Traffic Capacity

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1. INTRODUCTION. Traffic capacity is the capability of a waterway to deal with the traffic and when the traffic volume exceeds this limit traffic flow stops, as is often experienced on congested roads.

According to the U.S. Government *Highway Capacity Manual* the capacity of a highway with four or more lanes and free from conditions hindering smooth traffic flow has a maximum value of $V/Y_{\min}$ per lane, where V is the speed of a group of vehicles and $Y_{\min}$ is the average minimum separation of cars. Since $Y_{\min}$ is a function of V and increases rapidly and continuously with speed, there is a maximum value for $V/Y_{\min}$ which is a function of the speed. This is called basic capacity. Several examples of capacity together with the speeds of the transportation facilities are given in Table I.

When a waterway is so crowded that overtaking is almost impossible, and vessels form into groups with almost equal speed, we may say that the traffic volume has reached the capacity of the waterway.

In a one-way channel and under ordinary navigating conditions for vessels of almost the same size, L, and speed, V, we may write the basic

TABLE I. CAPACITIES OF TRANSPORTATION FACILITIES

Facility	Vehicle	Speed (km/h)	Hourly capacity	Passengers per hour
One lane of highway	passenger car	50	2400 vehicles	9 600
One line of express railway	electric train	80	30 trains	100,000
New Tokaido steam line	electric train	200	12 trains	12,000
Air route (1000 ft. alt.)	jet plane	1000	6 planes	1 200
Promenade (4 m.)	pedestrian	3	20,000 passengers	20,000

capacity, $C_{bas(L,V)}$, as $W\rho_{max} V$, where L is the length between perpendiculars, W the width of the waterway and ρ_{max} the maximum density.

The maximum density is determined by the size of the 'effective domain', which we define as the domain around a vessel under way which most navigators of following vessels would avoid entering. This definition may be regarded as static, others define the 'range of evasion' which may be regarded as dynamic. However it will be shown that the two definitions are equivalent.

Many factors affect the estimation of theoretical maximum values for the traffic volume of a waterway, i.e. its possible capacity:

(i) The size of the effective domain corresponding to C_{bas} as a function of L and V.
(ii) The influence of weather, sea conditions, visible range, tidal currents &c. on the size of the effective domain.
(iii) The influence of route conditions such as depth, width, presence of obstacle &c. on the size of the effective domain.
(iv) The effect of vessels with different sizes, i.e. the determination of a standard size for the route and the equivalent number of vessels of different sizes.
(v) The effect of vessels proceeding in opposite directions.

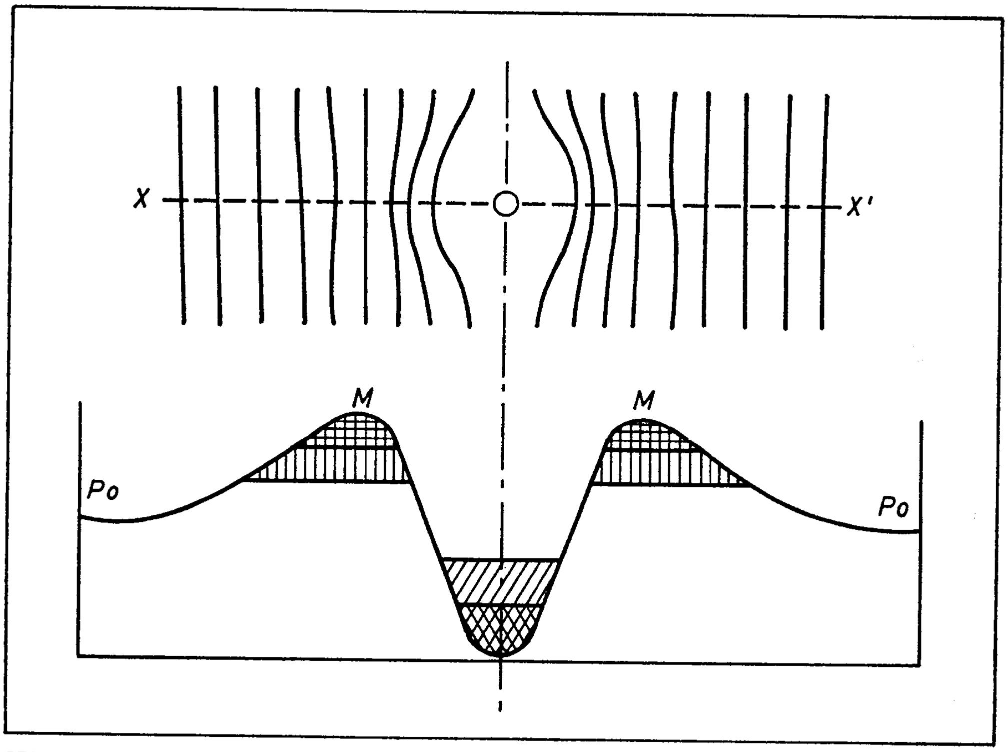
The capacity of crossing areas is also an important factor.

The practical capacity, which may be called the design capacity, is obtained from the possible capacity by allowing for the frequency of bad weather and sea conditions and safety factors for the route; this last factor is at present being studied with the aid of simulators. Basic capacity, possible capacity and the capacity of crossing areas are discussed in the following sections while theoretical consideration on the effective domain and on design capacity are reserved for a later paper.

2. BASIC TRAFFIC CAPACITY. *Determination of the boundary of effective domain.* The boundary of the effective domain is more of a psychological barrier than a stone wall. Suppose two particles with electrical charges of the same sign approach each other; the repulsive force increases as the separation decreases, and may be derived from the potential field, the

Coulomb field. In the same way it is convenient to assume a potential field around a ship which causes an imaginary repulsive force for approaching ships and a weak attractive force for distant ships. Fujii has pointed out that the repulsive force causes an avoiding motion while the attractive force causes grouping, much as in crystal growth.

For a first approximation the potential field may be regarded as a rigid wall surrounding a ship and the boundary defined as follows. Let us take the simple case of an obstacle in a fairway where there is a uniform traffic flow with a density ρ sufficiently far from the obstacle. In Fig. 1 the



Extraordinarily high

Considerably high

Considerably low

Extraordinarily low

FIG. 1. Wake lines and cross-section defining boundary of effective domain

density along a line X–X' will be of the form shown in the cross section. The terms 'extraordinary' and 'considerable' are used in a statistical sense as explained in our introductory paper in this *Journal*. The boundary of the effective width of the obstacle is defined by the point M at which the density reaches a local maximum nearest to the object, provided that the density at M is 'extraordinarily' high and that this maximum is fairly stable when the size of the elementary domain for the calculation of density is varied. We attach considerable importance to the definition of this boundary because it is determined by long observation and elaborate data treatment; the definition of the boundary has a significant influence on capacity estimates.

Determination of the effective domain corresponding to basic capacity. Lengths, speeds and vessel separations have to be measured for the

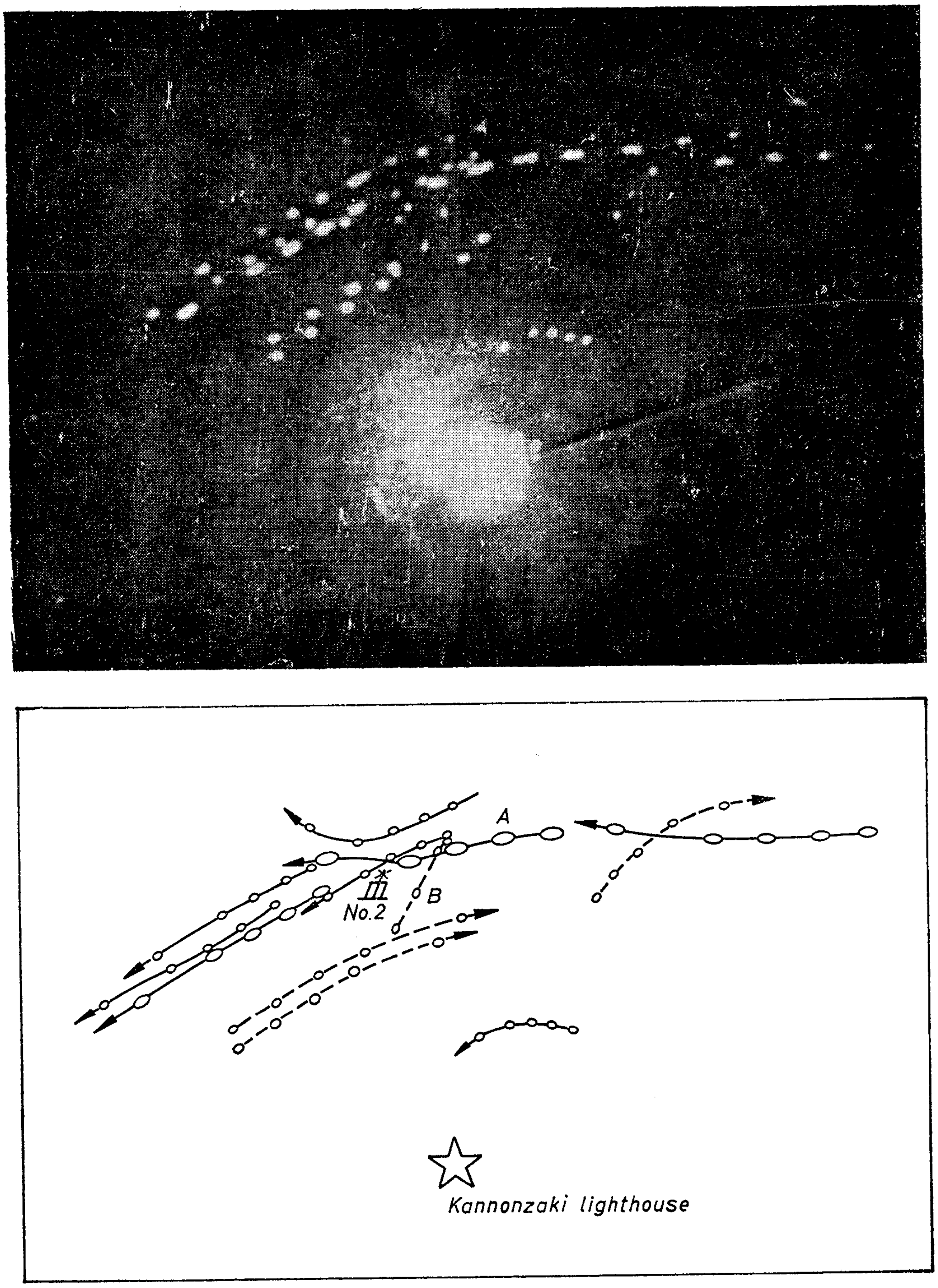


FIG. 2. Programmed radar photograph showing mm.-wave radar from Kannonzaki Lighthouse. The diagram below shows the circumstances of the collision of 7 August 1968.

determination of the effective domain. Speed is measured directly by pass-time recording while length and separation can be obtained from the speed and other data. The measurement of position at suitable time intervals is more convenient, either by 'photo-positioning' from radar photographs or better still by the Programmed Radar Photograph method, an example of which is shown in Fig. 2. Incidentally the photograph includes an actual collision though this was not entirely by accident as there were a dozen collisions in the Uraga Strait in 1968 and the observations continued over two weeks. Six frames of 35 mm. film were exposed every minute, the fifth being omitted in the figure to eliminate directional ambiguity. An electrically operated long recording camera capable of taking 250 frames is used and the film roll is changed once a day. A photograph taken with the improved Programmed Radar Camera is shown in Fig. 3 which gives a vivid impression of the heavy traffic in Tokyo Bay.

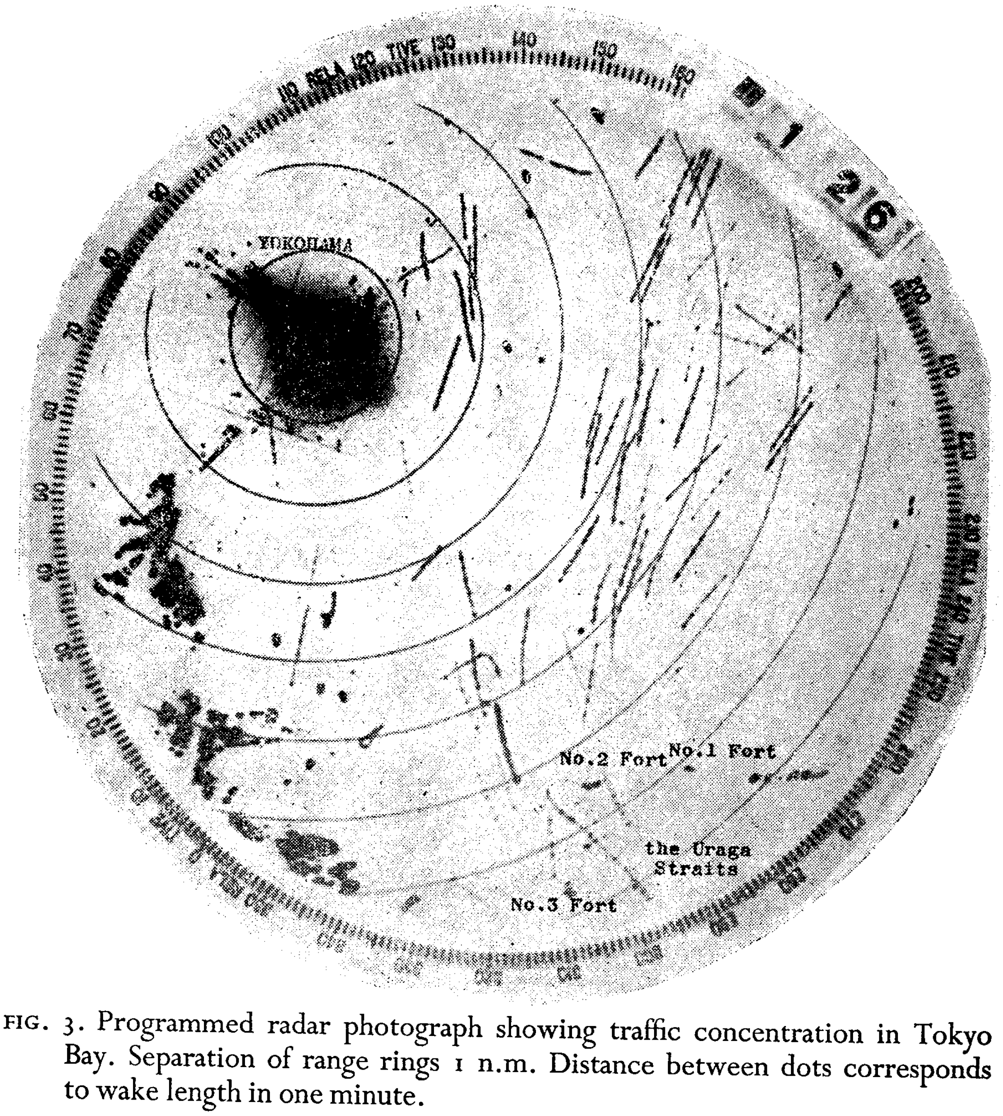


FIG. 3. Programmed radar photograph showing traffic concentration in Tokyo Bay. Separation of range rings 1 n.m. Distance between dots corresponds to wake length in one minute.

Figure 4 shows the distribution of separation between centres of ships whose lengths are between 70 m. and 140 m.; since the distribution does not differ much to the left and right of a vessel the left-hand distribution has been turned over on to the right. The presence of an effective domain is clear. Following the procedure already described for determining the boundary of the effective domain, it is seen to be a half-ellipse having a semi-axis major of about 500 m. and semi-axis minor of about 300 m.

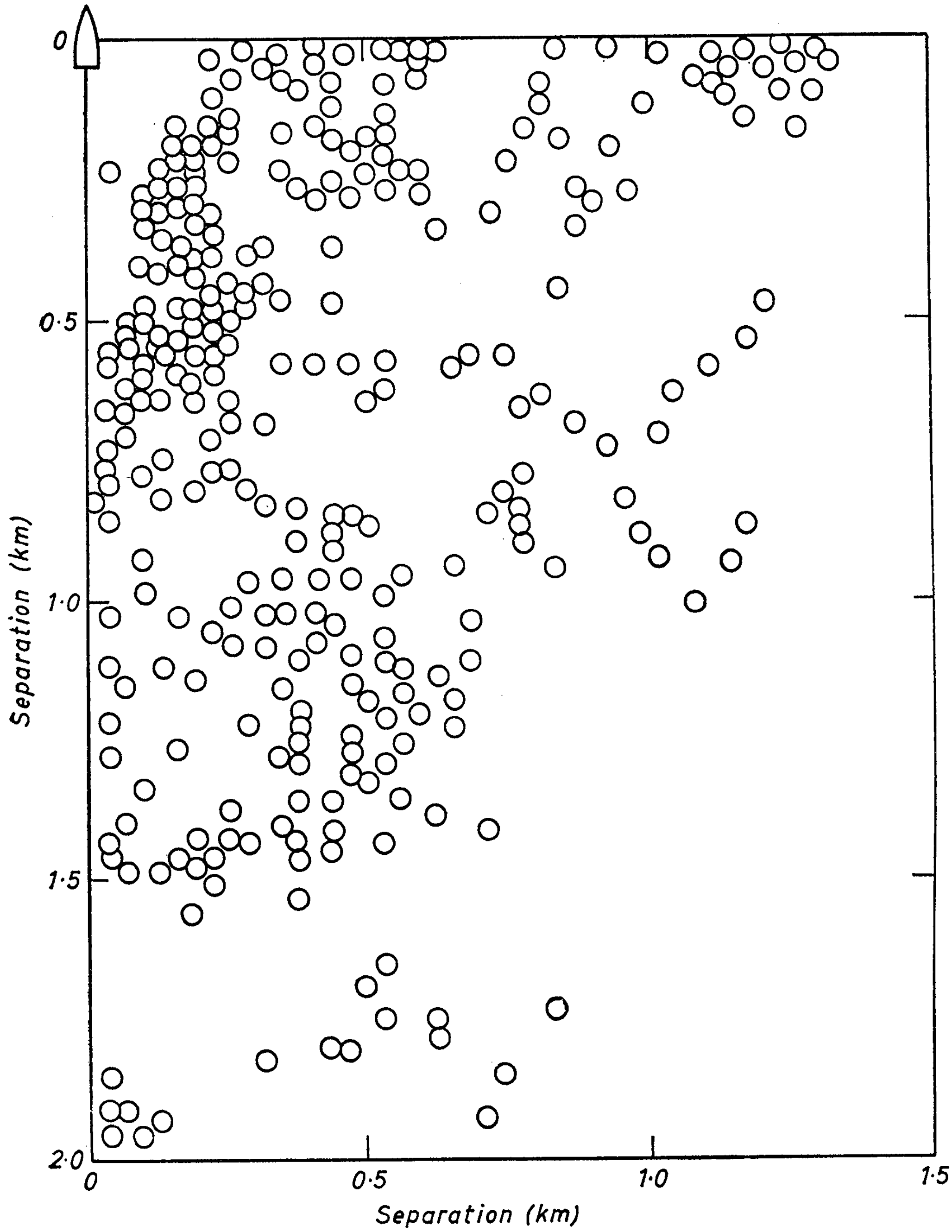


FIG. 4. Distribution of relative positions of the following vessels to a preceding vessel

Effective domain as a function of length of ship. Since the speed distribution obtained from several observations shows that ships navigate at about normal speed, we are concerned with the effective domain corresponding to normal speed, V_n, which from the motion characteristics of ships is:

$$\log_{10} V = 0{\cdot}29\lambda + 3{\cdot}78 \pm 0{\cdot}06 \qquad (1)$$

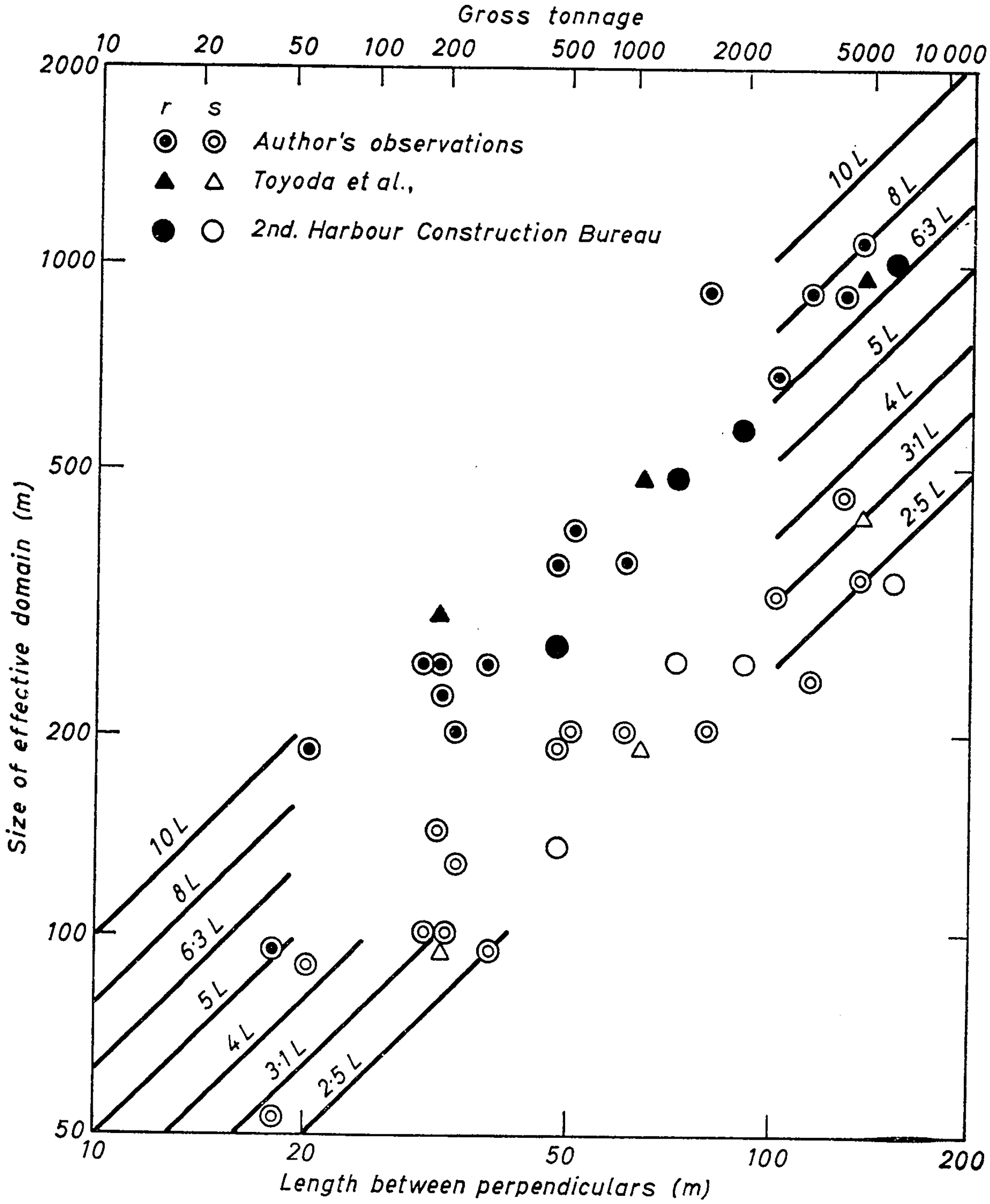


FIG. 5. Correlation of ship length with size of effective domain

where λ is $\log L$ and V_n and L are in metres per hour and metres respectively.

We have made more than six series of observations to obtain the size of the effective range, the semi-axis major r and the semi-axis minor s, each covering about two weeks. The results are shown in Fig. 5 which also includes data obtained by Toyoda and his colleagues. These results lead to the following estimates for the effective domain corresponding to L and V_n:

$$r = 7L \pm L, \quad \text{or} \quad \log r = \lambda + 0{\cdot}85 \pm 0{\cdot}06 \tag{2}$$

$$s = 3L \pm 0{\cdot}5L, \quad \text{or} \quad \log s = \lambda + 0{\cdot}48 \pm 0{\cdot}07 \tag{3}$$

Basic capacity corresponding to L and V_n. The size of the effective domain thus obtained allows us to calculate the maximum density, ρ_{max}. Since the separation between centres of ships must equal or exceed the size of the effective domain, the maximum density obtained by packing ellipses of this size will be:

$$\rho_{max} = 1{\cdot}15/rs \tag{4}$$

where 1·15 is the close packing ratio.

The basic capacity per hour, $C_{bas}(W, L, V_n)$ corresponding to L, V_n, and the width W can be derived from the above equations:

$$\begin{aligned}\log C_{bas} &= \log V_n + \log \rho_{max} \\ &= \log W - 1{\cdot}71\lambda + 2{\cdot}51 \pm 0{\cdot}11\end{aligned} \tag{5}$$

The probable error is calculated from the standard deviations of the equations. Table II gives the capacity for a waterway whose width is 1 nautical mile ($W = 1852$ m., $\log W = 3{\cdot}37$).

3. FACTORS AFFECTING THE DETERMINATION OF POSSIBLE CAPACITY. *Influence of weather and sea conditions.* Reduced visibility seems to increase the size of the effective domain, but a further deterioration in visibility does not appreciably influence its size. Ichinose reports that with poor

TABLE II. BASIC CAPACITY CORRESPONDING TO NORMAL SPEED IN A MILE-WIDE CHANNEL

Gross tonnage	20,000–100,000	3000–20,000	500–3000	100–500	20–100	5–20	1–5
Mean length (m.)	235	127	67	33	18	10·4	6·2
Normal velocity (kt.)	16·2	13·4	11·1	9·1	7·7	6·5	5·6
Observed velocity (kt.)	14	14	12	9	8	7	7
Basic capacity per hour	53	150	440	1500	4500	11,000	27,000

visibility the mean speed of vessels is not appreciably smaller, so that capacity seems to be little affected.

Tanaka *et al.* express the influence of tidal current on the size of effective domain in the form:

$$r = 7L + 5L_0^2 u / L u_0 \pm L \quad \text{and} \quad s = 3L \pm L \tag{6}$$

where u is the speed of the tidal current in knots and L_0 and u_0 are 40 m. and 10 knots respectively. The sign of u is positive for a fair current and negative for a counter current. Since the ground speed is $V+u$, a simple calculation shows that the influence of tidal current on capacity is small, especially for large vessels.

Influence of route condition. Since navigators avoid approaching shores, reefs and other obstacles, Yamaguchi *et al.*, Toyoda *et al.*, Makihata *et al.* and Tanaka *et al.* have all attempted to define the effective domain of an obstacle. Though little data is available the following relationships are suggested:

effective separation from a steel tower to a ship: about $4L$,
effective separation from a buoy: about $2L$,
effective separation from an artificial island: $5L$.

Mizuki and Fujii recently made observations to determine the effective separation between a bridge pier and a ship, using a scale model of a cross-channel bridge, and obtained a value of $1{\cdot}5L$ for boats of from 10 to 40 m. in length.

Influence of other vessels of various sizes. Tanaka and others, continuing their observations on the separation between vessels of different length, showed that for the effective domain $r \simeq 7L'$ and $s \simeq 3L'$, where $L' = [(L_1^2 + L_2^2)/2]^{1/2}$.

Where most of traffic consists of a single class of vessel, as in Table II, this may be called the standard class. It is 20–100 g.t. in the channels of Tokyo Harbour and 100–500 for the Uraga Strait.

When a larger ship traversing a waterway is surrounded by vessels of the standard class, the ratio of the area of the effective domain to that of the standard domain is defined as the 'equivalent number' and is roughly proportional to the square of the vessel's length. The equivalent number for a wooden barge in tow has been measured and is about 2 when the standard class is 20–100 g.t.; for a towed raft or group of barges it is about 3.

The converted traffic volume is defined as the weighted sum of the traffic volumes of each class, using the equivalent number as the weighting factor. It is practical to define the degree of congestion by the ratio of the converted traffic volume to the capacity for vessels of the standard class.

Separation of vessels on reciprocal courses. The effective domain for vessels crossing or going in opposite directions is now being studied and is indeed an important topic in modern marine traffic engineering. Toyoda *et al.* estimate the effective separation at about $4L$.

4. OTHER TOPICS CONCERNING TRAFFIC CAPACITY. *Influence of speed on capacity*. Though the dependence of basic capacity on ship's length has been established, its dependence on speed is not yet clear since observations are time consuming as most ships proceed at about their cruising speed. Watanabe, Toyoda and Fujii have separately estimated the speed dependence of basic capacity on theoretical grounds and Fujii considers the maximum value of C_{bas} to be increased by about 20 per cent at about half cruising speed.

Traffic capacity in crossing areas. There are many straits and sounds in Japanese waters and consequently many ferry services which cross main shipping routes. Fujii has calculated the capacity of a crossing by assuming a Poisson distribution for arriving vessels. He concludes that the capacity for ferry traffic decreases exponentially with increasing traffic volume in the main route when this exceeds a certain threshold value.

The capacity of an anchorage of refuge. Nishitani and Ogami have studied the capacity of Osaka Bay as an anchorage for riding out typhoons. By counting the number of closely packed circles of a diameter of 1650 m. within the anchorage area they conclude that the anchorage area in Osaka Bay is small since the number of circles (about 200) is less than the 250 berths in the harbour plan.