2, the time required for the attacker to fire is equivalent to enemy weapon response time. The outcome for this set of circumstances is a standoff. The platform capable of the greatest surveillance range decides whether P_A and P_B are equal to one (1) or zero (0). If it is decided to attack, the target is capable of successful counterattack. Thus, such a decision would be dominated by other considerations, e.g., if Red assessed the target to be of greater value than his platform or if the weapon systems were not of equal capability. If Red assessed his weapon to be more reliable and lethal than that of the enemy, he might attack even though he would incur retaliation.

Depicted in Case 3, is a situation whereby Red's velocity advantage is not adequate to bring about favorable results. If the attack does occur, a successful counterattack will result and $P_B = 1$. However, if Red is rational, he will avoid an encounter with the detected enemy and both P_A and P_B will equal zero (0). Case 4 depicts a hopeless circumstance for Red. He does not possess a velocity advantage to compensate for inferior weapons. Thus, his only alternative is to detect the enemy with his superior range surveillance system and to continue to avoid him. Any encounter will result in an advantage to Blue.

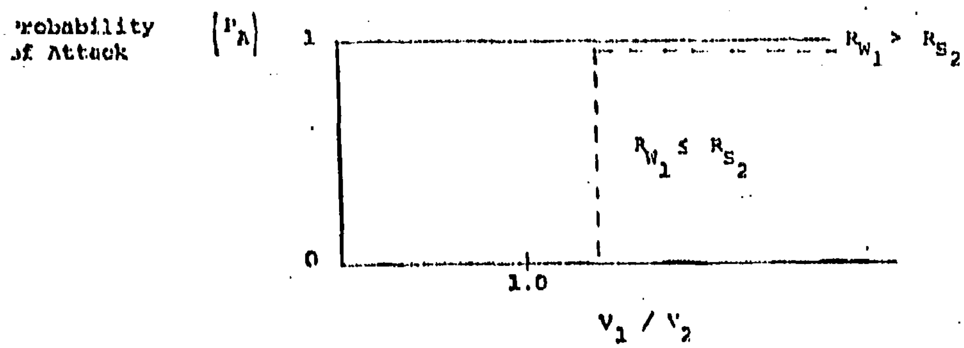
Case 5 in Table VII-2b presents the conditions of engagement which greatly favor Red. He possesses a surveillance range, weapon range and velocity advantage over Blue. Thus, Red can always initiate an attack at his discretion.

Case 6 in Table VII-2b is the remaining set of conditions to be considered. Since the potential target platform has a speed advantage and a surveillance range greater than Red's weapon range, he will probably choose to avoid the enemy by outdistancing him. Any encounter will result in an advantage for Red.

The results shown in Table VII-2a and in Table VII-2b can be consolidated into the simplified diagram of Figure VII-1.

Figure VII-1

Impact of Speed Ratios
on the Probability of Attack



Speed Ratio

In summary, as the solid line shows, whenever Red's weapon range exceeds Blue's detection range ($R_{W_1} > R_{S_2}$), for all speed ratios, the probability of attack by Red is unity. When Red's weapon range is less than Blue's detection range and the Red to Blue speed ratio is less than one, Blue can always avoid (i.e., $P_A = 0$). At some Red to Blue speed ratio (V_1/V_2) greater than one, Red can close and attack. The specific value depends on other parameters. The probability of Red attack depends on relative weapon capabilities and the other factors previously indicated.

Figure VII-2 illustrates an example in which an attacker can use a speed advantage to compensate for an inferior weapon. In this case, Red used the interval of Blue's weapon response time to attempt to close at high speed and launch his own weapon prior to Blue's weapon launch.

Figure VII-2

Impact of Relative Speed and System Ranges on Weapon Response Time

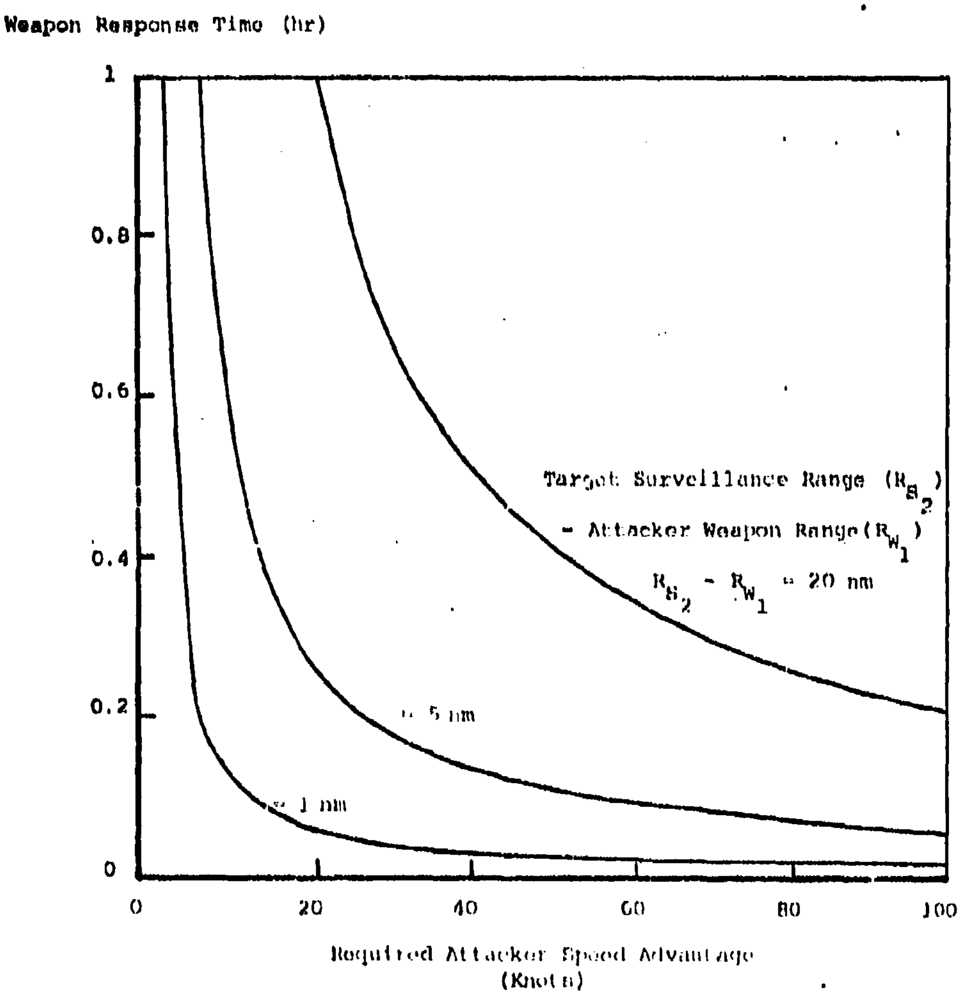


Figure VII-2

Impact of Relative Speed and System Ranges on Weapon Response Time

Purpose

To show the degree to which an attacker's speed advantage can compensate for an inferior weapon range whenever the target's weapon response time is greater than zero.

Basis for Calculation

The time available for a potential target to counterattack is a ratio of specific system ranges to relative speeds as shown in the following equation:

$$T = \frac{R_{S_2} - R_{W_1}}{V_1 - V_2}$$

where:

T = Weapon response time of initial target (Blue)

R_{S_2} = Detection range of initial target (Blue)

R_{W_1} = Weapon range of attacker (Red)

V_1 = Velocity of attacker (Red)

V_2 = Velocity of initial target (Blue)

Assumptions

-- The attacker (Red) detection range exceeds the initial target (Blue) detection range (i.e., $R_{S_1} > R_{S_2}$).

-- Blue weapon range exceeds Red weapon range (i.e., $R_{W_2} > R_{W_1}$).

Red desires to deliver a lethal weapon against Blue. However, because Red's weapon range is less than Blue's, Red must prepare for launch and then drive to a position inside his maximum weapon range before Blue counterattack. Blue detects Red at a range R_{S_2}, and must respond or counterattack prior to the time that Red closes to within R_{W_1} nautical miles.

Principal Points

1. Figure VII-2 shows that for the case where Blue's detection system exceeds Red's weapon range by 20 nm, a Red velocity advantage as great as 100 knots still permits successful counterattack by Blue if Blue's weapon response time is less than 0.2 hours or 12 minutes. Modern tactical weapon systems have much shorter response times.

2. For lesser range differences ($R_{S_2} - R_{W_1} = 5$ nm), a relative velocity of 100 knots limits Blue's weapon response time to 3 minutes for successful counterattack. This value also might be more than adequate for a tactical weapon.

3. The third case whereby $R_{S_2} - R_{W_1} = 1$ nm results in a maximum weapon response time of approximately one minute, when Red's velocity advantage is 40 knots or greater. Thus, it can be seen that a speed advantage must be large in order to ensure the first shot unless the detection range of the initial target and the attacker weapon range are nearly comparable. It might be reasonable to assume that a greater payoff results from improving weapon ranges than from increasing platform speed. However, after weapon launch, speed may be very advantageous in degrading enemy weapon accuracy. This application of speed in attack is addressed in the following section on maneuver and avoidance.

C. ATTACK AGAINST AN ESCORTED TARGET

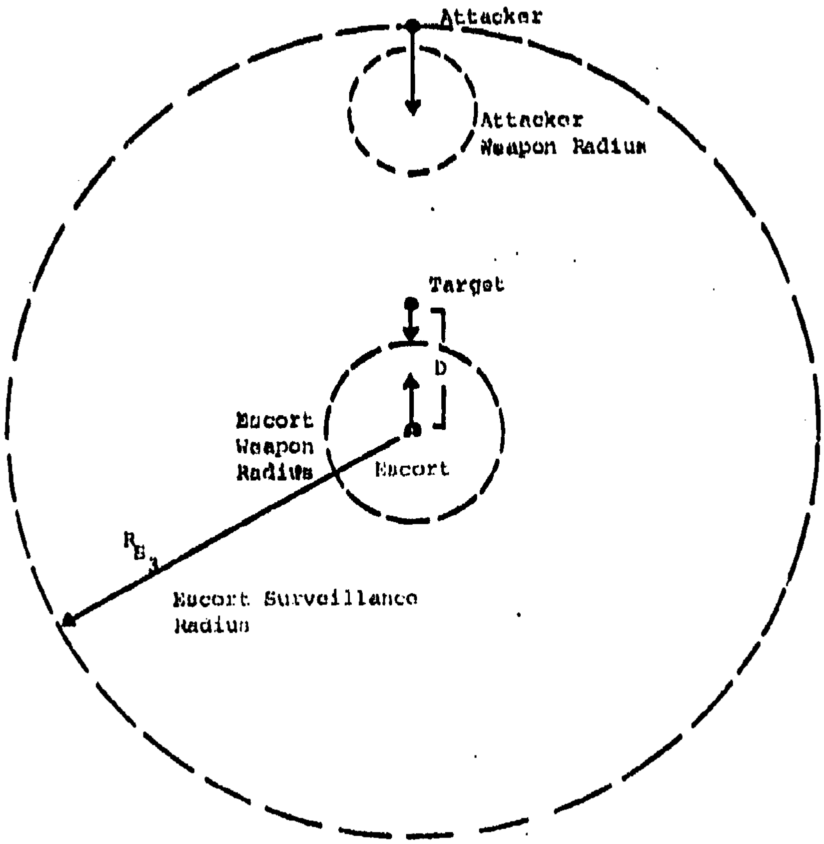
An interception scenario incorporating an escort platform was addressed in the section on Convoy. A similar situation is considered in this subsection, emphasizing the general parameters of attack and counterattack.

Figure VII-3 shows the geometry of the three platforms involved. Initially, an attacker (Red) detects a primary target and makes an approach for weapon launch. The primary target is escorted by a defensive platform which is employed for counter detection and defense. To greatly simplify the analysis, it is assumed that Red approaches from a direction directly opposite the escort vehicle (i.e., points representing attacker, target and escort are located on the same line). At the moment of counter detection, the target turns directly away from Red, toward the escort vehicle. The escort simultaneously speeds directly toward Red.

Pertinent parameters are listed in Table VII-3.

Figure VII-3

Geometry for Escort Intercept of Attacker



(D = Initial separation distance between convoy and escort)

Table VII-3

Parameters for the Interception Scenario

	RED	BLUE	
		CONVOY	ESCORT
Speed	V_1	V_2	V_3
Weapon Radius	R_{W_1}		R_{W_3}
Time interval between counterdetection and readiness to launch	T_{W_1}		T_{W_3}
Escort surveillance range			R_{S_3}
Distance between Escort and Convoy at time of detection of Red			D
Distance traveled by Red from time he is counterdetected until he can launch his weapon	X_1		

Using the parameters of Table VII-3, the distance (X_1) traveled by Red from the point of counterdetection to potential weapon launch is:

$$X_1 = R_{B_3} - R_{W_1} - D + V_2\ T_{W_1} \qquad (3)$$

and, since $X_1 = V_1 \cdot T_{W_1}$:

$$T_{W_1} = \frac{R_{B_3} - R_{W_1} - D + V_2\ T_{W_1}}{V_1} \qquad (4)$$

or

$$T_{W_1} = \frac{R_{B_3} - R_{W_1} - D}{V_1 - V_2} \qquad (5)$$

A corresponding calcualtion for X_3, the distance traveled by the escort vehicle from the time of counterdetection to potential weapon launch against Red, is:

$$X_3 = R_{B_3} - \left[R_{B_3} - R_{W_1} - D + V_2\ T_{W_3}\right] \qquad (6)$$

It follows that:

$$T_{W_3} = R_{B_3} - \left[R_{B_3} - R_{W_1} - D + V_2\ T_{W_3}\right] - R_{W_3} \qquad (7)$$

or

$$T_{W_3} = \frac{R_{W_1} + D - R_{W_3}}{V_2 + V_3} \qquad (8)$$

Table VII-4 shows relative conditions of T_{W_1} and T_{W_3} and corresponding results of potential encounters.

The results are simple in that, if Red requires longer to position himself for launch than does the escort, attack will fail (Case 1). A lesser time requirement results in successful attack (Case 3). From the equations depicting T_{W_1} and T_{W_3}, relative speed can be seen to impact upon the potential results. However, some situations exist when speed has little impact. These can be determined by observing equations (5) and (8).

Table VII-4

Conditions and Results of Interception Scenario

Case 1:

Condition:

$$T_{W_1} > T_{W_3} \quad \text{or} \quad \frac{R_{B_3} - R_{W_1} - D}{V_1 - V_2} > \frac{R_{W_1} + D - R_{W_3}}{V_2 + V_3}$$

Result:

$$P_A = 0 \; ; \; P_B = 1, 0$$

Case 2:

Condition:

$$T_{W_1} = T_{W_3}$$

Result:

$$P_A = 0, 1 \; ; \; P_B = 0, 1$$

Case 3:

Condition:

$$T_{W_1} < T_{W_3}$$

Result:

$$P_A = 1 \; ; \; P_B = 0$$

The numerator of equation (5) becomes negative when:

$$R_{W_1} > R_{S_3} - D \tag{9}$$

This implies that, when the weapon range of Red exceeds the surveillance capability of Blue, a successful attack can be executed, regardless of the relative speeds of the three platforms of interest.

The numerator of equation (8) becomes negative when:

$$R_{W_3} > R_{W_1} + D \tag{10}$$

Thus, given that $R_{S_3} \geq R_{W_3}$, a successful defense can be carried out when conditions of equation (10) apply, regardless of relative speeds.

One further observation is noted from equation (5). If V_2 is greater than V_1, the target can always escape from Red, given that $R_{S_3} - D > R_{W_1}$.

Thus, there are many situations where speed can influence the outcome of attack - counterattack scenarios. Other parameters such as weapons and surveillance systems are equally important and the utility of speed should be considered in this context.

D. SUMMARY AND CONCLUSIONS

This section initially considered the general attack-counterattack scenario, identifying the potential relationships among the various parameters.

In Subsection B, ATTACK AGAINST AN UNESCORTED TARGET, the one-on-one situation was discussed.

There are four important variables for each platform (target and attacker) which impact on the outcome of attack and counterattack. Of course, speed of each platform is the primary one under consideration. The others are, for each platform, surveillance range (includes external sources), weapon range and weapon response time (measured from detection to weapon launch). Several cases, then, are relevant.

Case I. Attacker surveillance range and weapon range are both greater than the target's surveillance range. In this case, speed is irrelevant. The outcome is simple. Given detection, the attacker can always attack the target. The target never has the opportunity to counterattack or evade.

Case II. Attacker weapon range is less than the target weapon range, and additionally,

(1) Case II-1. The target surveillance range lies between the attacker's surveillance range and attacker's weapon range. In Case II-1, when the attacker's speed is greater than the target speed, the outcome depends on the target's response time.

The engagement consists of the attacker detecting (or receiving knowledge of) the target and closing the range to the target; but the target counterdetects the attacker before the attacker is in a position to launch his weapon. The target then turns away from the attacker and prepares to counterattack, an operation which takes some time. In the meantime, the attacker continues to close the distance until it reaches weapon range. For simplicity of description, weapon flight times are considered to be zero.

When the distance-speed relations are such that the time to close this distance is less than the target response time, the attacker always attacks and the target does not.

When the time to close is equal to the target response time, the attacker may choose to break off the attack, in which case the target never has the opportunity to do so (i.e., neither attacks) or the attacker attacks and the target also attacks.

Lastly, when the time is greater than the target response time, the attacker should break off his "attack"; otherwise, the target may choose to counterattack or it may break off the attack.

(2) Case II-2. The target speed is greater than the attacker speed. In this case, the attacker detects and, as before, the target counterdetects before the attacker reaches its weapon range. At this point the target can turn away and open or maintain range in a "Mexican stand-off" or the target might choose to allow the range to close further (even helping it) and engage the attacker.

Case III. The attacker's surveillance range and weapon range are each greater that the target's corresponding parameters, and the target surveillance range is greater than the attacker's weapon range. If the attacker's speed is also greater than the target speed, the attacker always attacks and the target never has the opportunity to counterattack. If, finally, the target's speed is greater than attacker's speed, the target will probably choose to avoid engagement.

In any of the above cases, when one player has the option to engage the other and, by so doing, allow a counterattack, it will choose to do so on the basis of factors other than those considered herein (e.g., relative worth of the two forces).

Subsection C, ATTACK AGAINST AN ESCORTED TARGET, addresses the case of a convoy escort (Blue) prosecuting a counterattack against Red, who is attempting to attack a convoy ship. Timely counterattack by the escort is found to depend on initial geometry, relative detection ranges and weapon ranges as well as on relative speed capabilities.

SECTION VIII. MANEUVER AND AVOIDANCE

A. GENERAL

In this discussion a maneuver is defined as any tactic that is employed by a naval platform which is designed to favorably alter the potential outcome of any offensive or defensive engagement. For example, a platform whose intent is to engage with an enemy force might possess a weapon range capability less than the target which is to be attacked. Consequently, a maneuver could be executed after coming within the weapon radius of the enemy to cause confusion and also to degrade the accuracy of weapons launched during counterattack.

Maneuvers, in general, relate to all of the topics addressed in the previous sections. In almost every case analyzed in those sections an offensive or defense maneuver can be visualized which has the potential to produce an advantage during engagement. This section will, therefore, be of a more general nature than the others. In many cases, the ability to carry out a maneuver is limited by relative speed ratios and other factors. Successful avoidance normally requires greater speed than that obtainable by the opposing force. Thus, the intent of this section is to present cases of maneuvers which might impact on the result of an engagement and the relative speeds required to produce a significant change.

Offensive and defensive maneuvers are discussed. Offensive maneuvers are those movements which are used to increase the probability of successful attack either by confusing the enemy or by achieving a favorable launch position; defensive maneuvers are used to achieve escape by avoidance or to reduce the accuracy and destruction potential of enemy weapons.

Three subsections follow which address, in order, the application of manouvers to pursuit, search and attack. A fourth subsection (E) consolidates findings of subsections B, C, and D, as they apply to convoy transit through an area under surveillance by a dedicated enemy.

B. PURSUIT

During the pursuit of Blue units by a Red force (in which Blue's counter-detection range is greater than Red's weapon range), a minimum speed advantage must be sustained by Red. This advantage must be sufficient such that the Blue is overtaken, detected and attacked prior to the accomplishment of the Blue mission.

The Pursuit section discussed two potential situations which might occur - pure pursuit with Red having continuous information as to Blue's location and pursuit with intermittent information. Little can be added, as far as maneuvers are concerned, with respect to pure pursuit. If Blue also has information on Red's location, he has two alternatives, preparation for attack, or attempt to escape. The choice will depend upon Blue's maximum speed and weapon capability relative to Red.

For the situation whereby Red receives intermittent target location information and Blue receives intermittent or total information, maneuvers or avoidance can be employed by Blue. The intent of these maneuvers would be to increase Blue's area of uncertainty during periods of Red blind pursuit and, thus, break Red's pursuit and impending attack or gain time in order to execute a mission objective prior to an inevitable Red attack. Given the requisite Red speed advantage and update frequency, an eventual engagement would be inevitable. Less frequent updates might result in escape. Of course, if Blue could outsprint the pursuer, escape would always be possible.

C. SEARCH AND DETECTION

The value to Blue of increased maneuvering speed to reduce the probability of initial detection by Red depends on other factors, such as the type of sensor system employed by Red. An example which illustrates some of these factors is that of Red searching an area A with randomly placed passive acoustic sensors (e.g., a field of passive sonobuoys). Assume that Blue is initially at the edge of the area A and Blue's mission requires transit of the area. His objective is to employ maneuver(s) at the appropriate speed(s) to avoid detection by these sensors.

The utility of Blue speed in this problem can be illuminated by considering the basic search equation for the case of zero searcher speed (sonobuoys) which has the following form:

$$P_D = 1 - \mathrm{EXP}(-N \cdot [Q(V)] \cdot L/A) \qquad (1)$$

where:

P_D = probability of detection of Blue

N = number of sensors

V = speed of encroaching Blue unit

Q(V) = detection area of one Red sensor for a specific Blue speed, monotonically increasing with Blue speed

L = length of Blue's path through A

A = total area being searched by Red

The acoustic sensors are assumed to be dispersed randomly throughout the total area of search (i.e., there are no barriers to be crossed).

The number of sensors, N, and the area A are parameters under control of Red. L and Q(V) are parameters controlled by Blue.

The smaller that Blue can make the product Q(V)·L, the lower the probability of his being detected by Red. Blue can minimize L by transiting over the shortest length path through area A. The specific form of the term Q(V) depends on the total radiated noise of Blue as a function of his speed, the environmental conditions and the capabilities of the Red sonobuoys.

For purposes of this discussion, the effect of the environment can be viewed as a background noise which establishes a lower threshold of detection and thus a value of Blue's total radiated noise below which Red's detection range (from each sonobuoy) would be essentially zero.

Blue's total radiated noise is composed of two major components. The first is internally generated noise which is approximately constant for all speeds. The second is a combination of flow-noises emanating from the hull itself and from Blue's propeller(s). For modern attack nuclear submarines, at speeds below about 10-12 knots the internal noise dominates and the total radiated noise level is approximately constant over the speed range from zero to about 10-12 knots. At higher speeds the flow noises dominate and the total noise envelope rises monotonically with speed.

To minimize the value of the term Q(V), Blue should proceed at a speed below about 10-12 knots. The expected value of Q(V) will be determined by the relationship among Blue's internal self noise, the background noise level, the attenuation of Blue's noise with spreading and the average capabilities of Red's sonobuoys (i.e., the Figure of Merit of the sonobuoys against Blue in the existing environment).

Thus, Blue's best tactic is to take the most direct path through A (i.e., minimize L) at a speed below about 10-12 knots (minimize Q(V)).

Rather than randomly employ sensors over the entire area, the Red force might elect to form a barrier across choke points. Again, the best tactic for Blue, acting only on knowledge of sensor capability and not on location or frequency of coverage along the barrier, remains to select the most direct route and choose his speed as discussed above. However, once information becomes available concerning barrier location and frequency of coverage, a sprint speed can be selected which will permit transit of the barrier between periods of sensor coverage. A similar rationale would apply to broad area search. Consequently, it is implied that a bounded speed is required of Blue when he is completely ignorant of Red's sensor deployment and tactics of operation. However, when this additional information about the Red force becomes available to Blue, he can apply speed to exercise avoidance.

For sensors employed by Red for detection whose range of detection is independent of Blue's speed, increased speed might or might not act as an asset for Blue. A sensor which is capable of continuously monitoring a transit area with a high probability of detection will identify a target presence, regardless of Blue speed. The following equation describes the basic situation:

$$P_D = 1 - (1 - P_G)^{N^*} \qquad (2)$$

where:

P_D = probability of detecting Blue

P_G = probability of detecting Blue per sensor glimpse

N = number of glimpses per available search time

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* Naval Operations Analysis, United States Naval Institute (Annapolis, Maryland, 1968), Chapter 4.

Equation (2) indicates that for a high single glimpse probability (P_G), probability of detection (P_D) would be near unity even for values of N = 1. A satellite with a large field of view, excellent resolution, and not affected by cloud coverage is an example of such a case. However, for those surveillance sensors with lower glimpse probabilities, an increased speed of transit immediately becomes beneficial to Blue. The number of glimpses (N) becomes fewer because the exposure time of the target is reduced and a smaller value of P_D results.

D. EVASION OF ATTACK

The Attack and Counterattack section addressed the probable outcome of an engagement based on the firing of a first shot. If one of the combatants was able to launch a weapon prior to the other, he was considered to be the winner of an engagement. However, to complete the analysis of attack/counterattack, the probability of target destruction after weapon launch must be considered. Presented in this subsection is a discussion of how speed might be applied to reduce the capability of an enemy weapon, subsequent to its launch.

A case which illustrates is one where Red has superior detection capability and higher platform speed than Blue, but Blue has the greater weapon range. Thus, Red has the option to attack or not, but must consider Blue's ability to fire first.

Initially, Red's problem can be represented by the following Lanchester equations:

$$\frac{dN}{dt} = -P_M \cdot M \tag{3}$$

and,

$$\frac{dM}{dt} = -P_N \cdot N \tag{4}$$

where,

P_N = probability of Red survival

P_M = probability of Blue survival

N = Red weapon capability

M = Blue weapon capability

t = time interval of engagement

Thus, Red's survivability function alters over time as a function of the product of Blue's weapon capability and the survivability of Blue and vice versa. However, since Red possesses the option to attack or avoid he should consider the expected value of the outcome. That is, Red should not normally choose to attack unless the following inequality holds:

$$U_1(1-P_N) < U_2(1-P_M) \qquad (5)$$

where,

U_1 = value of Red platform

U_2 = value of Blue platform

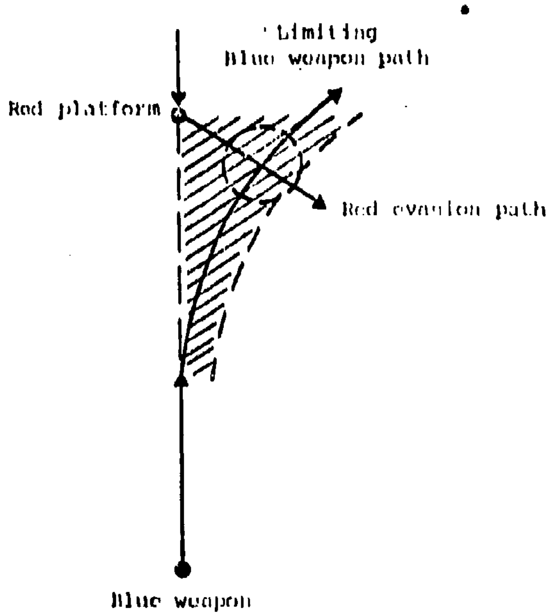
The left side of equation (5) represents the expected value to be lost by Red and the right side, Blue's expected loss. If this inequality were reversed, Red should not attack (except in the circumstance where some larger overall values at stake may so dictate).

The question is, how does Red favorably alter this inequality? The platform value terms are fixed so that Red's tactics (i.e., speed and maneuver) can only affect the kill probabilities, $(1-P_N)$ or $(1-P_M)$. In this specific case, since Blue has the greater weapon range, there is a time period (while Red is inside Blue weapon range but cannot yet reach Blue with his weapon) within which the only effect Red's tactics can have is to alter his own survivability against Blue's weapon. Our interest, thus, narrows to whether or not Red can sufficiently degrade Blue's weapon performance by means of Red platform maneuvers while closing Blue. The question addressed is the contribution of increased Red platform speed to this objective. Red's tactic is to detect and track Blue's weapon and execute a properly timed high speed avoidance maneuver. The purpose of this maneuver is to escape from the effective area of the weapon before the weapon arrives.

The assumed geometry is shown in Figure VIII-1. Initially, Red (who has the speed advantage) is pursuing Blue and has closed to within Blue's weapon range. Blue fires at Red. Red knows the characteristics of Blue's weapon, including the maximum turning rate at which the weapon can pursue him, shown as the limiting Blue weapon path. He also knows the radius of lethal effects of the weapon. These combine to produce the effective area of the weapon (shaded area). His objective is to cross this area and exit before the weapon arrives at any point where its radius of lethal effects (dashed circle) could intersect his platform.

Figure VIII-1

Geometry of the Weapon Avoidance Maneuver



Key parameters in determining the ability of Red to successfully execute such a maneuver include the speed of Blue's weapon, the radius of lethal effects of the weapon and its maneuverability.

Figure VIII-2 assumes a Mach 1.0 Blue weapon, and indicates Red escape capability as a function of Red platform speed. Escape capability is indicated by the radius of lethal effects which the weapon would require for selected weapon maneuverabilities (expressed as g numbers). Note, however, that the platform is assumed to have a zero turning radius. Realistic tactical diameters over the range of platform speeds indicated are as much as several thousand meters.

Figure VIII-2

Impact of Speed on Avoidance Maneuvers

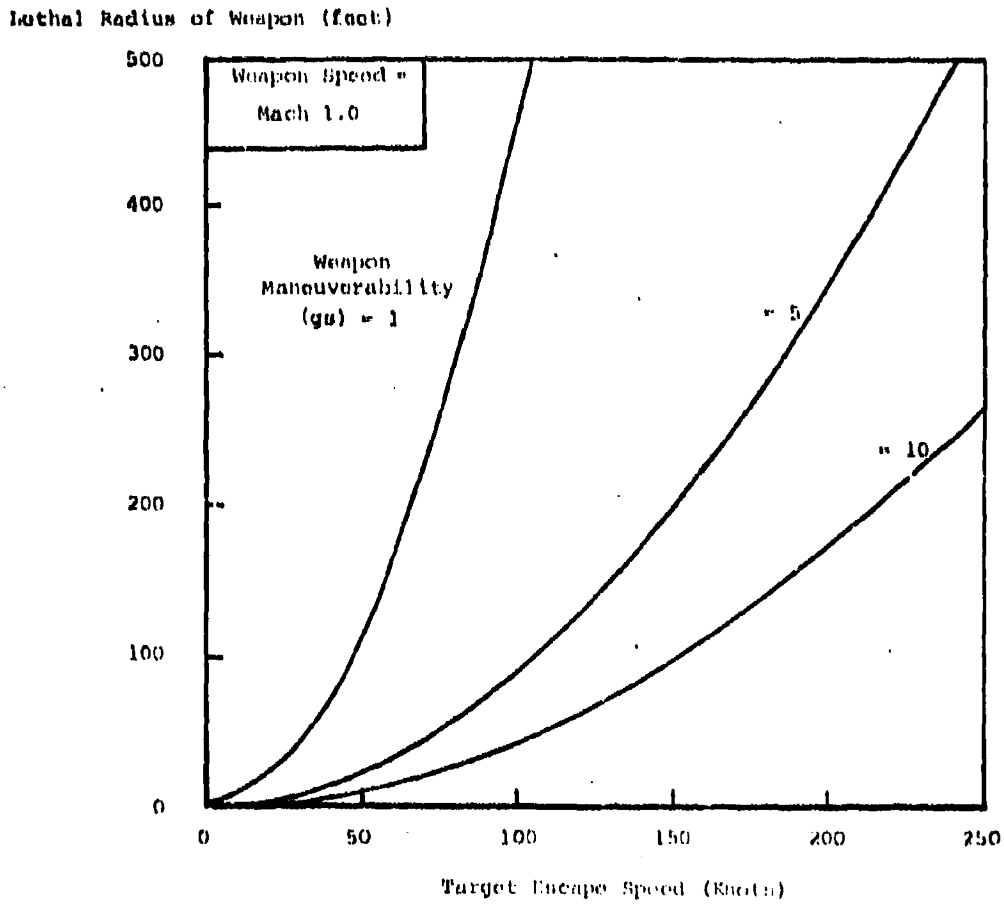


Figure VIII-2

Impact of Speed on Avoidance Maneuvers

<u>Purpose</u>

To show the effects of platform speed on the ability to successfully avoid an enemy weapon.

<u>Basis for the Calculations</u>

This is a plot of equation E-2.

This is a basic case for a target maneuvering to avoid a weapon. The target and weapon are assumed to be heading directly at each other before the target maneuvers. The weapon is assumed to have a minimum turning radius governed by the weapon speed and the number of Gs the weapon can pull. The target is assumed to turn instantaneously to an escape path which is defined to be normal to the minimum turning radius path of the weapon. Applying a weapon lethal effect radius to this path establishes the boundary of the area of effectiveness of the weapon. If the target can cross this boundary before the weapon can reach the target, he has successfully evaded.

<u>Assumption</u>

The target maneuvers instantaneously (essentially with a tactical diameter of zero). The turn is assumed to be made at the optimal separation distance from the weapon.

<u>Principal Points</u>

1. The three curves in Figure 2 represent three levels of weapon maneuverability (in gs which the weapon can sustain in a turn) and indicate, for such a weapon, the lethal radius which would just reach a target executing an escape maneuver at the speed indicated. Any greater target speed would constitute a successful escape. Thus, a 100-knot target could escape a one-g missile with a warhead lethal radius of less than about 500 feet.

2. At best, however, the figure can be considered as illustrative of the maneuver problem. Note that the target is assumed to turn instantaneously. In fact, tactical diameters of most surface platforms are directly proportional to the platform speed. In the 100-knot region, these are measured in thousands of meters.

E. TRANSIT AND CONVOY

A convoy transiting the open ocean during wartime is subject to the probability of enemy attack. This results from the conflicting objectives created by the convoy transport situation. Consider, for example, an objective function for a convoy designated Blue:

Maximize (M) (6)

Subject to:

$t \leq T$

$M = nC$

$n = N(1-P_K)$

$P_K \sim f\left(\frac{1}{V}\right)$

Where:

M = total tonnage transported from origin (A) to destination (B)

T = time available for transport

t = time required for transport

N = number of available transport platforms

n = number of platforms to complete transit from A to B

C = platform capacity in tons

P_K = probability of platform destruction during transit

V = average speed of convoy units during transit

The above objective function reflects an assumption that a mission has been defined and programmed whereby a collection of commodities must be moved between two points within a designated time period. The constraints have been simplified to indicate that a platform/unit of the fleet is capable of making only one trip from A to B during time T. However, by increasing speed, a potential of multiple trips during the maximum allowable time interval materializes. In addition, an unspecified relationship between survivability and transit speed has been assumed to exist. Further refinements such as a dependence of tonnage, C, and number of available platforms, N, upon the magnitude of transit speed, V, are subsequently discussed.

The dependence of survivability $(1 - P_K)$ upon V reflects an enemy (Red) capability which can be degraded by increased Blue speed. This degradation may occur in two ways:

1. Units of the Blue force can use speed to maneuver to avoid the lethal area of weapons launched by Red.

2. Blue escort vehicles can use speed to intercept Red and counterattack before he can successfully launch his weapons.

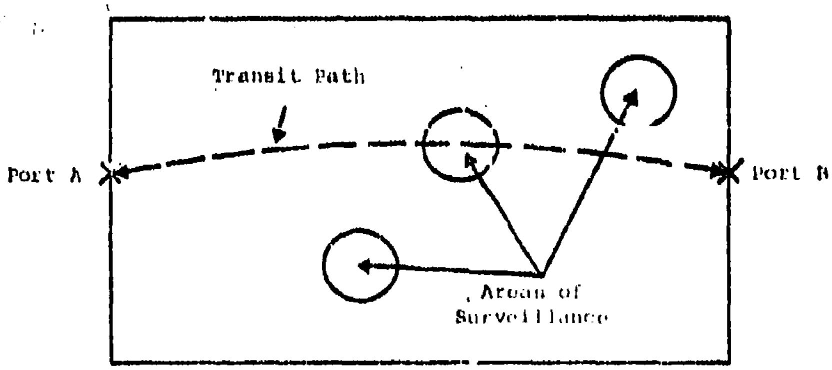
Increased convoy speed can also impact on the effectiveness of an enemy intelligence system. Improved transit speed reduces exposure time within a region in which an enemy might initiate attack. Unless the Red surveillance system is continuous in nature (i.e., the entire region is always monitored and collected information is interpreted in near real-time), uncertainty as to convoy location is introduced. This concept was previously discussed in Subsection B.

The total rationale for maneuvers and their quantitative assessment is described by P_K', the probability of platform destruction during transit. Defensive or Blue maneuvers are executed to reduce P_K and, conversely, offensive or Red maneuvers are initiated to improve P_K.

The transit scenario consolidated into equation set (6) can now be amplified to include descriptive parameters for both the convoy and the potential attacker. As previously noted, a convoy attempts to transit from port A to port B selecting a path through a region under enemy surveillance. This is depicted in Figure VIII-3.

Figure VIII-3

Convoy Transit Under Enemy Surveillance



The possible number of transit paths through the total operating region is infinite. However, bounds might be imposed by the maximum possible speed of transit and the allowable mission time. The areas of surveillance shown in Figure VIII-3 can take on various features. They might be mobile if contained on a platform. They also might monitor a region within their field of view continuously or intermittently. A sonobuoy field monitored by a remote station is an example of a continuous monitor. A sensor system aboard a platform with limited endurance or a satellite sensor affected by cloud coverage are examples of intermittent monitors.

The attacker (Red) could be located in the same position as the surveillance system or require deployment from a remote site. If remotely located, the probability of acquiring the convoy for weapon launch would be dependent on the amount of information supplied by the initial detection system during pursuit, the pursuit time, and the range or field-of-view of the on-board, pursuit detection sensor. Other factors must be considered by Blue when optimizing strategy. These include: number of pursuit and surveillance platforms; relative weapon ranges; and Red platform speed, endurance and range. Table VIII-1 shows the pertinent decision variables to be considered.

Table VIII-1

Convoy Decision Variables

Platform Variables:

BLUE	Symbol
• Number of Transit Platforms (cargo)	N_C
• Number of Escort Vehicles	N_E
• Maximum Speed Potential	V_C
• Maximum Cargo Potential	C
RED	
• Number of Surveillance Platforms	N_S
• Number of Attack Platforms	N_A
• Maximum Speed of Surveillance Platforms	V_S
• Maximum Speed of Attack Platforms	V_A

Sensor Variables:

BLUE

- Surveillance Range of Convoy — R_{S_1}
- Intelligence Level (i.e., information supplied regarding enemy activity by remote systems)
  1. Frequency — F_1
  2. Lead Distance (i.e., distance of enemy activity from convoy) — L_1
- Surveillance Range of Monitor System — S_2
- Surveillance Range of Attack Sensor — S_3
- Probability of Monitor System being operational at time of convoy transit through the detection region — P_2
- Time delay from convoy detection to attacker receipt — T_D

Weapon Variables:

BLUE

- Weapon Range of Escort — W_1
- Weapon Accuracy of Escort — σ_1

RED

- Weapon Range of Attacker — W_2
- Weapon Accuracy of Attacker — σ_2

The purpose of Table VIII-1 is to emphasize the descriptive detail of a transit operation which must be considered before a quantitative evaluation of the impact of speed and in particular the value of maneuvers in improving the objective function shown in equation (6) can be assessed.

A complete evaluation, using a set of defined values described in Table VIII-1 is beyond the scope of this effort. However, one can discuss in general terms the conditions and relative system capabilities which must exist before increased speed either for the Red or Blue produces an impact on the objective function shown in equation (6).

Consider an example where the convoy decision maker (Blue) does not know the location of the enemy (Red) surveillance zone. However, it is known that the zone does not cover the entire potential transit area. By employing greater speed, the tactic or maneuver of dispersion (i.e., divide the convoy units and create more transit routes) might be used.

Since the location of the surveillance zone is random, the probability of encounter by a dispersed transit unit remains the same as the probability of encounter when the convoy remained intact. It is assumed that target size does not affect the encounter probability. The expected value of the game (i.e., tons of cargo destroyed) for an intact convoy is:

$$G = A \cdot P_K \cdot P_D \qquad (7)$$

where,

G = tons of cargo destroyed

A = tons of cargo contained in the convoy

P_K = probability of destruction given an encounter

P_D = probability of encounter

Whereas the expected value for a dispersed convoy is:

$$G = N\left(\frac{A}{N}\right) \cdot P_K \cdot P_D \qquad (8)$$

where,

N = number of cargo units

It can be seen that equation (8) is equal to (7). Thus, the value of the game does not change, but the variance might. In the case of the intact convoy, the actual game can assume only two values: (1) zero if encounter does not take place, and (2) $A \cdot P_K$ given that it does. For dispersion, the actual game can assume values from 0 to $A \cdot P_K$ in increments of $A \cdot P_K/P$. Thus, it might be practical to disperse because even though expected losses are not decreased, the catastrophic event of losing most of the convoy is guarded against. An opposing rationale for remaining intact would occur if P_K the probability of destruction given encounter, were to increase for individual units.

Another reason for employing speed to disperse a convoy is to take advantage of a limited enemy attack capability. It might be possible for Red to mount enough platforms with multiple weapons onboard to destroy an intact unit. However, if the number of platforms were limited, they might not be capable of directing an attack against every detected Blue unit.

Regardless of which tactic is employed (i.e., dispersed or intact convoy) during transit, it might be necessary to cross a choke point near the termination of the mission at port B. An intelligent enemy would naturally take advantage of such a situation.

In any event, it must be recognized that the impact of speed and maneuvers upon a successful convoy transit is heavily dependent upon the relative capability of Red and Blue weapons and sensors, as well as the available number of platforms. A quantitative evaluation, using projected force numbers and capabilities, is required for an in-depth and complete appraisal of the impact of platform speeds and maneuvers on convoy transit.

F. SUMMARY AND CONCLUSIONS

A brief general discussion of the utility of vehicle speed in maneuver and avoidance was followed by discussion of application to the various naval vehicle functions analyzed in the previous sections.

From a pursuee's (Blue) point of view, there are two types of pursuit. In the first, the pursuer (Red) maintains continuous tracking on the pursuee. In this event, the only alternatives available to Blue are counterattack or (given a superior speed-endurance combination) escape.

When Red is limited to intermittent information, avoidance maneuvers can be employed by Blue during Red's blind periods to increase the area of uncertainty in order to escape (or complete a mission prior to capture). Increased platform speed enhances Blue's ability to do so.

Avoidance of detection by a searcher (Red) may also be enhanced by increased speed capability of the target (Blue). In the case of Red employing distributed sensors to monitor an area containing Blue (or which Blue must transit), Blue's best option is to take a direct, minimum length path at an optimum speed. When Red's probability of detection (P_D) increases with Blue's speed, Blue requires specific knowledge of Red sensor performance levels (as a function of Blue speed) in order to determine his optimum speed.

If Red's sensor performance is not sensitive to Blue speed, the benefit to Blue of increased speed is found to depend on key parameters of the Red sensor system. If each Red sensor monitors continuously with a very high P_D, speed is of no benefit to Blue. If, however, the sensors are characterized by intermittent glimpses with moderate or low P_Ds, Blue can use speed to reduce the number of glimpses and, thus, the overall P_D.

Given sufficient speed and maneuverability, a naval vehicle may be able to employ a timely maneuver to evade the lethal pattern of a weapon. However, against modern missile systems successful avoidance depends on a very high level of maneuverability as well as high vehicle speeds.

In the subsection on transit and convoy, it was determined that the benefits of increased speed of maneuver are highly scenario dependent and that other parameters, such as sensor and weapon performance and the numbers of vehicles involved, must be specified to make meaningful statements regarding the value of relative vehicle speeds.

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