AN INVESTIGATION INTO THE FEASIBILITY OF CONSTRUCTING A MATHEMATICAL MODEL OF SHIP SAFETY

A THESIS IN PARTIAL FULFILMENT FOR
THE DEGREE OF MASTER OF SCIENCE IN
MATHEMATICS AT
MASSEY UNIVERSITY

Ian Murray James Clarke

1996

Abstract

This thesis investigates the feasibility of developing a mathematical model to provide quantitative measures of total ship safety. Safety is an intuitive concept and is a subset of economic utility. There is economic pressure to transport goods at minimum cost and, without regulation, the frequency of shipping casualties could be unacceptably high.

Mathematical methods associated with elements that influence ship safety are reviewed. Techniques for analysing ships' structures, stability, motions and engineering reliability are well established, but those for assessing the effect of human involvement, and operational and organisational influences on safety are less developed. Data are available for winds, waves, currents and tidal movements, and their variability suggests that probabilistic models are appropriate.

Given the complexity of the international shipping industry, a simple computer model is developed in which 50 ships serve four ports. This allows safety to be assessed when input variables are adjusted. Obstacles to developing a mathematical model of ship safety are identified, and it is concluded that the feasibility of such a model depends on its required inclusiveness and utility.

Acknowledgement

I thank Dr. Robert McKibbin, Senior Lecturer with the Department of Mathematics, Massey University, for his helpful supervision of this thesis, and for his valuable advice.

Glossary of terms and abbreviations

Bilges: Wells or channels for drainage, located near the bottom of cargo holds or the engine room. Bilges also refer to the rounded part of a ship's hull between bottom and side plating.

Block coefficient (C_B): The volume of displacement divided by the volume of a rectangular block with dimensions equal to the ship's length, the waterline breadth and draught.

Bridge: The navigational control station of a ship, comprising the wheelhouse, chart room and lookout decks.

Bulkhead: A vertical partition that divides a ship into compartments.

Classification societies: Independent societies that make rules for the construction of ships, approve plans and materials used in their construction, and carry out surveys on ships. Classification societies carry out statutory surveys on behalf of some national maritime administrations. See also IACS.

Constructive total loss: When a ship is damaged so that the cost of repair is greater or equal to the value of the ship.

Cost benefit analysis (CBA): A technique that attempts to evaluate the social costs and social benefits of an investment project.

Deadweight (DWT): The mass of cargo, water, fuel, stores and anything else that a ship carries.

Depth (D): The vertical distance from the bottom of the keel to the side of deck, measured at mid-length.

Displacement (W): The total mass of a ship and anything that it carries.

$$\text{Displacement} = \text{Lightweight} + \text{Deadweight}$$

Draught (d): The vertical distance from the underside of the keel to the waterline.

Dynamic loading approach (DLA): A computer based method for assessing stresses acting on a structure.

Externality: The effect the actions of one party have on the welfare of others who may have no direct financial interest in such actions.

Failure mode and effect analysis (FMEA): A formal method for analysing the effect of different types of failures.

Finite element method (FEM): A method in which a structure is divided into small elements for analysis.

Freeboard (Fbd): The vertical distance between a waterline and the side of the deck, measured at the mid-length of a ship.

Founder: To take in water and sink as a consequence of heavy weather or structural failure.

Global positioning system (GPS): An all-weather navigation system that can derive accurate positions from signals received from satellites.

Global Maritime Distress and Safety System (GMDSS): A distress and safety communication system that uses satellite communications as well as terrestrial radio to provide 24 hour coverage on a world-wide basis.

Gross tonnage (GRT): A measure of the size of a ship given by the formula specified in the International Tonnage Convention (1966):

$$GRT = (0.2 + 0.02.\mathrm{Log}_{10}.V).V,$$

where V is the total volume of enclosed spaces of a ship.

Grounding: Contact with the sea bed during the operation of a ship, for example by misjudgement of the limits of a channel.

Heel: Inclination of a ship about its longitudinal axis caused by an external force.

Hogging: Longitudinal bending of a ship caused by a resultant upward force at the mid-length and resultant downward forces near the ends. Opposite to sagging.

Hydroelasticity: The interaction between inertial, hydrodynamic and mechanical forces.

International Association of Classification Societies (IACS): An association of the major classification societies.

International Convention for the Safety of Life at Sea (SOLAS): Conventions agreed to by the maritime nations at international conferences held in 1914, 1929, 1948, 1960 and 1974. The conventions deal with many aspects of ship safety.

International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW convention) 1978.

International Maritime Dangerous Goods Code (IMDG code): A reference manual published by IMO giving details of dangerous goods (explosive, flammable, corrosive, etc.) and precautions for their carriage in ships.

International Maritime Organisation (IMO): The United Nations agency formed to promote co-operation among government in technical matters affecting shipping. The IMO has a responsibility for the safety of life at sea.

Length (L): Various definitions of ship's length are used: Overall length (L_{OA}) is measured from the forepart of the stem to the aftermost part of the stern. Other lengths are: register length (L_R), subdivision length (L_S), waterline length (L_{WL}) and length between perpendiculars (L_{PP}).

Lightweight (LWT): The mass of an empty ship.

Lifesaving appliances (LSA): Lifeboats, davits, liferafts, lifejackets, buoyant apparatus and rescue boats.

List: A steady inclination of a ship about its longitudinal axis caused by an unsymmetrical distribution of mass.

Load lines: Marks indicating several maximum depths to which a ship may load in various circumstances.

Margin line: A reference line used in subdivision calculations, 75 mm below, and parallel to, a deck to which bulkheads form watertight compartments.

Master: The person in command of a merchant vessel.

Metacentric height (GM): The vertical distance between the centre of gravity and the transverse or longitudinal metacentre.

Periodical survey: Survey of hull, machinery and equipment at intervals (not exceeding five years) specified by a ship's national maritime administration.

Pilot: A person with local knowledge and ship-handling skills who navigates a ship in harbour or coastal waters. The master remains responsible for navigation and safety, but is usually obliged to follow the pilot's instructions. The word pilot also means a reference book for coastal navigation (eg. New Zealand Pilot).

Principal dimensions: Length (L), breadth (B) and depth (D), etc. of a ship.

Response amplitude operator (RAO): The ratio of reaction amplitude to excitation amplitude of forced harmonic motion in a linear system, as a function of frequency.

Sagging: Longitudinal bending caused by a resultant downwards force at the mid-length and resultant upward forces near the ends. Opposite to hogging.

Scantlings: The dimensions of components of a ship's hull structure, for example the thickness of plates, frames and girders. Originally the term applied to timber, but its use is extended to include steel components.

Seakeeping: The behaviour and movement of a ship in a seaway.

Significant wave height: The average height of the 1/3 highest waves.

Still water bending moments (SWBM): Longitudinal bending moments acting on a ship floating in still water. See also WBM.

Stranding: Driven ashore by force of weather.

Tactical diameter: The diameter of a ship's turning circle for a given speed and condition of loading.

Trim: The difference between the forward draught and the aft draught. When the keel is parallel to the water surface, a ship is on an even keel, otherwise the ship is trimmed by the head or by the stern, depending on which draught is greater

Twenty-foot Equivalent Unit (TEU): A measure of the capacity of a container ship, given by the number of ISO twenty-foot containers the ship can carry.

Unattended machinery space (UMS): Machinery space fitted with a control system and alarms, and with bridge control of propulsion machinery so that it does not require continuous manning by a duty engineer. Machinery space may be classed as UMS.

Wave bending moments (WBM): Longitudinal bending moments acting on a ship in a system of waves, usually considered for a wave system in the direction of the ship's longitudinal axis, with trough or crest amidships. See also SWBM.

Contents

Chapter 1

A mathematical model of ship safety

This investigation was motivated by proposals that a scientific approach should be used for the assessment of total ship safety. Analytical methods are used in several areas of ship design and operation, but the techniques in use apply to particular problems, and not to the much wider concept of total ship safety. Safety involves technical processes such as designing, building and outfitting a ship, as well as the on-going management, operations and maintenance necessary to fulfil its commercial purpose. External hazards such as bad weather and vessel traffic need also to be considered. A scientific approach requires assessment on the basis of objective evidence and, given the nature of the problem, this raises doubts about whether such an approach is possible. Objective evidence implies quantitative measures, and it is the aim of this study to investigate the feasibility of developing a mathematical model that will enable the evaluation of relative levels of ship safety.

The concept of a scientific approach to total ship safety is not new, and in his book "The Safe Sea", Abell (1932) said:

"If there is needed any guide to international understanding it is to be found in the agreements made in 1929 and 1930, by all maritime countries, to work to one code of conduct for all that makes for safety of life on their ships - the ships of the seven seas. These sea laws have been built up in a scientific way - first from the simple experiment, then the considered result, followed by another trial and perhaps error, repeated again and again, until the twentieth century sees the result of 120 centuries of sea adventure."

Present day writers do not appear to share this view that safety should be allowed to evolve through trial and error, and advocate a more active approach to the assessment of total ship safety, including the development of mathematical models:

"So the assessment of the 'fitness for purpose' of a ship must include not only a realistic analysis of the strength of the component parts but also an appraisal of the reliability of the safety of the ship as a single entity ... The latter necessitates the use of probabilistic techniques and mathematical modelling to include the effect of component interaction and of random occurrences such as human or material failure. Acceptable risk levels for possible hazardous events must be determined so that the performance of a ship, in terms of reliability and safety, can be rationally assessed and quantified for comparison purposes."

(Aldwinckle and Pomeroy, 1982)

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"Safety does not depend only on the structural integrity of a vessel. Safety is commonly associated with the total integrity of a vessel. There is no doubt that the operational aspects have to be considered in addition to structural and seakeeping practice..."

(Kwon. 1994)

The above statements. made twelve years apart. indicate that the need for assessment of total ship safety is well established. but that the methods and general approach are still under discussion. Casualty records show that during this twelve year period. 3206 ships with a total gross tonnage of more than 16.8 million were lost (Curry. 1995). The records are for ships with gross tonnage 100 and over. but do not include ships that were repaired after damage. nor do they indicate deaths. injuries. third party damage and damage to the environment as a consequence of ship casualties.

Casualties may result from material or equipment failure. incorrect judgement or action by mariners. poor organisation. a hostile environment. or from a combination of several factors. There is usually a significant element of chance in any accident. and ship owners are generally aware of the risks associated with operating ships. Known risks can be reduced by taking precautions. but this usually incurs an economic penalty. and while ship owners bear the full cost of safety precautions. they may not have to bear the full cost of accidents. The international safety conventions and national shipping safety regulations prescribe minimum standards for ship construction. equipment. and the qualification of seafarers. These regulations are introduced to improve particular aspects of safety. often as a reaction to particular types of casualties. However there are disadvantages to prescriptive regulations; attempts to minimise compliance costs can make the final outcome of a regulation uncertain. and can result in a poor reallocation of resources which may provide a lower overall standard of safety.

Recognising these disadvantages. the International Maritime Organisation (IMO) and other organisations involved with ship safety have considered alternatives to prescriptive regulations. The aim of most proposed alternatives is to provide means of showing that a ship achieves a level of safety performance that is at least equivalent to some standard. The following extract notes the desirability of defining and setting levels of safety (Cleary. 1989):

"There has never been an actual equating of levels of safety in international regulations. in spite of equivalency statements included in each maritime convention requiring the Administration to maintain equal safety approaches to the published rules. It would be highly desirable for the nations gathered at IMO to state the target safety levels for each major safety function in the load line. SOLAS. MARPOL. and other IMO agreements and also to state the expected interactions between the main safety functions."

Ship safety performance involves a complex interaction between many different factors. and the problem of defining. setting and measuring levels of safety has not been solved. This is evident in the following statement made by the House of Lords (1992) Select Committee on Science and Technology in its report: "Safety Aspects of Ship Design and Technology":

"If ship regulation is to move from 'rule of thumb' to a more scientific basis, ship science must provide the regulators with the analytical tools to do the job"

Total ship safety is a difficult concept to put into practice because its components are assessed in different ways. by different specialists. who may have different objectives from one another.

Tools that can be used in the definition and assessment of total ship safety still need to be developed and evaluated, and a mathematical model of ship safety could be one such tool.

It is necessary to question why a mathematical model should be of any help in assessing ship safety. Safety is a subjective quality, while mathematics deals with objective quantities. Safety arises from a complex and subtle interaction between materials, situations and objectives, while a mathematical model is an abstract, simplified view of reality, developed with a particular purpose in mind. There are great contrasts between the practice of safety and the discipline of mathematics, but the precision and clarity of mathematics may be utilised to make safety concepts more objective. Having said that, it is recognised that mathematical modelling is only one of a number of possible approaches to the improvement of safety assessment, and there have been developments in areas such as non-destructive testing, training of surveyors and the documentation and recording of inspections.

Mathematical methods are used in several areas that are important to ship safety. The finite element method is used extensively in structural evaluations, ship motions are derived from model tests using dimensional analysis and differential equations, and measures of equipment reliability are based on probability theory. These techniques are useful in the evaluation of parameters critical to ship safety, and it may be possible to combine such parameters with others so as to determine a measure of safety as a whole, rather than restrict the examination to whether a ship will fail under load, or how it will respond to a particular wave spectrum. Integrating safety elements is possible only when there is a suitable model, and without a mathematical model there may be no objective definition of total ship safety.

The process of building and evaluating models may promote improvement in ship safety. Concise expression of a problem in mathematical terms enables manipulation of the elements and encourages experiments. Standard mathematical theorems may simplify complex situations that are otherwise too difficult to solve, and isomorphisms can provide ready made solutions to difficult problems; for example the standard frequency distributions are used to model sea spectra, variable loads in a ship, navigational errors and the incidence of failure. Model building is in itself an iterative process in which objectives and attempted solutions are progressively refined. The development and use of mathematical models may thus focus and improve general ideas about ship safety.

The aim of this study is not to promote the advantages of a mathematical model of ship safety, but to evaluate its feasibility. The feasibility of a model depends on what it is expected to achieve, and while it may be entirely feasible to create models that will reflect safety in some way, this may not be particularly useful. A model in which the level of safety is calculated simply by entering measurable ship variables into a formula would obviously be useful, but given the complexities and uncertainties of individual safety elements, it seems unlikely that such a model could be developed. The evaluation must therefore recognise the trade-off between utility and feasibility in models.

In this study, Chapter 2 examines the concept of total ship safety, and looks at ways in which it can be measured or expressed in mathematical terms. Chapter 3 discusses safety in the context of the international shipping industry, and reviews the possible safety objectives of shipping companies and institutions associated with shipping. Chapter 4 focuses on the elements that affect safety and examines the mathematical methods that are available for their detailed analysis. Some of the approaches discussed are incorporated into a simple computer model of ship safety which is described in Chapter 5. In Chapter 6 the findings are reviewed and the feasibility of a mathematical model of ship safety is discussed.

Chapter 2

What is ship safety?

Definitions and measures

Although the terms "measure of safety" and "level of safety" permeate technical maritime literature, safety is an intuitive concept, and attempts to define it in quantitative terms generally measure particular aspects of safety. Professor Kuo of Strathclyde university defined safety as "... a perceived quality that determines to what extent the engineering and operation of a system would be free of danger to lives, property and the environment." (Francescutto, 1992). This definition provides insight to the nature of safety and indicates that some restriction of the concept is necessary in order to quantify or measure safety.

"Perceived quality" implies that safety is subjective, and depends on the experience and expectations of the observer. Faced with a simple situation involving a degree of risk, for example using a gangway to board a ship, opinions may vary about whether the gangway is safe to use. Attitudes are influenced by the general look of the structure, how it is rigged, the distance the user may fall, as well as the user's weight and experience of similar gangways. Although much more complex, a similar thought process determines whether a ship is considered safe for navigation. A ship is deemed seaworthy provided it complies with the applicable safety regulations and appears in good condition to the inspecting surveyor. Regulation and survey standards reflect the perception of the legislature and the safety administration. A mariner may consider a ship to be acceptably safe when looking for employment, but his perception may change when the ship encounters violent storms at sea.

Ordinal measures for perceived safety are possible. Specialists could observe several ships and their crews in operation, and could rank them in order of perceived safety level. But this would be of very limited value, and if the ships were of different types, sizes and working under different conditions then such a subjective measure of safety would prove difficult. A perceived quality is not a practical unit for the output of a mathematical model, and more objective measures are necessary, even though this necessitates narrowing the definition of safety.

Professor Kuo's definition includes the engineering and operation of a system. Engineering aspects refer to the design, construction and structure of a ship, which must withstand forces, keep water out, restrict possible flooding and the spread of fire, and be capable of being handled by people with appropriate skills, and also propulsion and auxiliary machinery, control systems and equipment. The term operation refers to the human involvement, organisation and decision-making necessary to carry out the functions for which the ship is intended, that is to transport cargo in return for payment.

The three areas of concern in ship safety are lives, property and the environment. The scope of this study is limited to losses caused by ship casualties, such as collisions, fire and structural failure. Accidents such as people falling down holds or being asphyxiated in tanks are not included. Neither is damage to the environment which is not a consequence of a ship casualty, for example through the deliberate pumping of oily water, or through creating a wake that damages the coastal environment. Such incidents are important in their own right, but are not part of this study.

The definition of ship safety may be restricted to "... a quantitative measure of the extent to which the engineering and operation of a ship would minimise the level of damage due to ship casualties", and it remains to examine the types of measure that could be useful. Although an intuitive concept, safety conveys something that is real. There is a number of attributes that may be independent or related to one another that determines what is safe. This intuitive concept formed by combining real attributes is similar to the idea of "utility" used in economics. Although in its most general form, utility is not quantified, it is used in explaining economic phenomena, and the way in which utility changes for different economic variables can be explained and understood. The concept of safety may be a subset of the concept of utility, and can be treated in a similar way. Figure 2.1 illustrates safety indifference curves for two attributes, the abscissa represents resources allocated to physical safety such as the strength of hull and reliability of machinery, and the ordinate represents resources allocated to operational safety such as organisation, management and personnel.

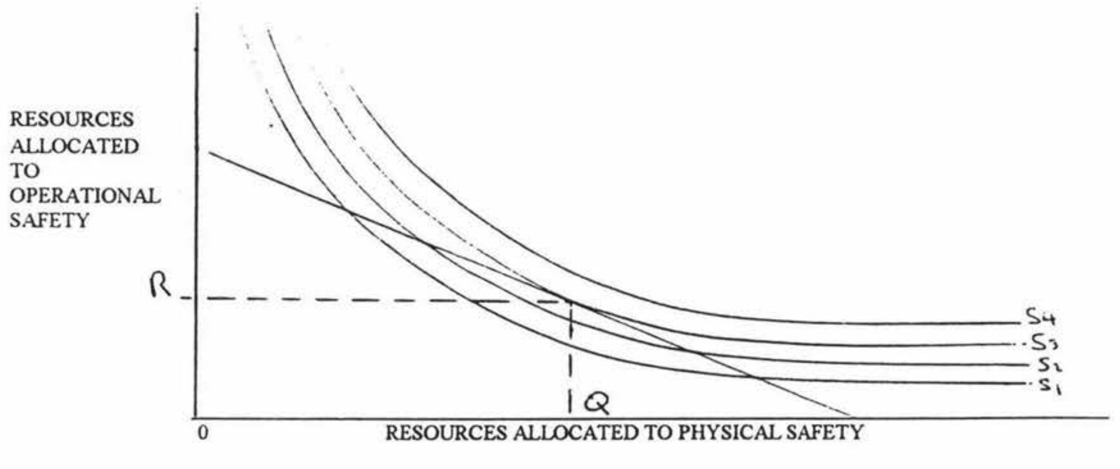


Figure 2.1 Safety indifference curves.

In Figure 2.1 the curves that are nearest the upper right corner represent the highest levels of safety. For investment OQ in physical safety and OR in operational safety, the level of safety is S_3. Additional investment in physical safety moves (Q,R) horizontally to the right and additional investment in operational safety moves (Q,R) vertically upwards. In both cases an increasing incremental investment is necessary to achieve the next safety indifference curve, and a better strategy is to invest in a combination of physical and operational safety so as to move (Q,R) in a direction normal to the safety indifference curve. The tangent to the curve at (Q,R) is the marginal rate of substitution of resources between physical and operational safety. If the objective of investment is to achieve maximum safety, the total resources invested should be divided between physical and operational safety so as to achieve the highest curve.

If it is possible to express a measure of safety as a function of two or more variables, then a number of mathematical methods are available to optimize the level of safety. As an example, suppose that safety is given by the function:

$$z = f(q, r)$$

where q is a measure of resources allocated to physical safety
and r is a measure of resources allocated to operational safety.

Resources allocated to safety are limited, and there is a constraint $g(q, r) <= s$, for example, let $q + r <= s$.

Using the Lagrangian method of constrained optimization, a new function Z is defined, where

$$Z = f(q, r) + \lambda.g(q, r) = f(q, r) + \lambda.(q + r - s)$$

The critical values of the new function are found by setting the first order partial derivatives to zero, and solving the resulting simulataneous equations.

$$Z_q = f_q(q, r) + \lambda = 0$$

$$Z_r = f_r(q, r) + \lambda = 0$$

$$Z_\lambda = q + r - s = 0$$

The maximum is given by the bordered Hessian $|H|$,

$$\text{where} \quad |H| = \begin{vmatrix} Z_{qq} & Z_{qr} & g_q \\ Z_{rq} & Z_{rr} & g_r \\ g_q & g_r & 0 \end{vmatrix}$$

(Bunday and Garside, 1987)

However, as discussed later in this study, there are many other considerations, besides safety, that influence the level of investment in physical and operational aspects. The many interacting attributes that make up total safety present problems in any attempt to define and measure safety. One view is to consider safety as a function of all its attributes.

$$\text{Safety} = f(x_1, x_2, \ldots, x_n)$$

While it is possible to identify attributes $x_1, x_2, \ldots, x_n$, and to express many of them in quantitative terms the form of the safety function has not been established. For a simple situation such as a rod of strength x_1 under tension x_2, the safety function could be:

$$f(x_1, x_2) = \begin{cases} (x_1 - x_2) / x_1 & \text{if } x_1 >= x_2 \\ 0 & \text{if } x_1 < x_2 \end{cases}$$

Even a simple function such as this involves some conceptual difficulties. Assuming that failure occurs only when $x_2 >= x_1$, then if $x_1 > x_2$ the rod will not fail. It is only when variation or uncertainty with respect to the parameters are considered that it makes sense to think of the situation where x_1 is five times greater than x_2 as being safer than when x_1 is twice x_2

Variation and uncertainty affect virtually all aspects of ship safety; the condition of a ship, quality of an organisation, competence of crew, different cargoes carried on different routes, the weather, encounters with other ships, reactions of individual mariners, and the response of the structure, machinery and equipment. The stochastic nature of these elements indicates that a probabilistic approach is appropriate in order to evaluate safety, and this would require:

Identification of elements that are significant to ship safety;
Knowledge about the probabilities associated with these elements;
Assumptions about the functional relation between the different safety elements, to determine how individual probabilities can be combined.

There is an extensive literature associated with ship safety, including many accident investigations, and it is likely that the more significant safety elements have already been identified. However, some ship casualties have been the consequence of what may have been regarded as minor oversights and lack of attention to detail. For example, failure to secure steel pipes stowed on deck of the tanker Braer began a chain of events that led to the loss of the ship in January 1993 (Acker, 1994). The rapid growth in significance from relatively minor conditions to a major event is the realm of chaos theory (Gleick ,1987), and is beyond the scope of this study.

Probabilistic data

The need for probability estimates or distributions associated with the various safety elements is a major difficulty. An increasing volume of good data is available; examples include oceanographic and climatological observations, and recorded data about forces and moments on ships' structures, but records of machinery reliability and operational aspects that are commercially sensitive usually remain confidential, and information about vessel traffic levels and human reliability is scarce.

Probabilistic data is derived from three main sources, each with advantages and limitations. There are probabilities derived or calculated logically, for example in a port with 10 berths, if allocation is random there is 0.1 probability that a particular berth is used. Probabilities based on frequency observations are used extensively, and records may indicate that ships docking at number ten berth have twice the number of contacts which result in damage than at number one berth. Probabilities can also be derived from intuition and informed opinion, a mariner may consider the width of waterway and the effect of wind and tidal stream, and decide that there is a high probability of damage if he attempts to put his ship along side number ten berth. He could, after some deliberation, estimate the probability of contact damage to be about 0.05, for example.

Logically derived probabilities are reliable and the most easily verified, but depend on the randomness of the situation. In the example used, port authorities would avoid allocating a large ship with poor manoeuvrability to a difficult berth. Most situations are too complex for an analytical derivation of probability, and frequency observations are necessary. The use of observed data assumes no significant change in conditions, which may be reasonable for observations such as wave heights and wind strengths, but could be misleading for the reliability of components where manufacturers may be trying to improve their product, or reduce costs. Intuitively derived probabilities may be useful for model-building when no suitable observed data is available, and it may be possible to fit upper and lower bounds to such distributions and to test the sensitivity and limitations of the model to changes in data. It is essential to document the type and source of data used in a model, particularly where a mixture of data type and quality is used.

A number of different methods based on probability theory have been applied to particular aspects of ship safety and industrial safety. It has long been recognised that safety is related to systems reliability (Abell ,1932) which is a probabilistic concept. The mathematical theory of reliability is based on the idea of a survival function v (t) :

$$v(t) = \Pr\{ T > t \}$$

where T is the average lifetime of a component which, at any time, is either functioning or has failed.

The failure rate for similar components $\lambda(t)$ is given by:

$$\lambda(t) = -\frac{v'(t)}{v(t)} \qquad \text{where } v'(t) = \frac{dv}{dt}$$

and if the failure rate is assumed constant this gives:

$$\frac{v'(t)}{v(t)} = -\lambda = \text{constant}$$

on integrating

$$v(t) = \exp\{ -\lambda . t \}$$

If a system is decomposed into components, and the survival function for each component is known, then is possible to determine the survival function or reliability of the system. It must be possible to represent the system as a network linking the components in series and parallel. As for components, a system considered has only two states, it is either working or not working (failed), depending on the state of the components, and the positions of working/failed components in the network. Some mechanical, hydraulic, pneumatic and electrical systems can be analysed in this way, although the theory assumes that the lifetimes of individual components are independent of one another, which is usually not the case.

The requirement for independence of component lifetimes, and the restriction to two states means that the mathematical theory of system reliability does not extend to the structural and operational reliability of ships and the human reliability of ships' crews. Restriction of human reliability to two states would mean that a human operator could be either fully functioning (fit and alert), or dead, whereas most safety considerations involve reduced human performance due to overload, fatigue or boredom.

For structural reliability, the stochastic nature of forces and capability are considered. The probability of structural failure can be defined in principle by the following integral:

$$P_f = \int_{F=0}^{\infty} P_l(F) . P_s(F).dF \qquad \text{(Hansen, 1977)}$$

Where	F	=	force
	P_f	=	probability of failure
	$P_l(F)$	=	probability of a force equal to F
	$P_s(F)$	=	probability of structural strength equal to F

This concept has been extended to models of the accident-related behaviour of groups and organisations, where the probability of failure is defined as the probability that the momentary demands of a task exceed the momentary abilities of individuals in the group or organisation (Sanders and McCormick, 1987). But in human and organisational related behaviour the analysis is complicated by the fact that through chance events, both safe and unsafe behaviour can lead to accidents and failures.

Quantitative risk analysis

A standard method used in formal safety assessment is that of quantitative risk analysis (QRA) in which both the frequency and the consequence of failure are taken into account as follows:

$$\text{Risk} = \sum_{i=1}^{n} N_i \cdot f(d_i)$$

where N_i is the expected number of incidents of type i, and d_i is the level of damage, which could be measured as lives lost or the cost of property damage,

$f(d_i)$ is a function of d_i which could reflect a subjective attitude towards large accidents. For simplicity it is sometimes assumed that $f(d_i) = d_i$, and

the calculated risk is equal to expectated loss, which can be used for comparing projects of similar size.

Quantitative risk analysis may be suitable for estimating safety performance of industrial processes which are reasonably stable, and where there are frequent accidents of a routine nature. However in relation to shipping casualties there are problems with the available data and the nature of incidents which limit the usefulness of QRA. The characteristics of ship casualty data is discussed next.

Shipping casualties

Each year, Lloyds Register of Shipping publish world fleet statistics and casualty returns for merchant ships of gross tonnage 100 and over. The casualty returns are for "total losses", including "constructive total losses", and do not include casualties where ships are repaired and returned to service, nor casualties that include loss of life in which a ship has not been lost. Although there are limitations to this global type of data, there have been a number of thoughtful reviews based on Lloyds casualty returns, and this information will be useful in developing a mathematical model of ship safety (Curry, 1995; Cashman, 1977; Beer, 1968).

Shipping casualties are classified as:

Foundered
Fire / Explosion
Missing
Collision
Contact (with wharves, sunken wreck, obstructions, etc)
Wrecked / Stranded
War losses / Damage during hostilities
Hull / Machinery damage
Miscellaneous (including losses that have not been classified)

(See glossary for terms used)

Figure 2.2 shows the frequency of each type of casualty as a proportion of the total number of casualties recorded for the period 1990 to 1993 (Curry, 1995). The casualties shown in the figure represent the loss of 690 ships, and the accompanying table shows the incident of each type of loss as a percentage of the total number of ships at risk. Using the frequency definition of probability, the numbers suggest that the probability of a ship being lost as a result of any type of casualty in one year is 0.00275, and the probability of loss due to foundering is 0.00118

Foundered	0.118
Wreck/Stranding	0.058
Fire/Explosion	0.044
Collision	0.032
Contact	0.011
Lost	0.0097
Missing	0.0043
TOTAL	0.275

Figure 2.2 Shipping losses 1990 to 1993 for all types of merchant ships.

The sample of 690 ships is small and larger samples are necessary for reliable estimates of probabilities, but for a larger sample it is necessary to go back in time and include pervious years. Chapters 3 and 4 of this study describe some of the significant developments which could affect the frequency of various types of casualty, and it is likely that earlier casualty distributions will be less reliable for predicting the probable distribution of future incidents.

Figure 2.3 shows the general trend in total losses since 1960. The numbers are for loss as a percentage of the ships at risk, and there has been a decrease in the total numbers of ships lost in recent years.

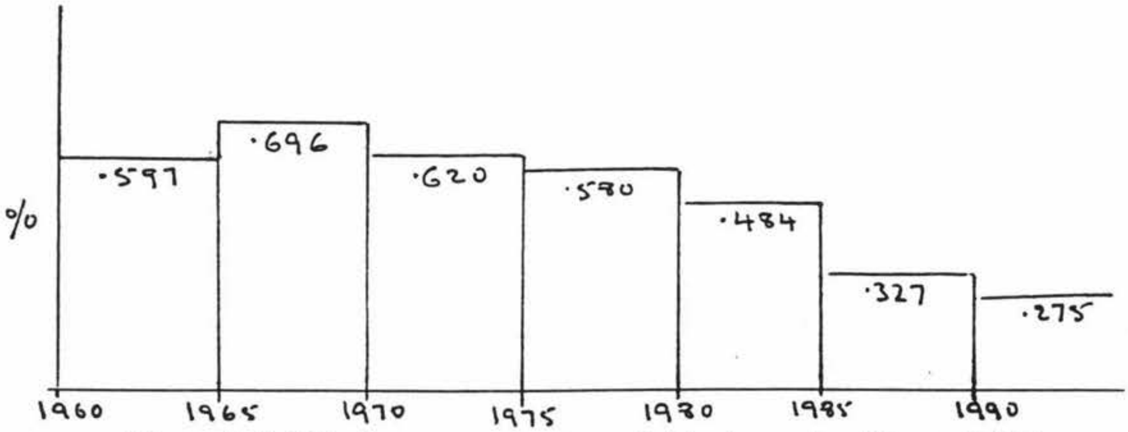


Figure 2.3 Ships lost as a percentage of ships in service (Curry, 1995)

If a merchant ship is expected to remain in service for 25 years, then a casualty rate of 0.5 percent suggests that about one ship in every eight will be lost as a shipping casualty. By the same reasoning, for a mariner who works in ships for 40 years, the probability of being on board a ship at the time it is lost as the result of a casualty is about 0.2. Similar reasoning cannot be extended to the probability of loss of life resulting from a shipping casualty, because certain types of casualty are more likely to involve loss of life than others. This is illustrated in the distribution of ship casualties and lives lost as a result of ship casualties, extracted from Liverpool Underwriters casualty returns for 1969 to 1975 by Hansen (1977).

Table 2.1 Comparison of lives lost to ships lost

CASUALTY	% SHIPS LOST	% LIVES LOST	LIVES / SHIPS
Foundering	2	10	5.15
Stability	4	17	4.38
Structural	7	21	3.09
Fire/Explosion	23	24	1.08
Moorings	2	2	1.03
Collisions	26	19	0.75
Grounding/Contact	25	3	0.12
Machinery	7	nil	0.0
Other	3	3	1.03
TOTAL	2102 ships	2167 persons	

(Hansen, 1977)

From Table 2.1 it is apparent that there is a greater risk of human casualties from foundering, instability or structural failure than for other types of casualties. The type of casualty involving high loss of life are associated with rough weather which makes the launching of lifesaving appliances difficult, and the sudden catastrophic nature of capsize or structural failure.

There are a number of limitations to inferences about safety derived from total loss statistics. Although between 200 and 300 ships in a year represents a huge loss in terms of lives, property and damage to the marine environment, the number is small relative to the 80,000 or so seagoing merchant ships with gross tonnage 100 or more. Inferences drawn from a sample of 0.3 percent of a population are not likely to prove reliable and random events overwhelm the other factors which determine safety. It is also likely that not all ship losses are included in the statistics gathered by any maritime organisation (Kwon, 1994).

Another limitation is that total losses account for only a small proportion of ship casualties. Every year there are many thousands of incidents such as fires, machinery breakdowns, collisions, groundings and contact that do not result in the loss of a ship. Many of these incidents cause serious damage and loss of life, and so should be included in any assessment of ship safety. The situation is similar to that observed for industrial accidents, where there are far more minor accidents than major accidents. The ratio of minor to major accidents appears to vary widely between industries. For example, in a survey of industrial accidents in the USA, the ratio of "lost time injuries" to "no lost time injuries" to "damage only accidents" was 1 : 10 : 30 for a range of industries, but 1 : 100 : 500 in the steel industries (Jardine Insurance Brokers Ltd, 1987).

A knowledge of casualties that do not involve loss of ships is important to the development of a reliable mathematical model of ship safety, but the collection and use of such data involves many difficulties. Maritime nations record, investigate and report marine accidents, but it is doubtful if a significant proportion of the accidents that occur world-wide are reported. Classification of such accidents is difficult; for example, when a large container ship lands heavily on a wharf during berthing manoeuvres, the cost of repairs may be several times the cost of what would be considered a serious accident or even the loss of a smaller ship. Some types of incidents are more likely to be reported than others; a fire which is quickly brought under control and causes little damage is likely to be reported and investigated, whereas a ship which develops an instability list, which is quickly recognised and brought under control may have been in a more dangerous situation than the ship with the fire, but if there was no obvious damage the incident is less likely to be reported. There have been a number of attempts to collect and disseminate wider information about casualties and near misses, such as the Nautical Institute's International Marine Accident Reporting Scheme (Beedel, 1992), but lack of suitable, reliable data is a drawback to the validation of a model of ship safety.

While discussing casualty data, it is useful to consider the objective of measurements related to safety performance. Tarrants's (1980) view was " ... the ultimate objective of measurement is not 'accidents'. Rather it is some intrinsic property that might be thoutht of as 'safety expectation', which, depending upon the generally strong role of chance, governs the probability of occurence of any given number and severity of human accidents during some specific future time interval or some particular amount of human exposure. This property is, of course, not directly measurable but must be inferred from the measurements of other attributes or events that are observable - including, but not necessarily limited to, current accident rates."

Although total loss data is limited for validating models, inferences can be made to motivate investigation of the chains of cause and effect that could lead to the development of models of ship safety. Some inferences derived directly from casualty statistics are:

The frequency of ship casualties decreases with SIZE of ship;
The frequency of ship casualties increases with AGE of ship;
Particular classes of casualty are more frequent for some TYPES of ship than others.

In an analysis of world merchant shipping losses, Cashman (1977) found that between 1949 and 1975, 4751 ships of gross tonnage between 100 and 1000 were lost, representing 66 percent of all losses. Losses were not related to the number of ships at risk in each category, but it appeared that the loss ratio for small ships was much greater than for large ships. Cashman suggested that small ships were more vulnerable than large ships because:

1. They generally work close to the coast. The trade carried out by small ships involves short sea passages and frequent port arrivals and departures, which involve greater risk than passages in open waters.

2. Small ships are more likely than large ships to experience stability problems in rough weather.

Vulnerability of small ships is also related to the economics of ship operation. Capital and operating costs vary in less than linear proportion to a ship's carrying capacity, and in general ships are subject to economies of scale. This increases commercial pressures on small ships, allowing less tolerance for delays and less time and resources for planning, preparation and maintenance. There is also less money to pay crew, leading to smaller crews which have to work longer hours for less pay, and are generally less well qualified than the crews of large ships. Small ships are subdivided into fewer compartments than large ships (usually there is one cargo hold) so that if the structure is damaged or fails in the region of the cargo hold the ship is likely to sink. The vulnerability to sinking is increased because small ships have a smaller ratio of reserve buoyancy to total volume than large ships.

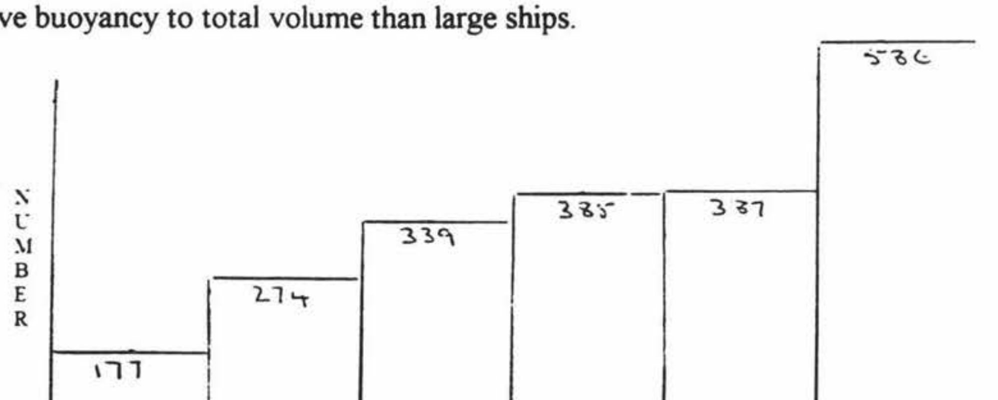


Figure 2.4 Ships lost according to age during 1967 - 75 (Cashman ,1977).

Figure 2.4 shows a distribution of ships lost according to age for the period 1967 to 1975. The distribution indicates that for ships more than 14 years old, age is more significant than all other factors combined. Apart from corrosion, ships do not wear out the way that certain tools and equipment do, and it is more likely that there are a number of factors related to age which result in an increase in the incidence of collisions, groundings, fire and structural overloading than for new ships. A new ship involves a large investment and there is a great incentive to manage and operate it in an efficient manner. As a ship ages, its value depreciates and at the same time it requires more maintenance and becomes more expensive to operate. A company may seek to maximise profits by purchasing second-hand ships and using them to transport low-value goods with minimum expenditure and this results in a minimum outlay on replacing equipment, maintenance, stores and crewing. Thus older ships may be operated by companies with different objectives from those operating relatively new ships, the structure and equipment deteriorate because of reduced maintenance, while less able and demoralised crew, operating old and possibly faulty equipment, are more likely to have accidents than the crews operating new ships. These observations are of general tendencies, and there are many sound ships of more than 14 years being operated successfully and efficiently. Conversely, new ships exist that are poorly operated, and are vulnerable to casualties, as illustrated by the MV Pacific Charger which grounded at Baring Head, and became a total loss on the ship's maiden voyage (Korburger, 1982). This clearly indicates that the relevant factor is not the age of a ship, but the underlying elements of ship operation that correlate with age, that determines the safety of a ship.

The loss of large well-found RORO ships such as the Herald of Free Enterprise and European Gateway highlighted the vulnerability of these ships to flooding and capsize (Spouge, 1989). Although the watertight integrity and subdivision of ships' hulls are basic requirements known to all naval architects, these principles were compromised in the interest of commercial efficiency. The result is the acceptance of a type of ship that is vulnerable to a particular type of casualty, and extensive research is presently being conducted to improve the safety of RORO ships, while maintaining their economic efficiency over conventional ships. Another example of association between a type of ship and a particular kind of accident is the vulnerability of passenger ships to fires. The passenger ship Angelina Lauro was lost as a result of fire in March 1979 (Safety at Sea International August 1982, pp 15 - 23). This type of accident has resulted in revision of the fire safety standards in Chapter II-2 of the 1974 Safety of Life at Sea Convention.

During the 1960s oil tankers were extremely vulnerable to fire and explosion. Since then the incidence of loss caused by fire has been reduced by fitting inert gas systems and through intensive precautions to reduce the risk of fires. More recently the loss of large bulk carriers has caused concern and there has been much research and speculation into the causes. Research into this problem is particularly relevant because of the wide range of disciplines and interests involved. The loss of MV Derbyshire, operated by a reputable company, classified by Lloyds Register of Shipping, and manned by qualified and experienced mariners generated extensive discussion and investigation using mathematical methods such as hydroelastic analysis. (Bishop et al., 1991; Ramwell & Madge,1992) Naval architects have examined the principles of design for large ships (Brooking, 1991), the operational aspects such as maintenance, loading and manning have been reviewed (Ferguson, 1991; Moore, 1992) and the minimum standards prescribed by the safety conventions relating to these ships have been questioned (Birkenhead, 1993). The literature reviewed gives the impression that all aspects such as the initial design, quality of construction, operation, maintenance and crewing are relevant to the high incidence of bulk carrier losses.

Casualty statistics imply that ship safety is related to size, age and types of ships. But a ship does not sink simply because it is small, or old, or designed to carry bulk cargoes, but because of a number of root elements that may correlate strongly with size, age and type. A rational approach to modelling ship safety is to find quantifiable parameters that describe the root elements, and to investigate the functions that relate these parameters to one another and to ship safety. Ship design and operation has a long history, and there is an extensive literature that should allow the root elements of ship safety to be identified with reasonable certainty. Many aspects of ship safety can be quantified, but the functional relation between the parameters and safety remains a key problem in the development of a mathematical model of ship safety.

Chapter 3

Ship safety, the system to be modelled

Types of merchant ship

Total loss statistics show a correlation between the size, age and type of ships, and the frequency of the different classes of casualty. Commercial factors influence ship safety, and determine the quality of ships, the organisations that operate ships, the levels of maintenance, crew competence and pressure to carry more cargo with fewer delays. This section takes a broad view of the international shipping industry in order to identity the aspects that influence safety performance. The various types of ship are reviewed briefly as these relate to different types of accident, and consequently to the level of safety. The factors that determine the composition, size and age of the world fleet are then discussed, and the functions necessary for the operation of a merchant ship are outlined, so as to provide the context for the more detailed treatment of ship safety elements in Chapter 4 of this study.

The function of a merchant ship is to earn a return on investment by providing transport services. To remain in business, ship owners must be able to transport cargo competitively, and the most prevalent method of being competitive is through specialisation. Of the 80,000 or so merchant ships with gross tonnage over 100 in world trade, just over half are cargo-carrying ships, the rest being passenger ships and special purpose vessels such as fishing vessels, factory ships, supply ships and ocean-going tugs. Some passenger ships carry cargo, for example RORO ships carry passengers and their cars, as well as cargo on trailers.

The largest tankers transport crude oil from the oil-producing areas to refineries, where it is broken down into petroleum products, which are distributed by smaller tankers. Crude oil and oil products account for nearly half the world's seaborne trade on a tonne-mile basis, and an estimated 7000 vessels transport about 1500 million tonnes of oil each year through an average distance of 4700 miles (SBS, 1991; Gold, 1994) Tankers also carry liquefied gas, chemicals, molasses, vegetable oil and a great variety of other liquids.

Dry cargo ships include bulk carriers, container ships, refrigerated cargo ships, livestock carriers, general cargo ships and a number of other specialised vessels. Bulk carriers that transport huge volumes of bulk minerals, ores, coal, grain, scrap iron and logs, range from small sea-going ships of a few hundred tonnes to large ships that can carry more than 180,000 tonnes of cargo. In 1990 there were about 5000 bulk carriers of dead-weight more than 10,000 tonnes (Isbester, 1993), and probably a similar number of less than 10,000 tonnes deadweight.

Container ships are part of a complex international container transport network, with large ships built to carry up to 6000 twenty-foot-equivalent units (TEUs) between major terminals, and numerous smaller ships distributing containers on a more localised basis. Between them bulk carriers and container ships carry most of the trade that was the province of general cargo ships until the late 'sixties. A relatively small number of general cargo ships are in service, serving regions of the world that have not developed facilities for handling large numbers of containers, or where the volume of cargo does not warrant containerisation or the use of bulk carriers. Container ships transport large numbers of refrigerated cargo containers, but specialised refrigerated ships are also employed in some trades.

Several characteristics effecting safety are shared by all types of merchant ships. Apart from some small fibreglass or aluminium vessels, ships are built of steel, which gives high strength but is subject to corrosion in the marine atmosphere. Essentially a hull is a hollow watertight shell, supported by longitudinal and transverse frames and webs, and divided into compartments by steel bulkheads and tanks. Steel decks are provided with openings for cargo and for access, and these are made watertight by hatch covers and doors. In most modern ships the propulsion machinery is located near the after end to simplify power transmission to the propeller. Superstructures may be constructed of steel or aluminium, and provide accommodation and service spaces, with the navigation bridge at the top level to give adequate visibility. The form of the hull is a compromise between the desire for maximum carrying capacity, where large box-shaped compartments are usually ideal, and the requirements of efficient propulsion, stability, manoeuvrability and seakeeping. The safety of a ship is also effected by characteristics that are particular to, or more dominant in, certain types of ships and some of these characteristics are reviewed here.

Passenger ships

There are few ships that carry passengers on long international voyages, and the majority of passenger ships are either ferries that carry large numbers of persons on short voyages, or passenger cruise ships. The hull and superstructure of a passenger ship is divided into public areas and private cabins which are accessed through passage ways. Furnishings present a fire hazard, and the quantity of combustible material is kept to a minimum consistent with the need for passenger comfort. The hazard from fire is increased by the presence of a large number of people who may be unfamiliar with ships, and who have access to areas that are not under continuous surveillance. The need for heating, lighting and ventilation throughout the accommodation also increases the fire hazard.

Passenger ferries sail to timetables, and are expected to maintain schedules whenever possible. These ships usually operate in busy waters where there is a high risk of collision, and the short voyages mean frequent manoeuvring into and out of berths which increases the chance of contact damage. Passenger ferries are usually able to attract and retain highly competent mariners who are experienced in local conditions, but the pressure to maintain schedules can lead to operator fatigue and lack of time for adequate preparation.

Passenger cruise ships provide sightseeing and entertainment, and sometimes involve voyages into sea areas that are not frequented by ships of similar size. Masters of these ships may be required to overcome their reluctance to venture close to islands and enter lagoons that may not be charted adequately, and there is a real risk of grounding.

The large superstructures of passenger ships tend to give these ships a high centre of gravity and have resulted in problems with vessel stability. However there is relatively little variation in deadweight when compared with cargo ships of similar dimensions and, provided a ship has good initial stability, there should not be a problem in operation. The high sides and superstructure do result in greater wind forces than cargo ships are subjected to, and this can increase the risk of contact or collision when berthing or manoeuvring.

Tankers

Tankers are divided into large numbers of cargo tanks, which are fitted with small watertight hatches on deck, and this provides a high level of watertight integrity, so that there is less chance that a damaged tanker will sink than in the case of a passenger or dry cargo ship with a similar level of hull damage. The greatest hazard is fire and explosion in ships that carry crude oil or volatile products. There is also a risk of oil pollution as a consequence of structural damage, and research is being conducted into developing and evaluating new designs that minimise the risk of oil pollution.

The great size of crude oil tankers presents potential hazards. Large ships fitted with single screw and single propeller, and with relatively low powered propulsion machinery, can be difficult to control. Such ships have large turning circles and stopping distances, and if disabled on a lee shore, powerful tugs would be needed to prevent them from stranding. Large ships are also subjected to greater forces and moments than smaller ships, and damaging forces acting at the forward end may not be apparent to mariners in an accommodation block situated at the after end of the ship.

Roll on roll off ships

ROROs have large bow visor or stern doors, fitted with ramps for vehicles to be driven or towed on board. This is quick and efficient compared with loading and discharging ships through hatchways in the deck, but openings in a ship's hull makes it vulnerable to taking in water. Large vehicle decks which run the full length and breadth of a ship also present stability and fire hazards. The hazards associated with these ships have been known for many years, but the existence of a large number of ROROs which provide fast and efficient short sea transport for cargo and passengers makes it difficult to eliminate the hazards without a major change in the nature of the services.

Bulk carriers

Bulk carriers are relatively simple ships and generally have good strength and stability characteristics. The larger bulk carriers are subject to the same types of hazards as large tankers, but do not have the level of subdivision that is a characteristic of tankers. The high incident of bulk carrier losses has been attributed mainly to structural damage in heavy seas, and to damage caused when loading and discharging. Heavy ores are loaded at high rates which cause impact damage on tank tops and bulkheads. To avoid excessive stability and violent rolling when carrying high-density cargo, some ships load alternate holds, and this causes large shear forces on the longitudinal structure. While discharging, the structure is subject to damage by grabs and bulldozers working in the holds. After breaking the paint surface inside holds, wet and corrosive cargo accelerates the rate of corrosion of frames, brackets and plating, and the large holds without intermediate decks are very difficult to inspect closely enough to detect damage at an early stage.

An important aspect of the bulk trade is the relatively low value of cargo, which attracts low freight rates and puts economic pressure on ship owners to keep costs to a minimum. Bulk carriers have been called the heavy work-horses of the sea, and their unglamorous image and poor pay is unattractive to mariners. Factors such as poor image and the continuous repetitive nature of the work leads to poorly motivated and demoralised seafarers who are unlikely to achieve a high standard of safety performance.

Container Ships

Purpose built cellular container ships are fitted with vertical tracks to guide containers into slots and to secure them in place. Containers are loaded below the main decks and several tiers are stacked on top of the hatch covers. The ships are part of a complex transportation network and the tendency is for higher speeds than tankers and bulk carriers. Pressure to maintain schedules will tend to increase the risk of collision and grounding in areas with high vessel traffic density, and during poor visibility.

Loading containers across the full breadth of the upper deck increases the likelihood of transversely unbalanced masses between different holds, and container ships have large hatch openings and fine hull form, the structures of which are subject to significant torsional moments as well as vertical and lateral bending stresses. (Chen et al., 1986) Large, fast container ships driven at full speed into head seas are subjected to huge forces, particularly near the bow sections where ships' sides are flared to shed water sideways and to prevent excessive water reaching the containers on deck. The combination of speed and ships' motions can cause heavy vibration which can lead to metal fatigue and cracking of ships' structures.

Calculation of stability for container ships is dependent on accurate information about the mass and location of each container. This presents little problem for large ships on voyages between major container terminals, but smaller vessels find it difficult to obtain accurate information within the limited time allowed by the quick turnaround, and there is a risk of instability in some ships. When a container ship with three or four tiers of containers on deck rolls, the securing devices and securing points on the ship are subjected to large forces, and loss of containers on one side can cause a ship to take a dangerous list. Some container ships are fitted with fin stabilisers or flume tanks to reduce rolling and thus reduce the danger from excessive stress.

The economic pressures

International shipping is a vast complex and fragmented industry made up of many different types of companies, from single ship operators to large corporations with over one hundred ships. Some companies specialise in a single type of ship, while others operate mixed fleets which may include various types of tankers and dry cargo ships. The decision to invest in shipping is the subject of much study in its own right, and it is assumed here that a ship owner's objective is to make profit. A ship's lifetime of 20 to 25 years represents a long-term investment and during such a period there may be large and unpredictable changes in the pattern of world trade. The demand for ships is derived from the demand for shipping services for the goods in international trade, and this demand is subject to cyclical economic fluctuations as well as long-term trends. In 20 years there are significant changes in technology as well as regulatory requirements, so that many ships, their machinery and equipment are obsolete or uncompetitive long before the end of their intended life. Thus investment in shipping involves a large element of commercial risk that increases the pressure to reduce costs. When there is a surplus of ships due to oversupply or a fall in demand for shipping services, freight rates tend to fall, exacerbating the need to reduce costs. For an owner operating uneconomical or technically obsolete ships, the costs involved in the loss of a ship through an accident may be too low to provide incentive to maintain a high standard of safety.

If a reduction in the demand for shipping services tends to lower the general level of shipping safety, it would be reasonable to expect a rise in demand to improve safety. When ship owners expect the increase in demand to continue, they may order new ships, but the world's capacity to build new ships is limited and there is an interval of two years or more between an increase in demand and the resultant commissioning of new ships. When the new ships eventually do come into service, conditions may have changed so that there is an oversupply of ships, as was the experience of tanker owners in the mid-seventies (Storey, 1975). The more immediate effects of an increase in demand over supply of shipping services are:

- increased pressure for quicker turnaround and better utilisation of existing shipping capacity
- reallocation of ships carrying low-value cargoes to cargoes that pay higher freight
- recommissioning of ships that have been laid up
- extending the life of ships that are due to be scrapped

It appears that safety decreases with the level of change and uncertainty in world trade, and that the improved ability to forecast future trading patterns may be an important factor in improving ship safety. The complexity of forecasting the relationship between changing trade patterns and shipping services is illustrated by Taylor's (1976) dynamic model of supply and demand for shipping capacity. The time-dependent variables used in the model include: freight rates, total capacity of ships in operation, capacity of ships that are laid up, the rate of ordering new ships, delays and backlogs in shipbuilding, and the resultant building and scrapping rates. Both positive and negative feedback loops are included in the dynamic model, for example an increase in the building rate leads to an increase in the supply of shipping capacity, and a decrease in freight rates, which in turn reduces the rate of placing orders for new ships. It was noted that the statistical correlation coefficient for the joint variation of shipbuilding orders and freight rates was 0.76 when freight rates are lagged by two months, and that ship owners were strongly influenced by the current freight rate, and appear to have no memory of past variation in rates when a rush to place orders has been followed by a decline in demand for services. The situation is further complicated by interaction between the various markets such as for tankers, bulk carriers and container ships, and shifts in the global trade pattern where demand is a function of both volume of cargo and the distances through which it is transported.

Political and operational influences

As well as the global economic cycles, the demand for international shipping is affected by political events. The closure of the Suez canal in 1966 increased the length of the voyage between Europe and Asia, which increased the demand for both dry cargo ships and tankers. Other events of great significance to the demand for shipping services were the formation of the European Economic Community, the sudden increase in the price of oil in 1972 and 1979, the failure of the Russian wheat harvest and the massive investment by western banks in third world countries, which created new markets for goods and encouraged those countries to build up their merchant fleets.

Regardless of the uncertainties of international trade, there is sufficient investment in new ships each year to consume about ten percent of the world's steel production. Some ships are built to compete for charters in the open market, and others for a particular trade, and after the decision to build a particular type of ship has been made, the most significant decision is the ship's capacity and main dimensions. Provided sufficient cargo is available to fill a ship on each voyage, the cost per tonne mile of cargo transported decreases with the size of ship. When there is insufficient cargo, the largest ship that can be fully loaded on each voyage is more efficient. But a large ship is a greater financial risk, and in some parts of the world, port and repair facilities are not able to accommodate them. Large ships take longer to load and discharge, and this appears to have limited the size of container ships. Thus there are commercial and operational factors that limit the size of ships of various types.

Ship design is an iterative process which is partly technical and partly intuitive and based on experience. General features are selected first; capacity, main dimensions, speed, number of cargo compartments, and so on, in a process of refinement until the final design is decided. A naval architect's task may be to design a ship that meets the owner's specifications and all regulatory requirements at least cost. This is a process of constrained optimisation in which the designed ship is not necessarily the cheapest that can be built, but there is an attempt to minimise the combined capital and operational costs over the life of the ship. Hull plating, for instance, may be thicker than the minimum specified by the classification society, so as to reduce the necessity to replace large numbers of plates during the operational life of the ship.

Costs associated with safety

Suppose that a ship owner operates in an unregulated market, and the only objective is profit maximisation. A large number of companies operating in unregulated market implies perfect competition so that a ship can find as much cargo to transport as it can handle, provided the freight rate is competitive, and profit is made only when costs are minimum. It is also assumed that a reduction in expenditure increases the probability of shipping casualties. But casualties incur additional costs; such as the cost of replacing or repairing a ship, possible increase in insurance premiums, loss of reputation as the company appears less attractive to shippers, and the possibility of having to pay higher wages to attract or retain crew. In Figure 3.1 the curve C_s is the assumed relationship between expenditure on safety and the number of accidents, and curve C_a is the relation between the number of accidents and the cost of accidents. The curve TC is the vertical summation of C_s and C_a, and is the total cost associated with safety, and the minimum total cost is found for an accident frequency n_o (Goss, 1977; Underwood, 1991). A profit-maximising ship owner working in an unregulated industry is forced to accept an accident rate n_o, and any movement away from n_o results in higher total costs so that other companies can undercut the ship owner, who then loses access to cargo.

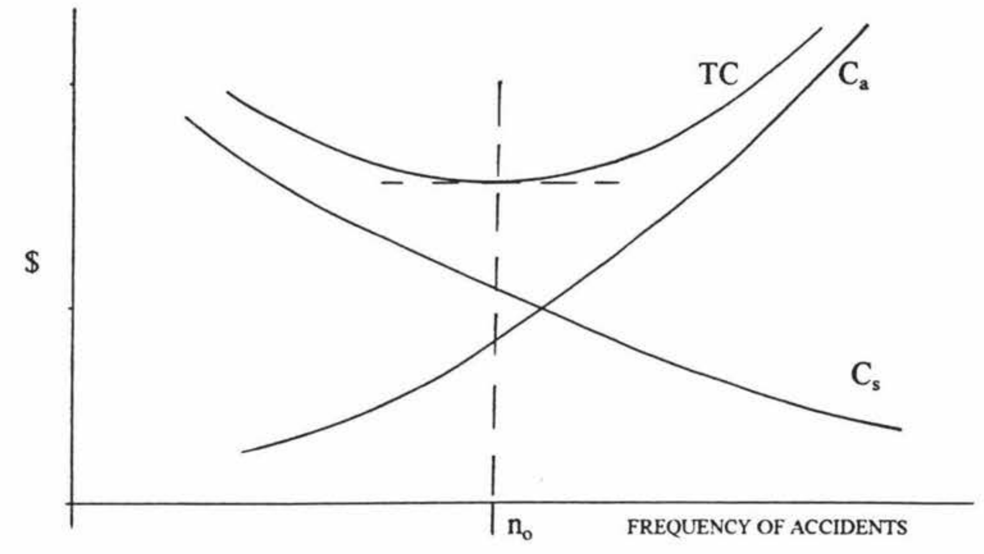


Figure 3.1 Safety cost curves

If there is a fall in demand for shipping services, and freight rates drop, a ship's earnings are reduced, and this will reduce the effective cost of shipping casualties. Figure 3.2 shows that the reduced cost of accidents can lead to an increase in the shipping casualty rate.

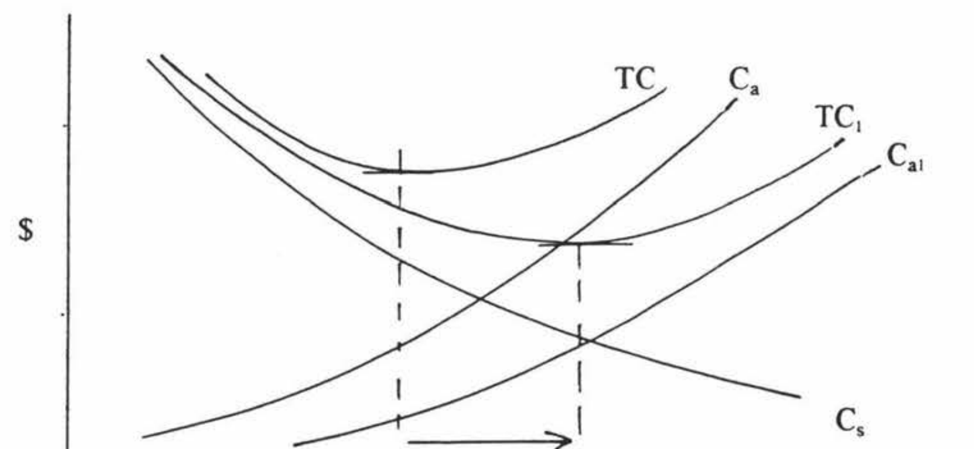


Figure 3.2 Effect of lower freight rates in increasing the number of accidents

Although this consideration of safety costs is abstract, it indicates that the absence of regulation should lead to a shipping casualty rate where the combined cost of casualties and expenditure on safety is minimum. Exactly what casualty rate this would result in is not known, but the relevant costs are those falling directly on ship owners, and not the full cost of accidents. Shipping casualties result in external costs such as third party damage, loss of life and damage to the environment which may not be fully compensated by the party at fault. The existence of external costs prevents self-regulation from optimising expenditure on safety, and the response of maritime nations is to enact shipping safety regulations to set minimum standards for ships, equipment and personnel. Provisions of the International Conventions on the Safety of Life at Sea 1960 and 1974, the International Load Line Convention 1966 and the International Convention on Standards of Training Certification and Watchkeeping for Seafarers 1978, are embodied in the national regulations of the nations that are signatories of these conventions.

Marine insurance

Another important influence on ship owners' attitude to risk is the facility to insure ships and their cargoes. Insurance premiums are determined by the value of property insured and the level of risk:

PREMIUM = VALUE x PROBABILITY OF LOSS + PROFITS + ADMINISTRATION COSTS

If the insurance companies' profits and administration costs are ignored the premium is equal to the expected value of loss. This implies that insurance is neutral, and that the expected value of loss due to shipping casualties is the same with or without insurance. A ship owner's desire to insure can be partly explained in terms of a Von Neumann and Morgenstern utility index (Tisdell, 1972). It is supposed that a shipping company's income utility function is characterised by diminishing marginal utility as shown in Figure 3.3. Let there be a probability of 0.9 that the company's income is X_1 and a probability of 0.1 that income is X_0. If X_1 has utility index U_1 and X_0 has utility index U_0, then the expected value of utility U_2 is given by:

$$U_2 = \sum_{i=1}^{n} P_i(X_i) \, . \, U_i = 0.1 \times U_0 + 0.9 \times U_1$$

If it could be certain that income would be X_2, then the utility of income would be U_3, where $U_3 > U_2$. The company would therefore be prepared to give up part of its income to ensure an income of X_2. The maximum amount that the company is prepared to pay to eliminate the uncertainty represented by $(X_1 - X_0)$ is $(X_2 - X_3)$.

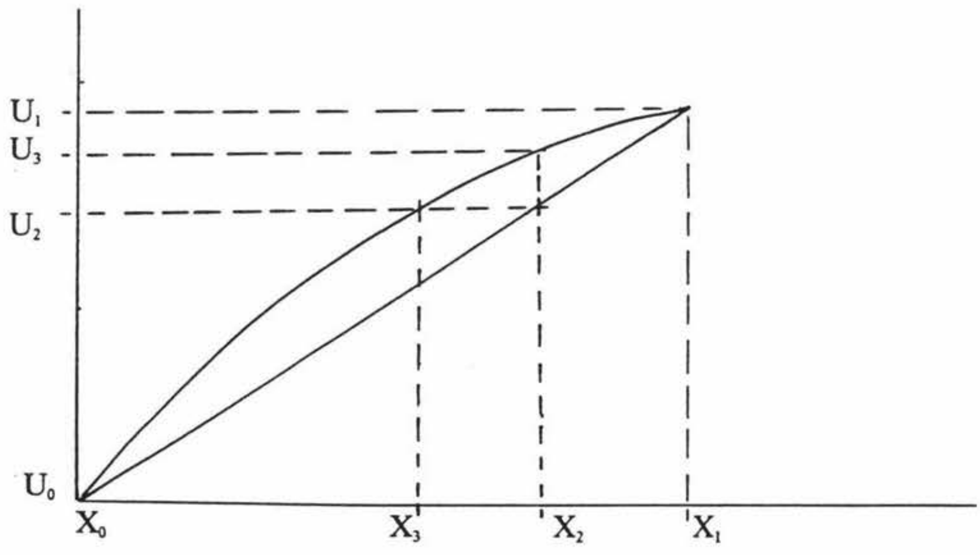


Figure 3.3 Effect of uncertainty on income utility

It appears that for marine insurance the premium is calculated from the probability of loss for the industry as a whole, and not on the safety performance of individual ship owners, and it is likely that the existence of insurance will induce greater risk for a given profit than would be acceptable without insurance. This is a form of externality, where the whole industry meets the additional cost attributable to the poor safety performance of individual operators. Before insuring a ship, insurance underwriters normally require that the ship has certification issued by a classification society. The major classification societies have developed standards for construction of ships, and classification society surveyors carry out inspections, measurements and tests to ensure that ships certificated by their societies meet these minimum standards.

Factors influencing safety

Although the dominant forces that determine the safety of ships are economic, it is seen that there are legal and commercial regulatory influences that appear to be directed at improving ship safety. Decisions which concern safety are made at international level by institutions such as the International Maritime Organisation, the International Chamber of Shipping and the International Association of Classification Societies, and are put into effect by national safety administrations, shipping companies and the classification societies. There are also technological developments that affect the design, materials and construction methods for ships as well as the equipment and operation of ships. Environmental effects on safety are pervasive, from dramatic phenomena such as storms, strong currents or high levels of vessel traffic, to more subtle effects such as corrosion and the cyclic stresses on ships at sea. The human operator also significantly influences safety, from managers making strategic decisions about the size and type of ship to operate, to the day-to-day operational matters such as how much ballast to load, when to overhaul an engine cylinder head, or whether to alter course for an approaching ship.

Some of these factors have immediate and direct consequences for safety; for instance, a decision to put to sea in foggy weather could lead to a collision. Other factors affect safety indirectly or interact with elements that affect safety. An administrative decision to improve standards of structural strength may force a ship owner to look for economies elsewhere, possibly by fitting less expensive machinery, or by employing fewer or less experienced mariners, or by reducing maintenance. The chain of possible influences is complex and subtle, and may never be fully understood. There have been a number of unforeseen results from the introduction of new regulations intended to improve safety, and ship designers and owners can be imaginative in their efforts to avoid excessive compliance costs. It may therefore be impossible to develop a model of ship safety that will fully reflect all such interactions and chains of cause and effect, and a more productive approach may be to look for rational ways to represent the main factors influencing safety.

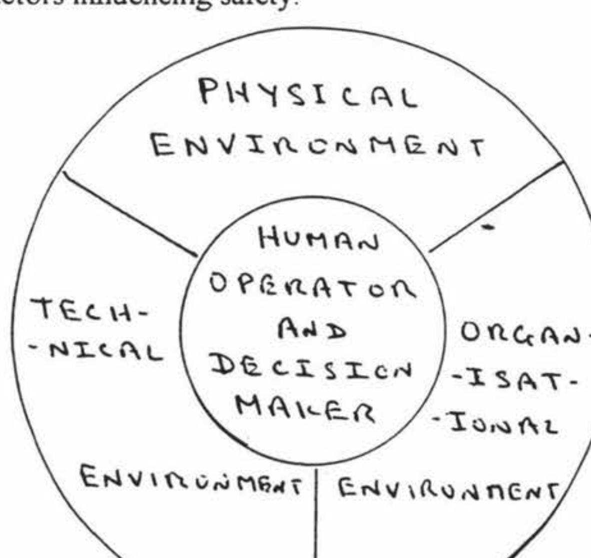


Figure 3.4 General areas of influence on ship safety

Figure 3.4 represents four general areas of influence on ship safety. The human operator and decision-maker is shown to have a central role; the other important areas of influence are the technology involved in the ship and its equipment, the organisational environment, and the physical environment in which the ship operates. Each region of the diagram is in contact with the other three regions, and this represents the possible interactions and mutual influences between regions.

The technology involved covers the design of a ship, its machinery and its equipment. A ship's structure must be able to withstand the forces due to wind and waves, and the sea environment must be considered in strength calculations. The structure must be able to resist forces due to cargo and other weights in the ship, and there is an interaction between the technological aspects of ship design and operational decisions about the carriage of cargo. Similarly, a ship's stability is determined partly by the design and partly by the disposition of weights loaded. In turn, loading is dependent on the type and weight of cargo, and the sequence of loading and discharging ports. Safety is only one of the considerations when planning the stowage of cargo and there are constraints placed on planning decisions. The skill of the human operator and decision-maker is therefore important in planning and executing a safe stowage. Factors such as the time available for planning, motivation and operator workload, which influence the outcome, are determined by the organisational characteristics of the company.

It is apparent that a mathematical model that takes into account all the physical, organisational, environmental and human interactions would be highly complex, and would include subtle and little-understood effects as well as direct and readily-observed actions. It is therefore necessary to first consider the main areas that affect ship safety in relative isolation from one another, and this is the theme taken up in Chapter 4, where the elements influencing ship safety are discussed.

For a mathematical treatment of safety to progress beyond the stage of providing an explanation in principle, it is necessary to be able to quantify the elements which influence safety. Many aspects relating to ships and their operation are quantified quite readily, while the quantification of other factors presents difficulties as indicated in the following list:

TECHNOLOGICAL FACTORS

Physical characteristics of a ship
- Size:
  - gross tonnage (grt)
  - main dimensions
    - length (L) metres
    - breadth (B) metres
    - depth (D) metres
    - draughts (d) metres
    - freeboards (fbd) metres
    - ratios based on main dimensions L/B, L/D, fbd/D, d/D
  - displacement (W) tonnes
  - deadweight (dwt) tonnes
  - volume of displacement (V) cubic metres
  - enclosed volume - cubic metres
  - wetted surface area (WSA) square metres
  - block coefficient (Cb)

Strength:

- scantlings - mm
- shear force - tonnes or kN
- bending moments - tonne metres or MN-metres
- maximum deck or tank top loading - tonnes per square metre
- load - tonnes or kN
- capability - tonnes or kN
- probabilistic safety indices based on load and capability
- fatigue index - kN, cycles

Subdivision:

- number of compartments - integer n
- flooding capability - n
- floodable length of compartments - metres
- probabilistic survival index

Stability:

- GM - metres
- GZ - metres
- area under the GZ curve - metre radians
- dynamical stability - kJ or tonne metres
- probability of capsize

Machinery and equipment:

- power - kW
- mean time between failures (MTBF) - hours
- system reliability
- system availability
- redundancy

Fire safety:

- number of fire barriers - n
- class of fire barrier (from standard fire tests)
- combustible material - tonnes
- calorific value - J/kg

OPERATIONAL FACTORS

Ship's trading profile:

- length of voyage - miles or days
- number of days at sea per year
- length of time in port
- length of voyage cycle
- quantity of cargo carried - tonnes or m^3
- number of different types of cargo carried
- hazardous nature of cargo - IMO classification
- angle of repose of cargo - degrees
- capacity of ballast tanks - m^3

ENVIRONMENTAL FACTORS

Climate:
- wind - Beaufort force or knots
- waves - height, period, length
- probabilistic sea spectra - height, frequency
- probability of encountering storms
- meteorological visibility - nautical miles and associated probabilities

Currents and tidal streams - strength, direction and associated probabilities

Tidal range - metres

Physical dangers:
- distance from danger - miles
- depth of water - metres
- decrease in depth per distance travelled
- type of bottom - rock, sand, soft mud, etc.

Vessel traffic:
- number of ships per unit area
- number of ships passed within a given distance per day
- size, course and speed of vessels encountered
- size weightings proportional to waterplane areas

HUMAN INVOLVEMENT

- number of crew
- qualifications - grade
- length of service - years
- work load - hours per day, mean and maximum
- fatigue indices
- human reliability

The above list is of items relating to a ship, its organisation, the environment and the persons that operate and control the ship, with regard to its safety. The list is not complete as there are many more items that can be measured or quantified, depending on the level of detail that is required. The list gives an indication that the physical aspects of a ship are the most readily quantified, followed by environmental factors. Factors related to human involvement and decision making are much more difficult to measure, and there are major problems in identifying and quantifying the fundamental influences that the organisation of a shipping company has on ship safety.

This impression is reflected in the literature reviewed. There are many technical papers describing research into ships' design, structural strength, stability, manoeuvrability and seakeeping. A large quantity of information on climatological and oceanographic observations are available, and have been used in studies on ship stress and response in waves. On the human involvement and organisational aspects, most of the published work is descriptive, and there have been few attempts to apply mathematical techniques to these factors, which have an important influence on ship safety.

The imbalance in depth of quantitative analysis is a problem that makes the assessment of total safety difficult. A mathematical model of total safety cannot achieve the full depth of quantitative assessment that is used for particular aspects such as structural safety, and at the same time deal with organisational influences and human involvement. Chapter 4 of this study considers the level of quantification presently applicable in each of these areas, with the objective of using available numerical and mathematical techniques in a model of total ship safety. While selective use can be made of the mathematical techniques that have been developed for assessment of physical safety, further quantitative development is necessary before human and organisational influences can be fully incorporated into a mathematical model of ship safety.

Chapter 4

The elements of ship safety

4.1 Structural strength and reliability

Merchant ships are large complex steel structures built to transport goods reliably and economically. A design objective is for a structure that will withstand the forces to which it will be subjected during its life but without excessive weight. Extra weight means that a ship will be more expensive to build, will have a smaller carrying capacity and will consume more fuel per tonne-mile of cargo carried. The basic structure of steel ships has evolved through a combination of intuition, experience, theory and analysis, with an economic incentive to design ships that transport goods with greater efficiency.

The traditional approach to determining a ship's structural strength is based on calculating the loads that the structure will have to withstand, and comparing these with values calculated for a similar structure that has proved itself in service. The classification society rules provide empirical formulae for minimum size and thickness of structural components that are critical to a ship's strength. Between 1960 and 1980 the size of new ships increased and there was a move away from general cargo ships to more specialised vessels such as bulk carriers and container ships. The increase in size and change of design principles meant that the traditional approach to determining structural strength and reliability was not satisfactory, and more sophisticated techniques began to emerge. Although the increase in size of ships has not continued, the new computer-based techniques have advantages and are used in conjunction with updated forms of the empirical methods.

A ship's structure is made up of plates, girders, frames, webs and brackets, which have to withstand forces from weights in the ship, water pressure, vibration and dynamic loads when the ship heaves, rolls and pitches at sea. A ship must also be able to withstand forces involved in dry-docking and possible grounding or contact with other objects. As well as providing strength, parts of the structure are designed to contain liquid in tanks, separate cargoes and restrict the spread of fire; such considerations may result in a structure that is stronger than that dictated by strength considerations alone. It is also expected that parts of the structure will deteriorate through corrosion and local damage or cracking, so an allowance must be made for these ageing effects.

Although a ship is a single unified structure, and failure of one component can lead to failure of other parts, the traditional approach to strength analysis is to separate forces into longitudinal, transverse and torsional components. The minimum capability of structural elements which must resist these components is identified and integrated with requirements imposed by local stresses. The forces that are resisted by a ship's longitudinal material are considered below.

Longitudinal strength

A ship's longitudinal strength is provided by longitudinal material in the structure such as hull plating, bottom, inner bottom and deck plating, longitudinal frames and girders. These must be capable of withstanding stresses imposed by the uneven distribution of mass within a ship as well as the dynamic forces due to waves and the ship's motion in a seaway. The methods for assessing load (or demand) and strength (or capability) are in a process of continual refinement, but the basis of the calculations is to treat a ship as a box girder and to apply the classical methods of beam theory to determine shear forces and bending moments acting on a transverse cross-section through the hull.

The procedure is illustrated in Figure 4.1.1. With the ship floating at a given draught in still water, buoyancy per unit length is proportional to the transverse cross-sectional area of the immersed volume.

Buoyancy = area x density of sea water ... in tonnes per metre

The transverse cross sectional area of the immersed volume at any point "x" in a ship's length can be determined by numerical integration directly from hull co-ordinates. A curve of buoyancy is obtained as shown in Figure 4.1.1 (a) The distribution of mass per unit length is determined by detailed consideration of the masses that make up the ship's structure. For loaded conditions this includes the mass of cargo, fuel, ballast, fresh water and stores. The area under the mass distribution curve is equal to that under the buoyancy curve, and both are equal to the ship's displacement in tonnes. The difference between the two curves at any point represents the net load on that section of ship.

Let
p' be load per unit length at point "x" in tonnes per metre
S be the shear force at point "x" in tonnes
M be the bending moment at point "x" in tonne-metres

then p', S and M are related by the equation:

$$p' = \frac{dS}{dx} = \frac{d^2M}{dx^2}$$

with $S = M = 0$ at the ends

Integrating with respect to x gives:

$$S = \int_L p' . dx \qquad \text{and} \qquad M = \int_L S . dx$$

The shear force is found by integrating the net load per unit length and bending moment by integrating shear force with respect to length. The curves of shear force and bending moments for a ship are illustrated in Figure 4.1.1 (d) and (e) (Rawson and Tupper, 1994).

The values of shear force and bending moment are for a ship floating in still water. The reliability of the procedure depends on the accuracy of the hull co-ordinates used and estimation of masses in the ship's structure and weights carried in the ship. The method is used by ship designers to determine stresses that have to be carried by the ship's structure, and is also used when planning cargo stowage to ensure that the maximum shear force and bending moments do not exceed set maximum values acceptable for the ship.

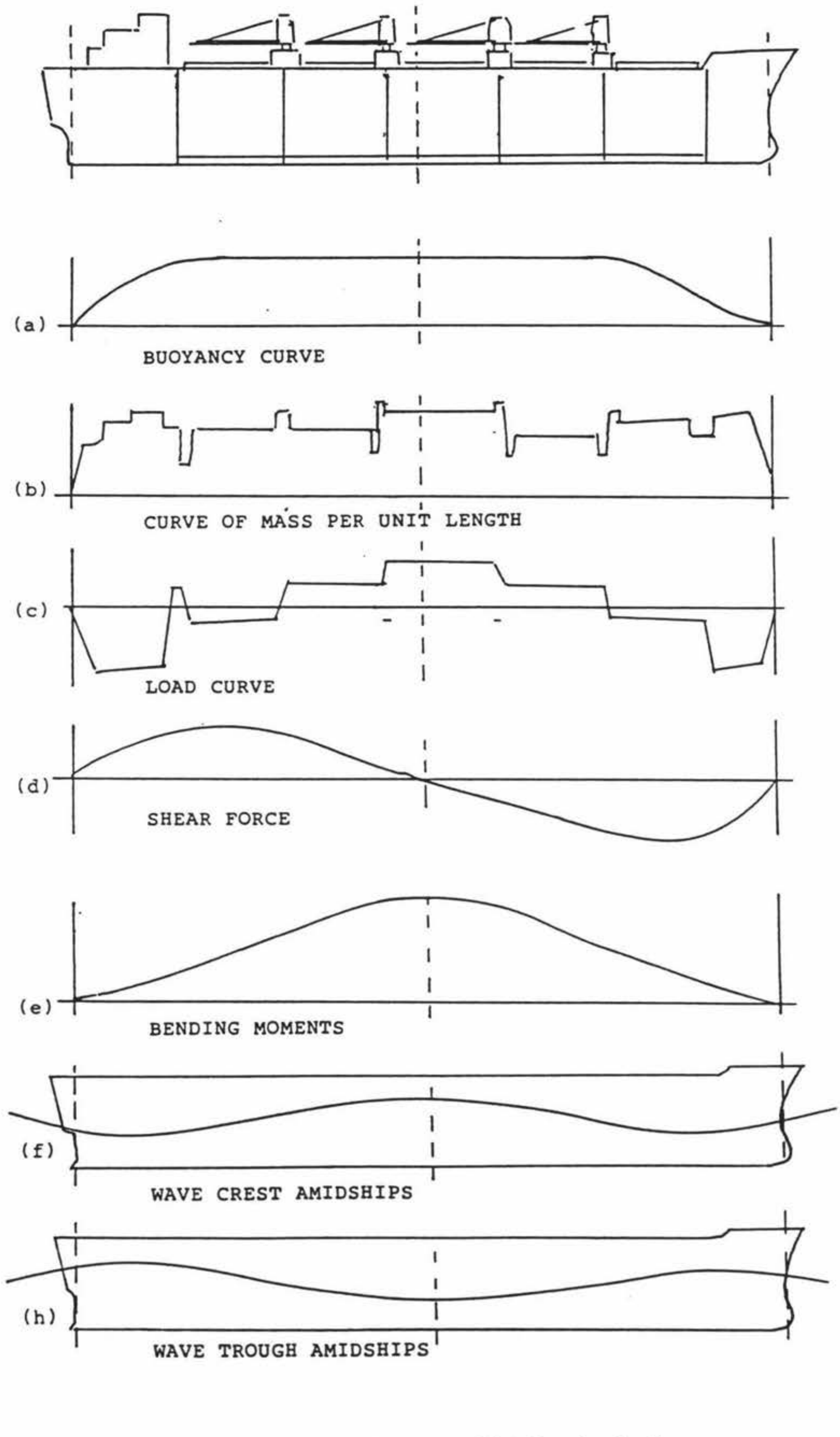


Figure 4.1.1 Forces acting on a ship's longitudinal structure.

Determination of the dynamic forces that have to be resisted by the longitudinal structure is more complicated. At sea a ship's motion is affected by wind and waves as well as forces generated by the propeller and rudder. A ship will flex and vibrate while pitching, rolling and heaving, and is also affected by change in the difference of temperature between air and sea. The initial approach to the loads imposed on a steel ship were based on observation and empirical formulae, with generous allowance for stresses that could not be estimated. The still-water method for finding shear force and bending moment is extended to consider a ship "balanced" on the crest of a wave, and across a trough, as shown in Figure 4.1.1 (f) and (g).

The rationale of this approach is that the greatest forces are due to a wave of length approximately equal to the ship's length. The maximum hogging forces are when the wave crest is amidships and the greatest sagging forces occur when the trough is amidships. A trochoidal wave was used as a reasonable mathematical representation of a sea wave, trochoidal waves having broader troughs and narrower crests than sinusoidal waves as shown in Figure 4.1.2

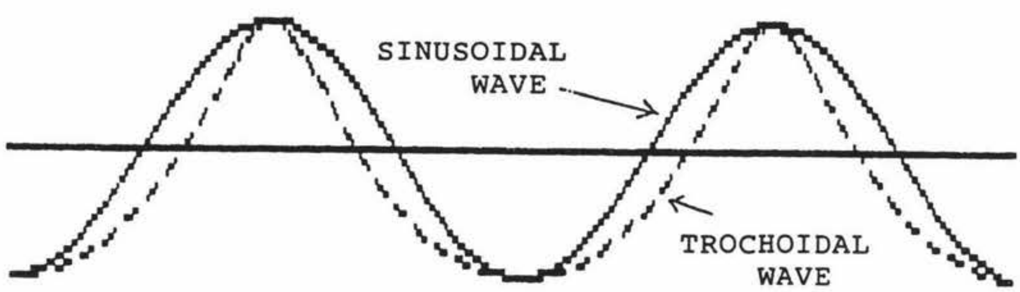


Figure 4.1.2 Trochoidal wave compared with a sinusoidal wave

The parametric equations for a trochoidal wave are:

$$x = \frac{L_w.\theta}{2.\pi} - \frac{H_w}{2}.\sin\theta \qquad\qquad y = \frac{H_w}{2}.\cos\theta$$

where L_w is the wave length and H_w is the wave height

The relationship between the height and length of sea waves has received much attention, and waves of height equal to $L_w / 20$ and $0.607.\sqrt{L_w}$ have been used as standard waves for the calculation. The method enables the maximum shear force and bending moments for various vessels to be compared, and as a comparative tool it is important that standard methodology is used, but both experience and theoretical consideration have shown that the method does not predict the maximum forces and moments for a vessel in a seaway.

An alternative approach that has been under development since the 1960s is to apply the equation of motion for a ship as a semi-rigid body floating freely in a viscous medium. The complexity of this approach calls for simplifying assumptions and this has led to a number of different techniques in the quest for practical results.

The basis of this approach is to view a ship as a more or less elastic body excited in a random manner by the sea. The excitation forces are periodic with various amplitudes and frequencies.

A ship is subject to very low frequency periodic forces such as those due to the cycle of loading and discharging of cargo, and regular heating and cooling. Swell and sea wave encounters involve a range of low to medium frequency periodic forces while propeller and engine vibrations provide higher frequency excitation forces. Considering the periodic excitement from moving through a system of waves, the sea itself is represented by waves of many frequencies with differing amplitudes that are superimposed on one another at any particular time and place. Of concern is the encounter frequency ω, which takes account of the ship's movement through waves. The ship's motion creates and diffracts waves further complicating the situation. The objective is to assess the ship's response to the wave spectrum, and to identify the resulting stress on components of the ship's structure.

The response of a ship to waves can be analysed by treating the structure as a damped mechanical system. From Newton's second law:

$$\text{mass x acceleration} = \Sigma \text{ forces acting on a body}$$

If z is the displacement of the body from its initial position, then:

$$\text{velocity } z' = dz / dt, \text{ and}$$
$$\text{acceleration } z'' = d^2z / dt^2.$$

so that the equation becomes:

$$m \,.\, z'' = \Sigma \text{ forces}$$

If the forces acting on the body consist of:

(1) a damping force proportional to velocity z', acting in direction opposite to z', then this force is $- c.z'$, where c is the damping coefficient, $c > 0$,

(2) a restoring force proportional to displacement z, acting in direction opposite to z, then this force is $- k.z$, where k is the spring modulus, $k > 0$,

(3) a driving, or excitation force r(t),

then: $$m.z'' = - c.z' - k.z + r(t)$$

or: $$m.z'' + c.z' + k.z = r(t) \qquad \ldots \quad (4.1.1)$$

The solution can be written as:

$$z(t) = z_{CF}(t) + z_{PI}(t)$$

where $z_{CF}(t)$ is the "complementary function", which is the solution to the homogeneous equation:

$$m.z'' + c.z' + k.z = 0$$

$z_{CF}(t)$ is of the form $A.e^{\lambda_1 t} + B.e^{\lambda_2 t}$

where λ_1 and λ_2 are solutions to the auxiliary equation:

$$m.\lambda^2 + c.\lambda + k = 0$$

$$\lambda = \frac{-c \pm \{ c^2 - 4.m.k \}^{1/2}}{2.m}$$

For a decaying transient, $c^2 > 4.m.k$, and $m.k > 0$, so that

$$0 < \{ c^2 - 4.m.k \}^{1/2} < c$$

making $\lambda_1 < 0$, $\lambda_2 < 0$, and both are real.

$z_{PI}(t)$ is a "particular integral", corresponding to the presence of $r(t)$.

Put: $$z(t) = a.\cos\omega t + b.\sin\omega t$$

and differentiate:

$$z'(t) = -a.\omega.\sin\omega t + b.\omega.\cos\omega t$$
$$z''(t) = -a.\omega^2.\cos\omega t - b.\omega^2.\sin\omega t$$

Substitute for $z(t)$, $z'(t)$ and $z''(t)$ in Equation 4.1.1 to give:

$$(-m.a.\omega^2 + c.b.\omega + k.a).\cos\omega t + (-m.b.\omega^2 - c.a.\omega + k.b).\sin\omega t = F_0.\cos\omega t$$

equate coefficients of $\cos\omega t$ and $\sin\omega t$:

$$(k - m.\omega^2).a + c.\omega.b = F_0$$
$$-c.\omega.a + (k - m.\omega^2).b = 0$$

solve the linear equations to find a and b:

$$a = F_0.\frac{(k - m.\omega^2)}{(k - m.\omega^2)^2 + c^2.\omega^2} \qquad b = F_0.\frac{c.\omega}{(k - m.\omega^2)^2 + c^2.\omega^2}$$

let $k = m.\omega_0^2$

$$a = F_0.\frac{m.(\omega_0^2 - \omega^2)}{m^2.(\omega_0^2 - \omega^2)^2 + c^2.\omega^2} \qquad b = F_0.\frac{c.\omega}{m^2.(\omega_0^2 - \omega^2)^2 + c^2.\omega^2}$$

To find the amplitude and phase of the response, put $Z_{PI}(t) = D.\cos(\omega.t - \eta)$

where $D(\omega)$ is the amplitude and η is the phase lag

$$D(\omega) = (a^2 + b^2)^{1/2} = \frac{F_0}{\{ m^2.(\omega_0^2 - \omega^2)^2 + c^2.\omega^2 \}^{1/2}}$$

and $$\eta = \tan^{-1}.\frac{b}{a} = \tan^{-1}.\frac{c.\omega}{m.(\omega_0^2 - \omega^2)}$$

In Figure 4.1.3 the amplitude magnification (D/F_0) and phase lag (η) are shown for a range of ω. The forcing function needed to provide input to the equations can be estimated using strip theory methods.

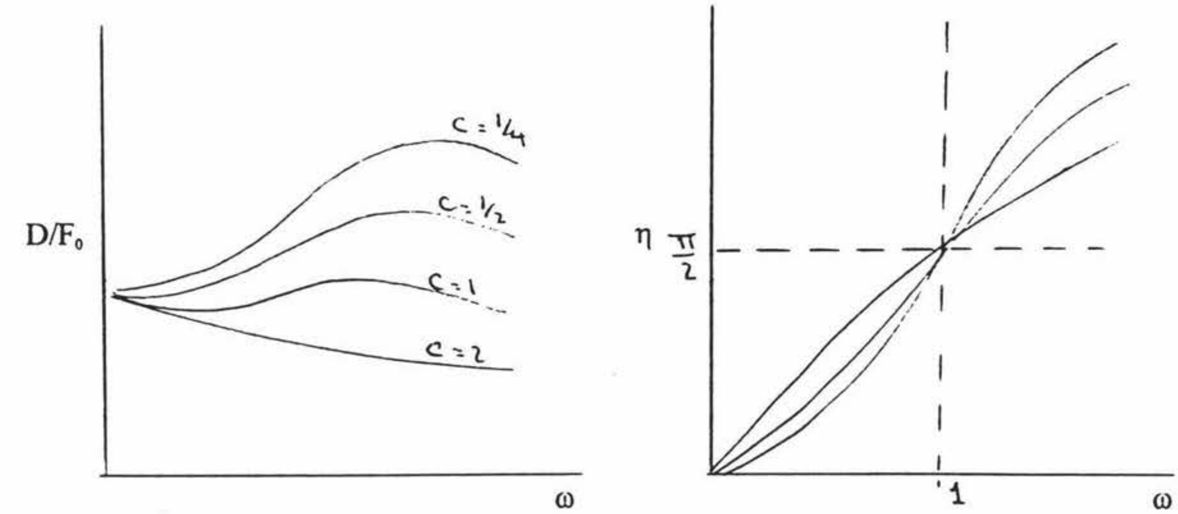


Figure 4.1.3 Amplitude magnitude and phase lag of response to excitation frequency ω. (Kreyszig, 1988; Rawson and Tupper, 1994).

The process of determining response to a given spectrum of encounter frequencies is summarised in Figure 4.1.4.

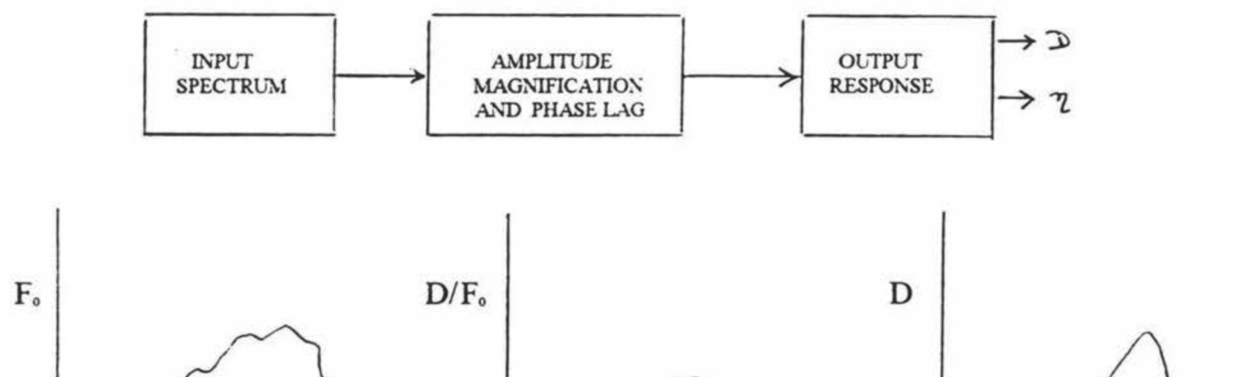


Figure 4.1.4 Response of structure to input frequency

Failure modes

Having determined the forces that will be imposed on a ship's structure, it is necessary to ensure the ship has sufficient structural capability to meet the maximum demand. The capability of a ship to resist stress depends on the strength and distribution of material in the ship. This may be illustrated by the ability of longitudinal material in the cross-section of a ship to resist the maximum bending moment on this section.

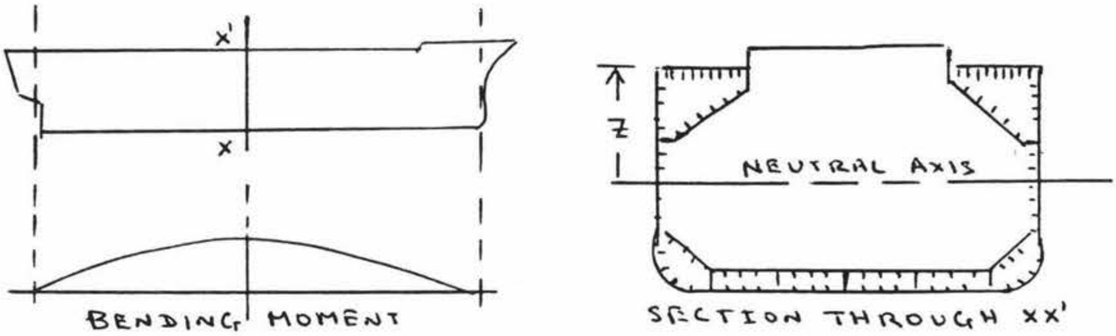


Figure 4.1.5 Material resisting longitudinal bending

In Figure 4.1.5 the material resisting longitudinal bending includes the shell plating, tank plating, longitudinal frames and girders. This material is distributed so that there is sufficient second moment of area about the neutral axis so that the stress "f" in any component as calculated by the following formula does not exceed an accepted value for the steel used in the construction.

$$f = M . z / I$$

where: M is the longitudinal bending moment at the transverse cross section
I is the second moment of area of the transverse cross section about the neutral axis
z is the perpendicular distance between the neutral axis and the component under consideration.

Acceptable values of stress have been established for different grades of steel used in ship building, and are typically about 20 to 25 percent of yield stress, so it is not likely that stresses will approach the level at which the material will fail under direct yield. However other modes of failure are possible which can result in stress many times that experienced in normal operations and can lead to yield failure. In Figure 4.1.5 the ship is shown as a hollow box section which is stiffened by the transverse structure. Longitudinal and transverse framing provides a grillage designed to prevent buckling of the hull and deck plating. Cracking may be initiated by cyclic loads or by stress concentrations and localised damage. Once initiated, cracks grow over time, and when they develop beyond their critical size may lead to rapid propagation and catastrophic failure. (Nishida, 1992) When part of a structure fails, forces in directions which are different from that expected may be experienced, leading to deformation, tripping and structural instability. Although the mathematical theory of grillages and crack propagation is well developed, the interaction between failure modes in a complex structure makes it difficult to predict the onset of failure without recourse to empirical and experimental data.

The beam theory approach of working out global stresses and strains on an entire structure has limitations for analysis of a complex structure, and a more detailed analysis can be carried out using the finite element method (FEM). In the FEM, the structure is sub-divided into smaller structures, which are themselves divided into finite elements that can be represented by plane surfaces and lines. The whole structure is represented by an assemblage of structural elements, and given the forces acting at a boundary to the assemblage, the forces, moments and displacements of connected elements can be calculated in a systematic manner. Large computer memory is necessary to store the variables representing the position and state of each node, and iterative procedures and matrix methods are used for the efficient computation of solutions

(Norrie and Devres, 1978). FEM provides a means of accounting for both local and global failure modes. Computer software for linear applications is a standard engineering tool, and more complex non-linear applications are well developed. In general the more complicated the pattern of deformation, the finer the mesh required in its analysis, and a knowledge of local deformation patterns is necessary to optimise mesh size (Kutt et al, 1985).

Structural safety

For structural safety, a ship's capability to withstand force must be greater than the maximum force to which it is subjected. The traditional concept of a safety factor is based on the ratio of capability to load; however both capability and maximum load have a stochastic element. Capability calculations are based on assumed properties of materials, which are likely to vary, as is the quality of workmanship, which depends on the conditions and degree of difficulty under which work is carried out. The maximum loads may differ from expected values as they depend on variables such as the density of cargo carried, and the external loads acting on the ship. Probabilistic and semi-probabilistic methods for assessing structural safety may be used to take account of the variation (Wolfram, 1982; Ardwinckle and Pomeray, 1982).

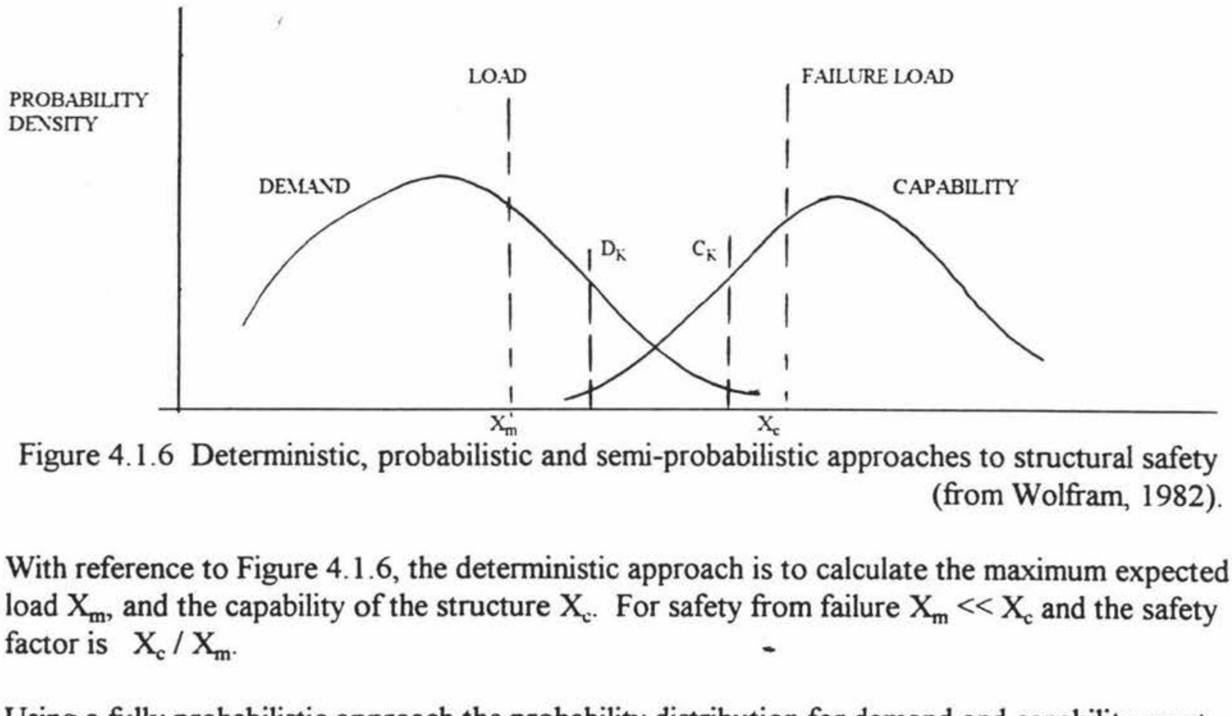


Figure 4.1.6 Deterministic, probabilistic and semi-probabilistic approaches to structural safety (from Wolfram, 1982).

With reference to Figure 4.1.6, the deterministic approach is to calculate the maximum expected load X_m, and the capability of the structure X_c. For safety from failure $X_m << X_c$ and the safety factor is X_c / X_m.

Using a fully probabilistic approach the probability distribution for demand and capability must be known. The probability of failure is represented by the overlap between the two distributions, and sufficient data to derive the distributions must be available to use this method.

When the complete distributions are not known the mean and standard deviations for demand and capability are calculated from available data and the distributions are assumed to be approximately normal. Partial safety factors D_k and C_k are calculated as:

$$D_k = \overline{D} + K_D \cdot \sigma_D$$
$$C_k = \overline{C} - K_C \cdot \sigma_C$$

where $\overline{D}$ is the arithmetical mean for demand;
$\overline{C}$ is the arithmetical mean for capability;
σ_D , σ_C are standard deviations for demand and capability;
$K_D = K_C = 1.65$ for a normal distribution.

Alternatively a safety index can be calculated

$$\text{Safety index} = \frac{\overline{C} - \overline{D}}{\sqrt{\sigma_C^2 - \sigma_D^2}}$$ (Wolfram, 1982)

From this review, it is apparent that the assessment of a ship's structural safety and reliability is a complex procedure. The applications of mathematics has a long history and is well developed with advanced techniques such as strip theory, response amplitude operators, finite element analysis, matrix algebra and probability theory. The expression of structural demand and capability as probability distributions is the result of much intricate calculation and observation, and the distributions, partial safety factors and the safety index could provide a sound basis for the intrinsic part of a mathematical model of ship safety.

4.2 Stability

During a sea passage a ship must be able to recover when pitched or rolled by the forces caused by wind and waves. The ability to recover in a safe manner when affected by external forces is dealt with under the general topic of ship stability, and safety from capsize has to be addressed during design as well as during the operation of a ship. The mathematics of ship stability are well developed and include ship geometry and methods of mathematical physics for dealing with the forces and moments which act on a freely-floating vessel.

Statical stability

A freely-floating ship is supported by water pressure on the hull. The horizontal components of pressure forces tends to collapse the hull which is stiffened to resist them, and in equilibrium the horizontal vector sum of pressure forces is zero. The vertical component of forces due to water pressure is equal in magnitude to the sum of gravity forces of the ship and its deadweight, and is referred to as buoyancy. Buoyancy is considered to act vertically upwards through the centroid of the displaced volume which is called the centre of buoyancy (B), and the sum of gravity forces is considered to act vertically downward through the centre of gravity (G). Since the magnitudes of buoyancy and gravity forces are equal to the weight of water displaced by the ship, both forces are referred to as displacement (W).

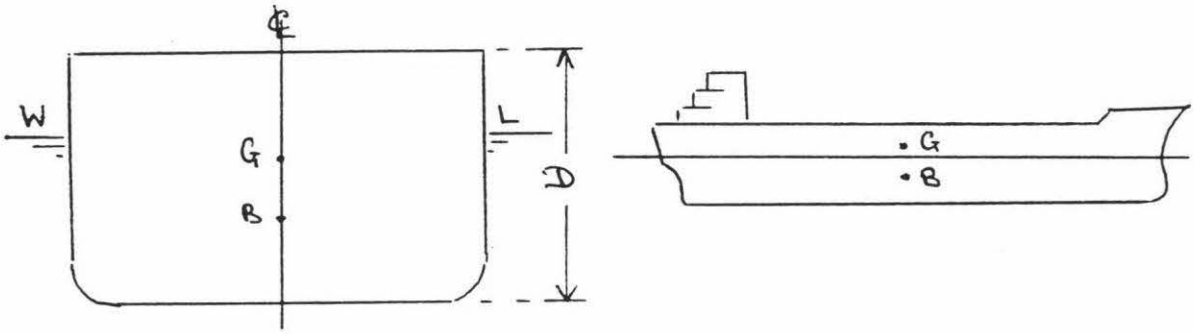


Figure 4.2.1 A ship floating freely and in equilibrium.

For equilibrium G and B lie in the same vertical. Assuming that the hull is symmetrical, the ship will float upright only when B and G are on the ship's centreline. If weights are unsymmetrically distributed so that G is not in the centreline (plane) the ship will list. If G is in the centreline, but the ship is acted on by an external force which has a horizontal component, the ship will heel.

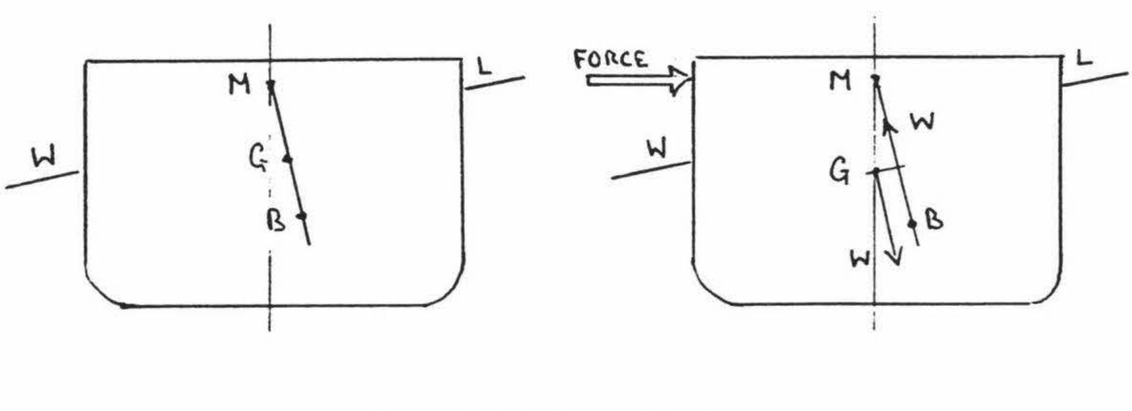


Figure 4.2.2 List and heel.

For convenience Figure 4.2.2 is drawn relative to the ship's co-ordinate system, tilting the water line, rather than the ship. As the ship heels or lists and B moves off the centreline, lines of force of buoyancy intersect at the metacentre (M), and the ship behaves as though supported at the metacentre. For small angles of heel the metacentre can be considered to be a fixed point on the centreline, but as heel increases the metacentre rises and may move off the centreline. The vertical distance between B and M (denoted BM) is given by: BM = I / V, where I is the second moment of area of the waterplane about the centre of waterplane area, and V is the displaced volume. This is a fundamental equation of ship stability, and is computed directly from co-ordinates describing the ship's geometry.

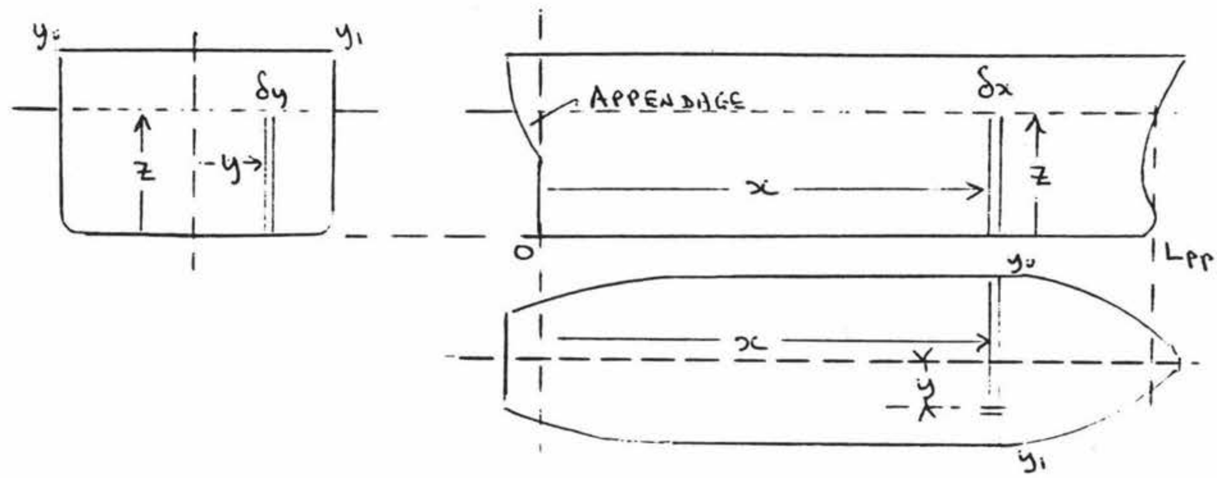


Figure 4.2.3 Co-ordinate system for describing the hull.

The procedure for finding displaced volume, KB and BM is summarised in the following equations:

Transverse cross sectional area at station x $$A(x) = \int_{y_0}^{y_1} (z - z_0).dy$$

Displaced volume to water line z $$V(z) = \int_{0}^{L} A(x).\,dx$$

Centroid of A(x) $$z(x) = \frac{1}{2\,.\,A(x)} \int_{y_0}^{y_1} (z - z_0).(3.z_0 + z).dy$$

Centroid of displaced volume $$KB = \frac{1}{2\,.\,V(z)} \int_{0}^{L} \int_{y_0}^{y_1} (z - z_0).(3.z_0 + z).dy.dx$$

Second moment of waterplane area $$I(z) = \frac{2}{3} \int_{0}^{L} y(z)^3.dx$$

Accuracy depends on the digitised co-ordinates of the ship's description and the method used for numerical integration. Finding the co-ordinates of the centre of gravity is not so straightforward because precise information about the mass and centre of gravity of each component of the ship's structure and outfit is required. Empirical methods based on knowledge of ships of similar design are used to estimate a ship's mass and centre of gravity, but these values cannot be precisely determined until the ship is built and an inclining test is carried out. This means that there is a measure of uncertainty about a new ship's stability until a short time before it is ready for service, and Burcher (1979) observed that completed ships are sometimes heavier and have higher centres of gravity than intended.

For a ship which is symmetrical about its centreline, upright and floating freely, G is on the centreline. If a known weight is moved transversely, G moves off the centreline and the ship lists, and after measuring the resulting list very accurately, the ship's KG can be calculated.

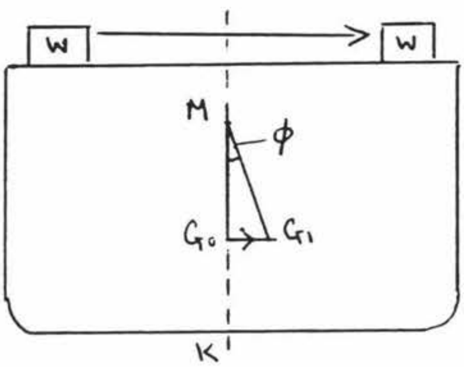


Figure 4.2.4 Inclining test.

$$G_0 G_1 = \frac{w.d.}{W}$$

w known weight
d transverse distance moved by weight
W displacement = V. ρ
V displaced volume computed from the ship's geometry
ρ density of water in which the ship is floating

$$\tan \phi = \frac{G_0 G_1}{G_0 M}, \quad \text{therefore} \quad G_0 M = \frac{w.d}{W} . \cot \phi$$

KB and BM are found from the hydrostatic particulars and hence the vertical centre of gravity above the keel (KG) is obtained from:

$$KG = KB + BM - GM$$

The centre of gravity found by the inclining test is the basis of stability calculations carried out during all loading and ballasting operations of the ship. The IMO minimum standards of stability for ships with gross tonnage over 500 specify a minimum GM of 0.15 metres for all acceptable conditions of loading, and smaller value of 0.05 metres is specified for timber deck cargo ships. The designer must therefore take care not to underestimate KG, otherwise certain conditions of loading may not be permissible, or measures would have to be taken to lower the position of the centre of gravity. There are economic penalties to such options.

During cargo operations the ship's chief deck officer is normally responsible for checking the vessel's stability. This involves a careful estimation of the mass and centre of gravity of each element of the ship's deadweight, which includes cargo, fuel oil, lubricating oil, fresh water, ballast and stores. The vertical centre of gravity is found by taking moments about the keel:

$$KG = \frac{\Sigma \ \text{Moments}}{\Sigma \ \text{Masses}}$$

For many cargoes there is an element of guesswork in estimating masses and the vertical centres of gravity. For consumable liquids such as bunkers and fresh water there will be a free surface effect for tanks that are partly full of liquid. Free surface reduces GM and is taken into account in the stability calculation. Good design would incorporate narrow longitudinal tanks to minimise the effect of free surface on a vessel's stability.

The task of calculating GM can be onerous, particularly when there is pressure to minimise time in port, when last-minute changes are made to cargo bookings, and when there are numerous other duties to be taken care of as a ship is prepared for a sea passage. Several types of stability calculators have been developed to mechanise the process of determining stability, but most are now obsolete with the advent of personal computers and sophisticated stability software customised for a particular ship. Remote tank level sensors can be used to provide input to stability computers, but the result is still dependent on the careful manual estimation, recording and entering of weights and co-ordinates of centres of gravity.

Dynamical stability

When a ship, initially upright and stable, is heeled by an external force, the shape of the displaced volume of water changes so that the its centroid moves away from the centreline. The forces acting through G and B form a couple that tends to restore the ship to the upright.

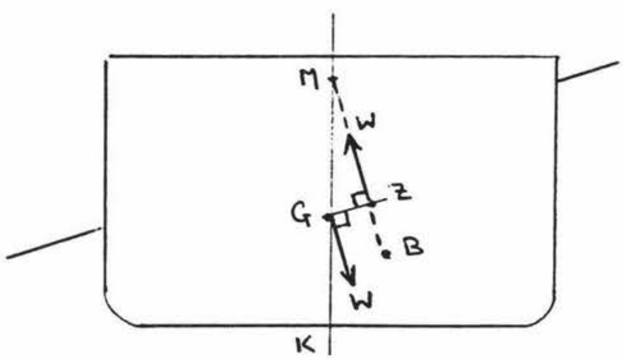


Figure 4.2.5 Righting couple.

The moment of the righting couple is: W.GZ , where GZ is the righting lever as shown in Figure 4.2.5. For small angles of heel M is assumed to be constant and the righting lever is given by GM. Sin ϕ. M is not constant for large angles, but the righting lever GZ can be found by integrating transverse moments of area over the length of the displaced volume. A ship's dynamical stability is the energy necessary to heel the ship to a given angle, and is given by:

$$E = \int_0^{\phi} W.GZ.d\phi$$

Since W is constant

$$E = W.\int_0^{\phi} GZ.d\phi$$

The energy necessary to heel a ship to a given angle is also a measure of the ship's resistance to being heeled and to recover after being rolled by wind or wave action. The curve of righting levers, referred to as the GZ curve, provides a means of measuring and comparing the stability of ships in various conditions of loading.

GZ curves for a given displaced volume and vertical centre of gravity may be computed directly from a ship's hull co-ordinates.

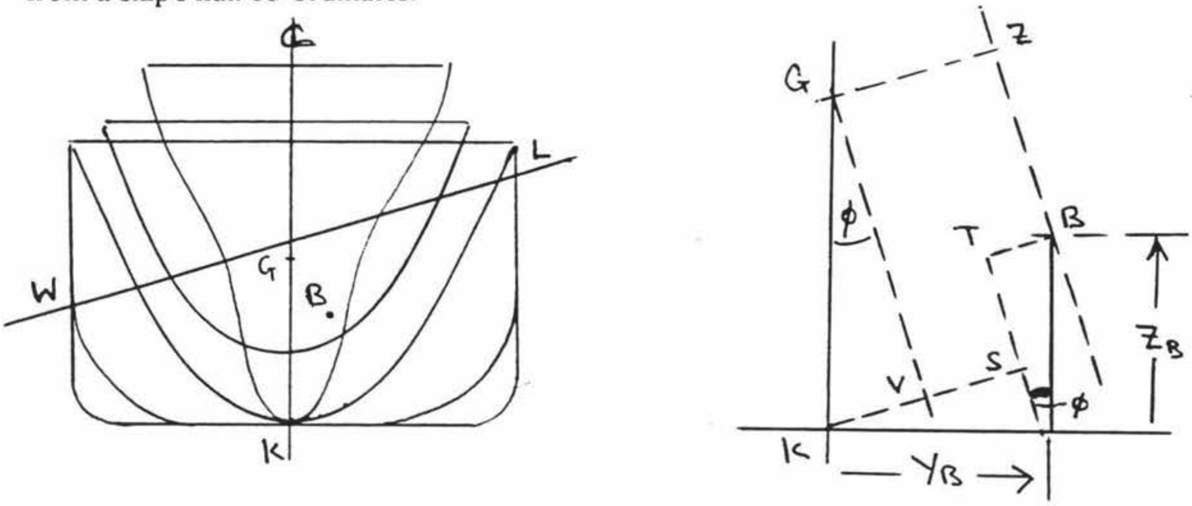


Figure 4.2.6 Determination of GZ..

In Figure 4.2.6, $GZ = KS + TB - KV$

$= Y_B . \cos\phi + (Z_B - KG) . \sin\phi$

WL indicates the waterline with the ship heeled to angle ϕ.
B is the centroid of the displaced volume and the horizontal and vertical components (y, z) are found by taking moments about K.

The GZ curve has a characteristic form for a traditionally shaped hull:

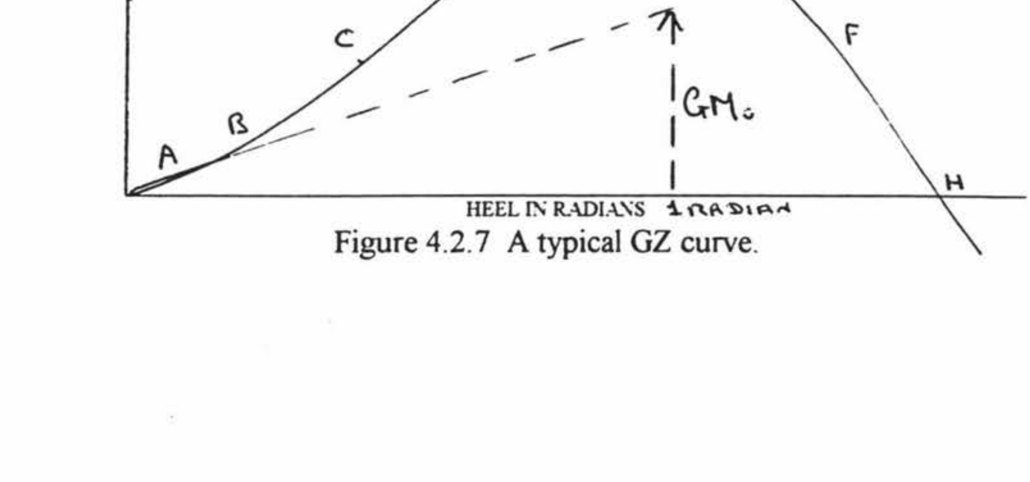


Figure 4.2.7 A typical GZ curve.

With reference to Figure 4.2.7 segments of the curve are identified by letters A to J:

A is straight. For small angles of heel the metacentre is almost constant and GZ = GM .ϕ.

B as the ship continues to heel, the waterplane area increases and so does I. From the equation BM = I / V the metacentre rises, and from GZ = GM .sin ϕ the curve is convex from below.

C when the deck edge submerges or the turn of bilge emerges, the waterplane area ceases to increase and may decrease with a further increase in heel.

D the region is concave from below.

E maximum GZ.

F decreasing GZ.

H GZ = 0, a ship which heels past this angle would capsize.

Stability standards referred to as the IMO standards to be met by ships in all probable loading conditions have been adopted by many countries and are contained in national shipping regulations. These are summarised below (The Load Line Rules, 1970):

(a) The area under the GZ curve shall be not less than -

(i) 0.055 metre-radians up to an angle of 30 degrees,

(ii) 0.09 metre-radians up to an angle of either 40 degrees or the angle at which the lower edges of any openings in the hull, superstructures, or deck houses, being openings which cannot be closed weathertight, are immersed if that angle is less,

(iii) 0.03 metre-radians between the angles of heel of 30 degrees and 40 degrees or such lesser angle as is referred to in (ii),

(b) GZ shall be at least 0.2 metres at an angle of heel equal or greater than 30 degrees.

(c) Maximum GZ shall occur at an angle of heel not less than 30 degrees.

(d) The initial transverse GM shall be not less than 0.15 metres, or for timber deck cargo ships 0.05 metres.

GZ curves are used to determine a ship's residual stability after an assumed shift of cargo. The IMO provisions for carriage of grain set out in Chapter VI of SOLAS 74 (IMO, 1992 a) are based on assumptions about the way that grain will settle and shift. The resultant heeling moment divided by displacement gives the heeling lever for the ship upright (λ_0). It is assumed that the heeling lever at 40 degrees is $0.8.\lambda_0$, and that the curve of heeling levers can be approximated by a straight line. The GZ and heeling lever curves are illustrated in Figure 4.2.8.

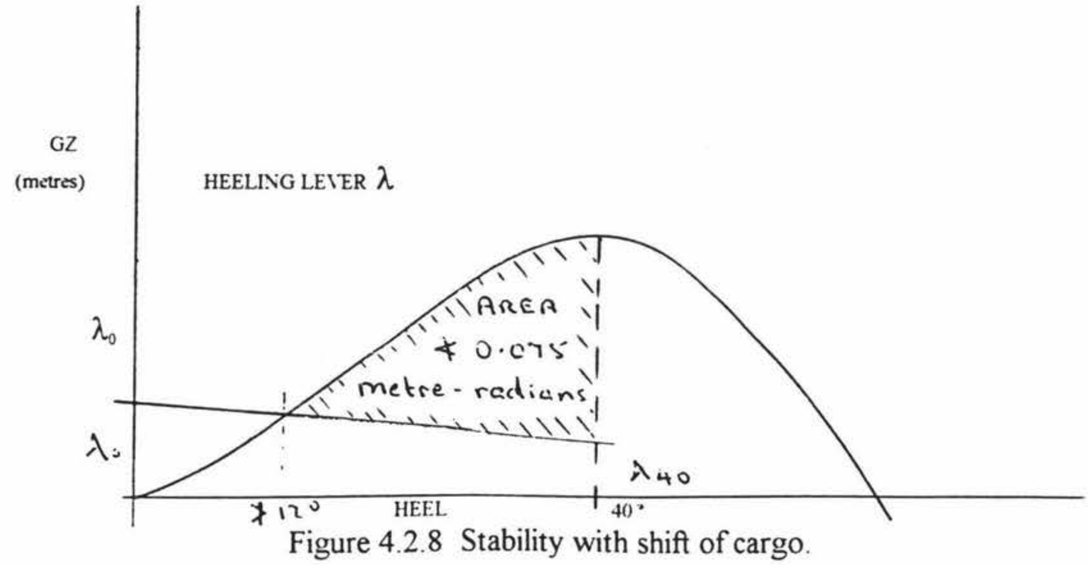


Figure 4.2.8 Stability with shift of cargo.

The angle of heel due to shift of grain should not exceed 12 degrees and the area between the GZ and heeling lever curve up to 40 degrees, or the angle where water would enter the ship, must be at least 0.075 metre-radians.

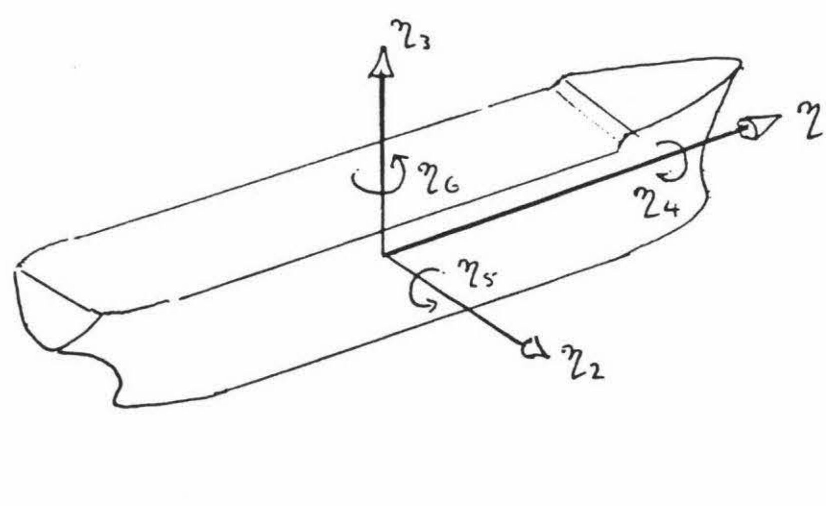
Similar approximations can be used to determine the heel due to wind, for example using the following empirical formula for wind heeling lever (Barrie, 1986):

$$M_w(\phi) = \frac{0.0514\, A\,.\,H}{W}\,.\,(0.25 + 0.75\cos^3\phi)$$

Stability standards such as those described have been criticised because the GZ curve is for a ship heeled by an external force while floating freely in still water. Although the IMO criteria are based on statistical data for known ship types, they do not fully take into account the dynamics of a ship at sea, which may be rolling, pitching and heaving under the action of waves. Small ships have capsized even though they met the IMO standards, and this has led to a search for more suitable standards.

Research into stability standards

The search for more appropriate standards has involved much detailed and complicated research. A ship floating freely has six degrees of freedom, three in translation and three in rotation.



X surge	Y sway	Z heave	ϕ roll	θ pitch	η yaw
η_1	η_2	η_3	η_4	η_5	η_6

Figure 4.2.9 Ship motions - six degrees of freedom.

Stability standards based on the GZ curve are concerned only with roll, and for small angles in still water it is reasonable to consider roll as de-coupled from the other degrees of freedom. However for a ship moving in a viscous medium which is also moving, and with the ship rolling to large angles, de-coupling roll from the other degrees of freedom may lead to unrealistic conclusions. A full modelling of the dynamic behaviour of a ship in waves is a formidable task,

and much effort has been put into studying particular aspects of the problems, particularly from the point of view of developing measures of safety from capsizing.
One approach to the problem is to compute GZ curves for a ship making way through a system of regular waves. For any dynamical simulation the number of parameters that can be selected is limited and the researcher must select parameters that are significant to the objective of the study. In the case of stability standards, the search is for the limiting conditions that may cause a ship to capsize. The condition under which a ship's stability is least favourable includes when the wave length is approximately equal to ship length, when the frequency of encounter is close to the natural rolling frequency of the ship, and for following or quartering seas.

A method developed at Strathclyde University called the "Levels of stability" approach is to compute a time varying roll restoring curve GZ (ϕ, t) as a ship rolls while encountering sinusoidal waves (Barrie, 1986). As the ship moves relative to the waves, the GZ curve changes. Compared with the still water curve, the righting lever increases when the wave crests are near the ends of the ship and the trough is amidships. For the crest amidships and troughs near the ends, GZ decreases.

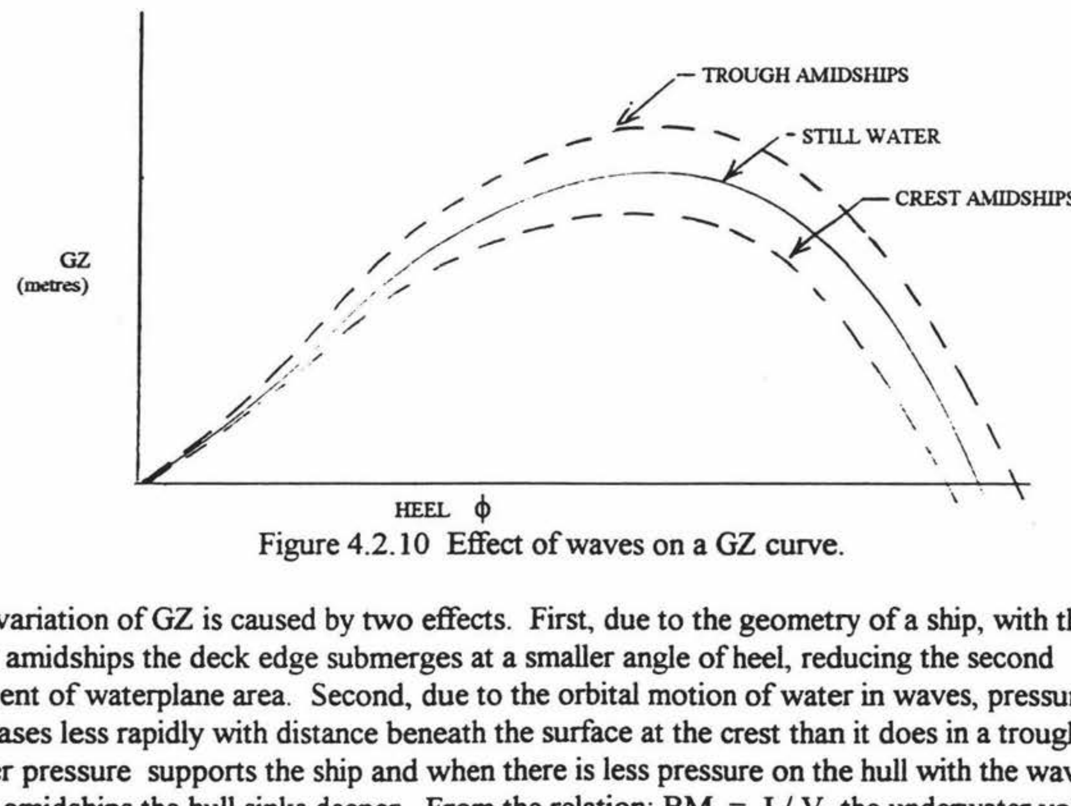


Figure 4.2.10 Effect of waves on a GZ curve.

The variation of GZ is caused by two effects. First, due to the geometry of a ship, with the crest amidships the deck edge submerges at a smaller angle of heel, reducing the second moment of waterplane area. Second, due to the orbital motion of water in waves, pressure increases less rapidly with distance beneath the surface at the crest than it does in a trough. Water pressure supports the ship and when there is less pressure on the hull with the wave crest amidships the hull sinks deeper. From the relation: BM = I / V, the underwater volume increases, so BM decreases and so does GZ.

A computer simulation over time enables GZ curves to be determined for a ship rolling in waves. For safety from capsize, the potential energy represented by the area between the GZ and heeling lever curves must be greater than the kinetic energy of the ship due to rolling (Abicht et al., 1977). The energy balance is shown by areas E and R in Figure 4.2.11.

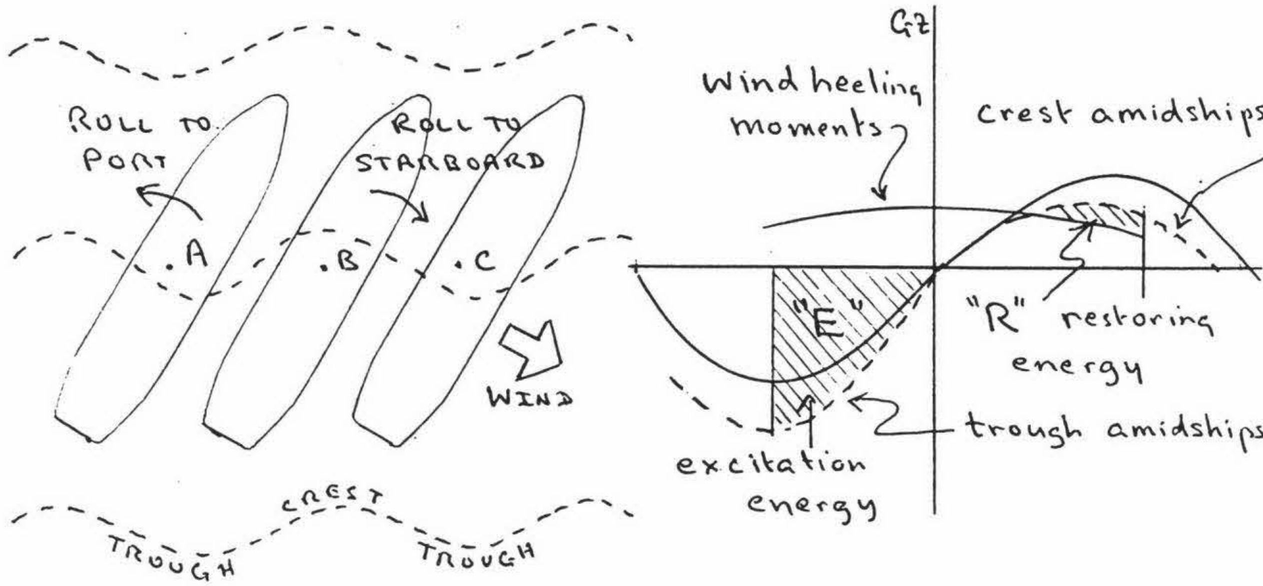


Figure 4.2.11 Energy balance with a ship rolling in waves.

The roll will be damped by the viscosity of sea water which will tend to improve safety from capsize from that indicated in Figure 4.2.11. The uncoupled equation of motion for rolling with one degree of freedom is:

$$\ddot{\phi}(\phi, t) + N(\dot{\phi}, t) + F(\phi, t) = K(\phi, t)$$

where ϕ is roll angle t is time
N = damping moment F = righting moment K = heeling moment

The equation enables measures of safety from capsize, other than those based on GZ curves, to be developed. One such measure is based on the phase plane diagram of roll angle and roll velocity as shown in Figure 4.2.12 (Abicht et al., 1977).

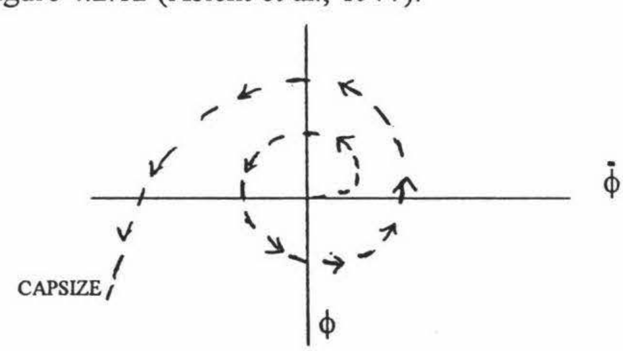


Figure 4.2.12 Phase plane diagram for stability.

The various approaches to investigating stability standards which consider simplifications of the ship's equations of motion, and attempts at full simulation of ship motions in random seas rely heavily on computing power. For these methods to be used in practical ship operations they must be capable of being checked quickly and easily before and during loading and discharging operations. This makes long computer runs on a shipboard computer impractical. A potentially useful approach is to provide the ship with criteria similar to the IMO standards, but individually tailored to each ship. Thus ships' officers can check that GM and the areas under the GZ curve are within acceptable limits for a particular draught, trim and anticipated weather conditions.

4.3 Freeboard

Freeboard is the vertical distance between the deepest permitted waterline and the uppermost complete deck, measured at the sides in the mid-length of a ship. Freeboard regulates the maximum weight that can be carried, and hence a ship's earning capacity. The determination of freeboard must enable ships to operate commercially, and there is a compromise between competitive ship operation and safety. Freeboard is associated with other safety parameters such as structural strength, water tightness, subdivision, stability, seakeeping and the sea environment, and these factors are taken into account to varying degrees in the calculation of freeboard.

In the mid 19th century the British government responded to public concern about the excessive number of ships lost, many of which were thought to be due to overloading. At that time ships' masters decided the maximum load that could be carried, and although there was no official regulation there were rule-of-thumb methods based on the successful practice of good ships' masters. (Abell, 1932) Board of Trade officers were instructed to detain ships if they were overloaded, and it was necessary to standardise the procedure to determine maximum loading. The UK Act of Parliament in 1876 made it compulsory for ships to be marked with load lines.

Several empirical rules were in use to determine freeboard, examples are:

- to give reserve buoyancy of one fifth of a ship's volume
- one quarter of the depth of hold
- one eighth of a ship's breadth
- the depth at side multiplied by a factor which varies with length

Since determination of freeboard is critical to the competitiveness of a ship, the method of calculation was formalised, based on existing practice. The original procedure has been modified to reflect improvements in design and construction, and years of experience in service. The present requirements applicable to ships of length 24 metres and over are contained in the International Convention on Load Lines 1966.

The method for assigning freeboard is based on tables of freeboard for a standard ship with Length/Depth of 15 and block coefficient 0.68 (see glossary). Two freeboard tables are used, one for Type A ships which are tankers, and the other for Type B ships which are not tankers. Type A ships may have less freeboard than Type B because of greater subdivision and more effective means of making compartments watertight. For dry cargo ships of length 100 metres or more, freeboard may be reduced by up to 100 percent of the difference between Type A and Type B freeboards, provided certain conditions for water-tightness, subdivision and stability after flooding compartments are met.

Figure 4.3.1 shows the ratio of freeboard to depth for Type A and Type B ships as functions of length. The curves are derived directly from the freeboard tables in Regulation 28 of the International Convention on Load Lines 1966, assuming that Length/Depth is 15. The freeboard-to-depth ratio is identical for Type A and Type B ships of less than 61 metres in length, and the difference increases with length. The freeboard ratio for small ships is relatively low, increasing with length to maximum ratios for ships of lengths between 150 and 200 metres, and then decreasing with length. The small freeboard ratio for small ships is surprising when it is considered that these ships have a worse record of total losses than larger ships.

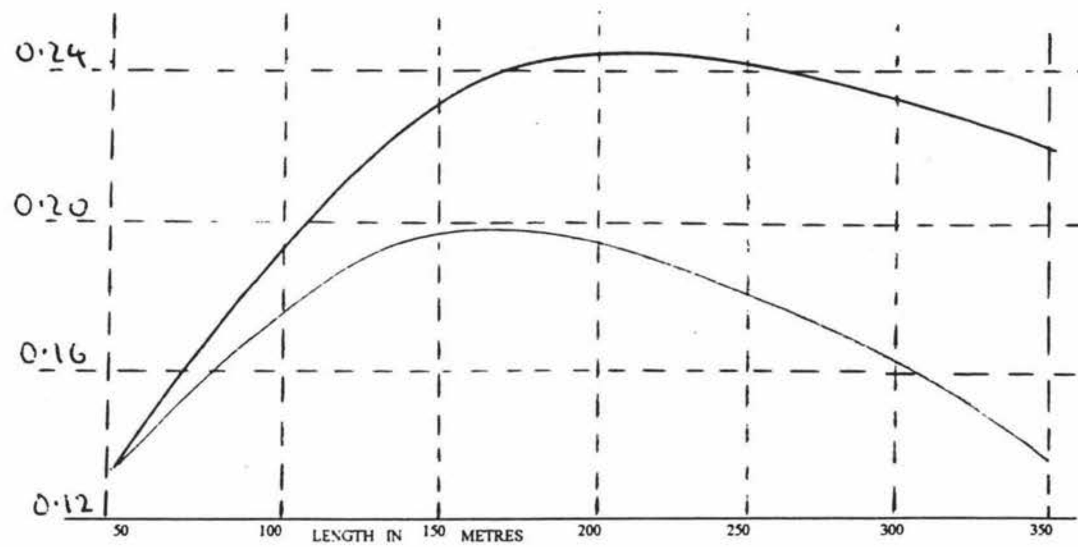


Figure 4.3.1 Freeboard ratio for Type A and Type B ships as a function of ship's length.

The assignment of relatively small freeboards to small ships has been criticised by naval architects. The original freeboard tables, compiled in England during the mid 19th Century, have been modified and expanded to provide for larger ships and to take into account improvements in construction and deck fittings. The tables are empirical and based on experience and economic constraints; there is generally more economic pressure on small ships than on larger vessels, so an increase in the freeboard ratio for small ships would affect their economic viability. There is also justification for the increase in freeboard ratio with ship's length based on physical considerations; Wendel showed that the increase is necessary because of forces from waves washing over a deck and acting on persons and the structure increases proportionally to ships' lengths (Abicht et al., 1977).

The tabular freeboards are modified to take account of differences in geometrical proportions between the standard ship and a new ship. Corrections are for differences in Length/Depth, block coefficient, shear of the deck and bow height, and freeboard may be reduced if a ship has a large superstructure which provides reserve buoyancy. The result is called the "summer freeboard", and denotes the freeboard at which the ship may float while in an area designated a summer zone. A ship is required to have a greater freeboard while in a winter zone, and may float at a smaller freeboard while in a tropical zone. By this means, climate is taken into account for different parts of the world and for the seasons.

To be assigned the minimum freeboards prescribed by the convention, a ship must meet specified requirements for structural strength, stability, bulkheads, double bottoms, and watertight security of openings in the hull and superstructure. There is an implied direct relationship between freeboard and safety. A decrease in freeboard reduces a ship's reserve buoyancy, and thus its ability to float if one or more compartments are flooded. Smaller freeboards allow more weight to be carried, possibly increasing the structural stresses. Stability is measured by initial GM and the characteristics of the GZ curve. For freeboard ratios in the range specified by the convention, a decrease in freeboard normally increases initial GM, but reduces maximum GZ, heel at maximum GZ, range of positive GZ and the area under the GZ curve. The effect on stability caused by a variation of freeboard is illustrated in Figure 4.3.2, and in general a decrease in freeboard reduces a ship's safety from capsize.

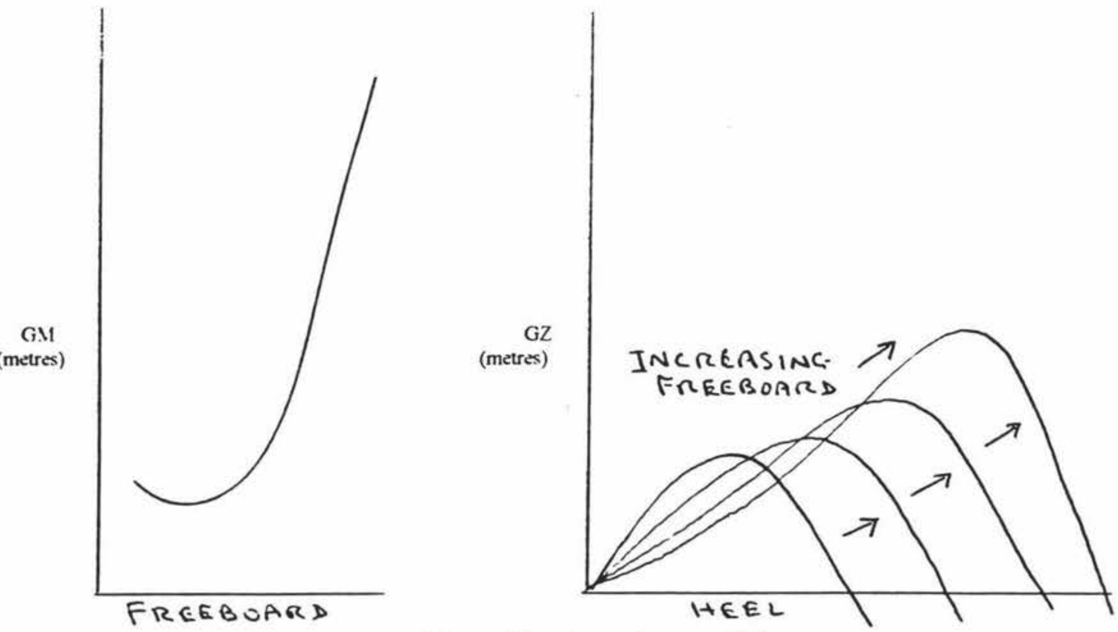


Figure 4.3.2 Effect of freeboard on stability.

This discussion of freeboard may provide enough insight to allow speculation about the functional relationship between freeboard, a ship's earning capacity and safety. Ships are designed to operate in a loaded condition, and very large freeboards can cause problems for the control and operation of ships, so that beyond certain values an increase in freeboard will not improve safety. There is however an approximately inverse linear relationship between freeboard and earning capacity. Hypothetical relationships between freeboard and earning capacity, and between freeboard and the cost of reduced safety are shown in Figure 4.3.3.

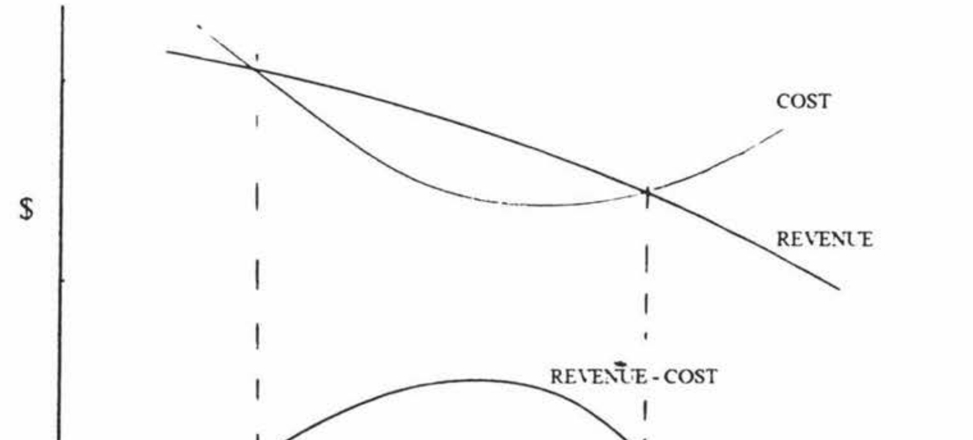


Figure 4.3.3 Revenue and costs as functions of freeboard.

It is expected that ships operate in the region enclosed by the cost and revenue curves in Figure 4.3.3, and that refinement of freeboard tables reflects the attempts to maximise the difference between revenue and cost.

4.4 Subdivision

Subdivision of a ship into watertight compartments limits the quantity of water that will enter the hull in the event of damage below the waterline. Passenger and dry cargo ships are fitted with transverse watertight bulkheads, double bottoms and tanks that provide structural strength, as well as subdivision. When a compartment is flooded the ship sinks to a deeper draught, and there may be a change of trim and loss of stability. If flooding is not symmetrical about the ship's centreline then the ship will list. The magnitude of these effects depends on the size and location of the compartment flooded as well as the ship's dimensions and initial stability. Fitting more bulkheads may increase a ship's chance of surviving hull damage, but too many bulkheads would prevent the efficient utilisation of spaces for passengers, cargo and machinery. Thus the level of subdivision and positioning of bulkheads involves a compromise between economic efficiency and safety from flooding.

To illustrate the effect of flooding on a ship's longitudinal stability, consider the ship in Figure 4.4.1 initially floating with waterline $W_0 L_0$. If a compartment is damaged, and the hole in the ship's side is large enough so that water can flow in and out without restriction, then the contribution of that compartment to the ship's buoyancy is lost. The ship sinks to a new waterline $W_1 L_1$ so that the buoyancy from increasing the draught replaces the lost buoyancy of the compartment. The position of the ship's centre of gravity is not affected by water flowing in and out of the damaged compartment, but the centre of buoyancy moves from B_0 to B_1 which is away from the centroid of lost buoyancy. The ship changes trim until the centre of buoyancy B_2 is in the line of force through the centre of gravity. The final waterline after flooding is $W_2 L_2$, and the ship may survive the damage provided the change of waterline does not allow water to enter other compartments. Flooding the compartment also results in a loss of water plane area, reducing the second moment of waterplane area (I), and from $BM = I / V$, there can be a reduction in the transverse metacentric stability. Safety from capsize depends on a ship's initial stability and the magnitude of the loss of stability.

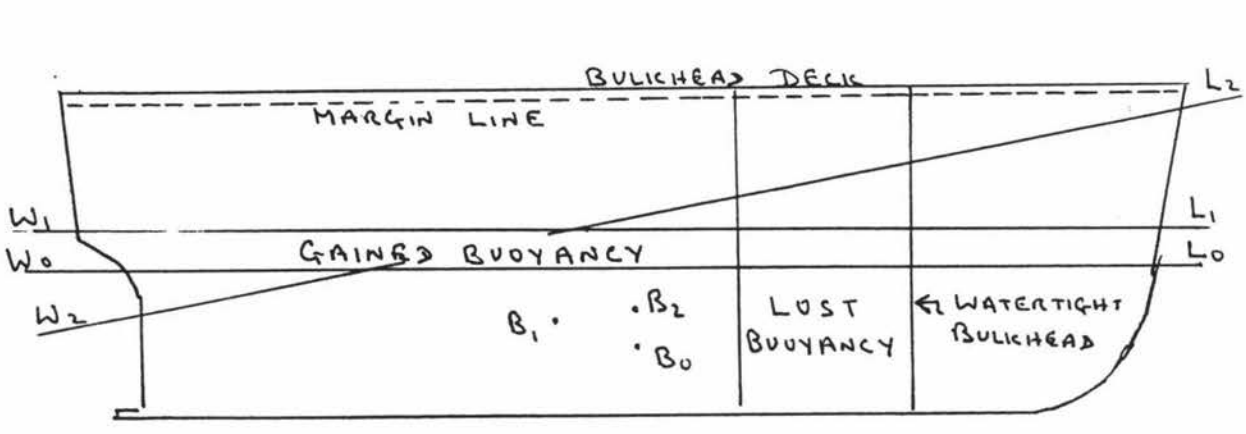


Figure 4.4.1 The effect of flooding a compartment

When the Titanic sank in 1912 the UK formed a committee to investigate requirements for the subdivision of passenger ships. The "Bulkhead Committee" recommended a method to determine minimum spacing of transverse watertight bulkheads that was later incorporated into the International Safety Conventions. The problem is to determine the maximum lengths of compartments which may be flooded so that the new waterline ($W_2 L_2$ in Figure 4.4.1) does not intersect the margin line which is drawn parallel to and 75 cm below the bulkhead deck. The method adopted by the committee was to use a standard ship form for the basic calculations and to make adjustments for differences between an actual ship and the standard form. The development of computer ship stability software means that the calculations can now be done from first principles, without need of a standard ship form, but the concept has not changed. Floodable lengths of compartments are determined for each point in the ship's length using standard assumptions about the permeability of compartments, depending on whether they are empty, contain cargo, machinery or passenger accommodation. Floodable lengths are multiplied by a factor of subdivision to give permissible lengths. The factor of subdivision is less than unity and takes into account the number of passengers, and the volumes of passenger, crew and service spaces in the ship. Figure 4.4.2 shows curves of floodable and permissible length, the height above the baseline of a point on a curve indicating the maximum length of compartment centred below that point. The curves enable the spacing of bulkheads be selected to take account of the ship's operational requirements, and to give a safety standard for one, two or three compartment flooding as deemed necessary.

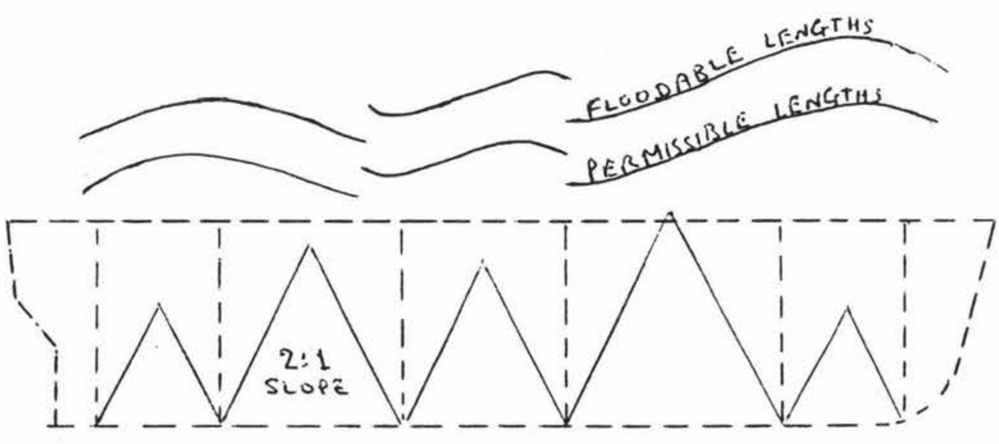


Figure 4.4.2 Curves of floodable and permissible lengths.

Earlier safety conventions provided subdivision standards for passenger ships only. The classification society rules for cargo ships require a collision bulkhead forward, watertight bulkheads between the engine room and other compartments, and additional watertight bulkheads depending on a ship's length, with restrictions on the maximum spacing of bulkheads. A Protocol to the International Convention for Safety of Life at Sea 1974 specifies standards for subdivision and damage stability for cargo ships based on a probabilistic method. This method applies to cargo ships of over 100 metres in length which were built after 1 February 1992, and is based on the calculation of a Required subdivision index (R) and an Attained subdivision index (A) R is derived from a statistical sample of the world's dry cargo fleet and A is found by detailed computation for the design of ship.

$$R = (0.002 + 0.009 . L_S)^{1/3}$$

where L_S is the ship's subdivision length, which is the length between perpendiculars taken at the extremities of the deepest subdivision load line, and:

$$A = \sum_i P_i . S_i$$

where:

- i represents each compartment or group of compartments under consideration
- P_i accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision
- S_i accounts for the probability of survival after flooding the compartment or group of compartments under consideration, including the effects of any horizontal subdivision

(IMO, 1992 a)

The summation to find A involves considering each compartment separately and also in groups of adjacent compartments. Assumptions are made about the level of damage and the probability that it will extend to a particular compartment. A ship is not expected to survive all possible damage situations, provided it survives a sufficient number to ensure that A is greater than R, more weighting being given if the ship survives after damage to high risk regions such as the forward end. The probability of survival depends on the final waterline and residual stability. If breaching a compartment results in a waterline that allows progressive flooding then the probability of survival for that case is zero. The probability of survival also depends on transverse stability after damage, i.e. the angle of heel, resulting GM and range over which GZ is positive. The calculations are carried out for a ship that is fully loaded and also in a partially loaded condition, and the resultant value of A is the average of the two values calculated. (Magill, 1990; Scott, 1990).

The method involves much detailed computation as a number of probable damage situations have to be evaluated. Iteration may be necessary for the designer to select optimum positions for bulkheads and tank tops in order to meet operational as well as damage stability requirements, and fast computer software is necessary for good results. The procedure is the first time that a probabilistic as opposed to a deterministic method is prescribed by shipping regulations, and the indices R and A could be very suitable for use in a mathematical model of ship safety.

4.5 Ship motions in a seaway

A ships' motion is determined by its response to the external forces from wind and waves, and in rough weather violent motions can cause a ship to capsize, founder or be structurally damaged. Excessive motion can also damage essential machinery and systems and will reduce the performance of crew. The motions of a ship in a seaway are therefore significant and should be incorporated in a model of total ship safety. As outlined in Chapter 4.2 on stability, a freely-floating ship has six degrees of freedom: surge, sway and heave being translationary motions, and roll, pitch and yaw being rotational motions. This section is concerned with roll, pitch and heave, which can cause capsize, damage or discomfort in heavy weather.

Roll is the dynamic equivalent of heel. When a ship heels because of an external force, the force of gravity and buoyancy create a moment which tends to restore the ship to the upright position. When the force is released, the ship rolls with decreasing amplitude, eventually settling at its initial attitude in the water. The frequency of roll depends on GM, and the approximate period of roll for small amplitudes where non-linear effects are negligible is given by the formula:

$$T_s = 2 \quad K \,/\, \sqrt{g \,.\, GM}$$

Where T_s is the period of roll in seconds
K is the radius of gyration of the ship in metres (approximately breadth / 3)
GM is the metacentric height in metres

The rolling period provides an approximate method of determining a ship's stability. A slow roll signifies that the ship has a small GM and there is risk of capsize. A large GM will quicken the roll, which can cause discomfort, violent forces on cargo lashings and even structural stress. A compromise is necessary to find a condition in which the ship has sufficient statical stability for safety from capsize, but not so much as to result in violent rolling.

The significance of roll motion to safety depends on the size and type of ship. In general, small cargo ships are the most vulnerable to capsize in rough seas. Tankers and large bulk carriers tend to have good transverse stability when correctly loaded and are least effected by rolling. Violent rolling can be a problem that effects large general cargo, roll-on-roll-off, and container ships and the motion can put great stress on cargo securing points (Renshaw, 1985). If cargo breaks loose and shifts the ship will list and will then be vulnerable to capsize in heavy weather.

Pitching is the longitudinal equivalent of rolling, but does not present danger of capsize for conventional ships. Longitudinal BM is given by the formula $BM_L = I_L / V$ where I_L is the second moment of area of the waterplane about the transverse axis through its centroid. Since I_L is large relative to the transverse second moment of area, it follows that BM_L and hence GM_L is large, of the same order of size as the length of ship. Therefore when a ship pitches there are large restoring moments which cause longitudinal stresses.

Pitching also causes periodic changes in the water pressure on the hull near the bow and stern, and results in panting stresses. Slamming occurs when the downward motion of the bow is arrested by water pressure, the effect being of a sudden impact followed by vibrations through the hull. Pitching can cause waves to break over the foc'sle and deck, and can result in damage to the ship's superstructure, deck fittings and cargo. At the after end the propeller may emerge, reducing its resistance to torque which causes the engine to race, and the possibility of protection devices operating to stop the engine.

Heaving is the vertical component of s ship's translation motion, caused by transient differences between the forces of buoyancy and gravity as waves are encountered. The heaving motion is heavily damped by the viscosity of sea water, and it is strongly coupled to the ship's pitching motion. The main effect is to add to the effect of pitch at the bow and stern, so that panting, slamming and propeller emersion are the results of both pitch and heave. Because of this, relative bow motion is used as a parameter of seakeeping.

The effects of ship motions are of concern to designers, builders, ship operators and mariners. A long history of operation experience resulted in the development of ships' hulls that withstand most sea conditions. Paffett (1986) commented critically "Build it so that it looks right, if it falls apart or turns over and kills the crew, then bump up the scantlings/beam/freeboard a bit next time and hope for the best". He went on to say "This empirical procedure, remnants of which persist to this day, is not to be despised; it works, but it is expensive in money and lives." Recently great effort has been put into developing procedures that enable good seakeeping qualities to be designed into a ship.

The elements of the problem of assessing a ship's motion in a seaway are summarised in Figure 4.5.1. In a calm sea, a steady speed is maintained at which the propeller thrust equals total resistance. Helm movements to keep the ship on the required heading cause yaw, which induces sway and roll, but these motions are only significant if the rudder is put to a large angle. As the ship encounters waves other motions are induced, and these create disturbances in the water which in turn affects the ship's motions. At the same time the helmsman or autopilot is controlling the rudder to prevent the ship from yawing off course, and if the motions are sufficiently severe, the ship's master will adjust course or speed to reduce the risk to the vessel. The figure represents a complex interactive system. Statistical data on the expected sea conditions is required in order to represent the sea mathematically as a series of superimposed sinusoidal waves. The forces acting on the ship can then be determined to provide an input to a model of the ship's motions.

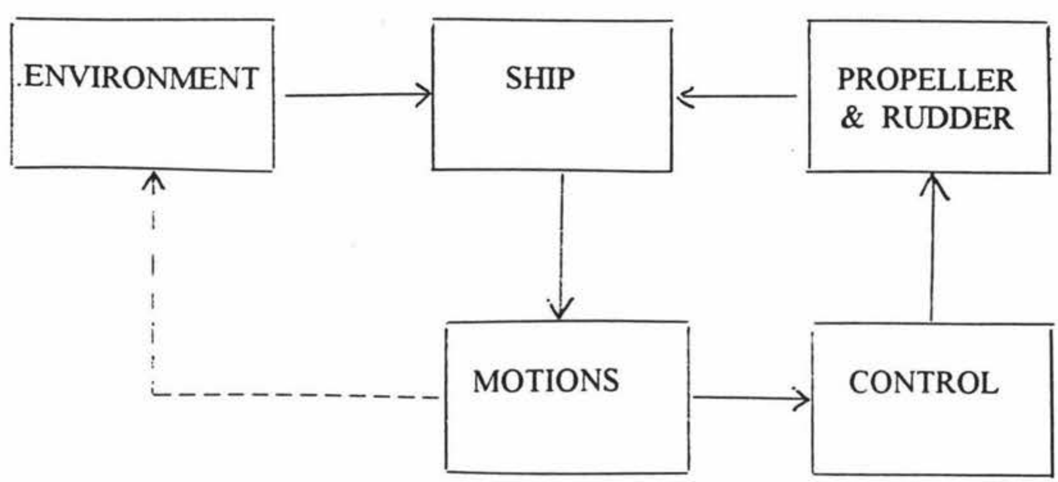


Figure 4.5.1 Ship motions when under way at sea.

Figure 4.5.2 illustrates a ship in a beam sea. Lines of wave crests lie parallel to the ship's fore and aft line and movement of the centre of buoyancy causes a couple which rolls the ship. As the ship rolls B moves in the direction of roll, creating a righting moment.

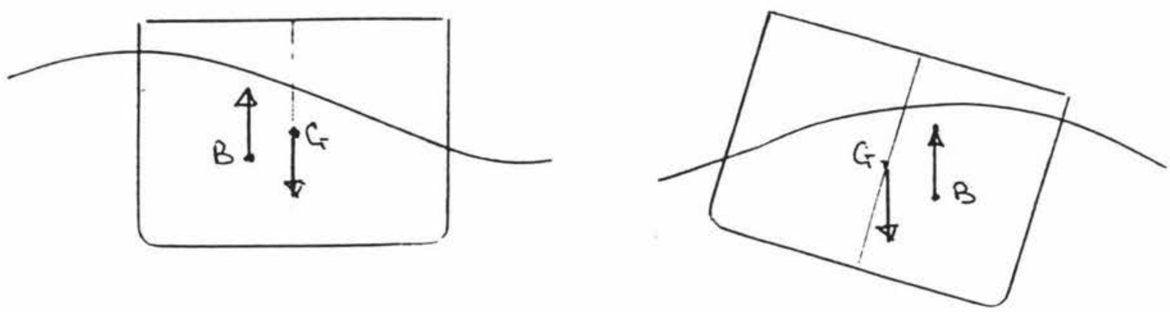


Figure 4.5.2 Rolling in a beam sea.

As the line of crests advances at right angles to the ship's direction, B moves in the direction of the crest, and the resulting movement of B will be determined by the component of its movement due to the roll and the component due to the movement of the wave. When the two components reinforce one another their combined effect will increase the amplitude of roll, and when they counteract one another by moving in opposite directions there will be less tendency to roll. Whether the components tend to reinforce or oppose one another depends on the ship's natural roll frequency ω_0 and the frequency of encounter with waves ω. When the two frequencies are close, resonant or synchronous rolling may develop, which could capsize the ship. If the two frequencies are not close then the amplitude of roll will be small, and so for a ship with a given natural frequency of roll the relationship between the wave amplitude and resultant amplitude of roll is a function of the frequency of encounter. Figure 4.5.3 shows the relationship between wave amplitude and roll amplitude, and an objective of good design and operation is to avoid designing and loading a ship so that its natural rolling frequency will be close to the frequency of encounter with waves.

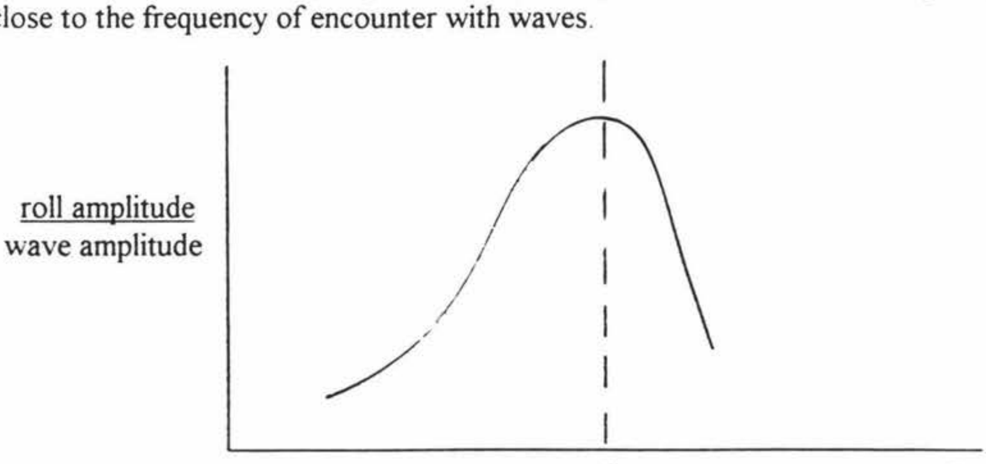


Figure 4.5.3 Roll amplitude magnification factor.

A ship's natural period of roll depends on its GM, the ship's inertia, damping characteristics of the hull and on the ship's geometry. Ship designers have some control over rolling characteristics, but there are constraints imposed by practical and commercial aspects of a ship's operation. Variables that affect the roll period are beam, freeboard, vertical and transverse distribution of weight, block coefficient and waterplane area coefficient. Other methods to reduce rolling include fitting bilge keels to increase hydrodynamic damping, or to fit an active stabilisation system as is done in some passenger and container ships. There are also methods available to the ship's master to avoid dangerous rolling, such as loading to ensure adequate but not excessive GM, increasing the ship's transverse radius of gyration by loading heavy weights away from the centreline, and by planning passages so as to avoid heavy beam seas.

A similar analysis is applied to a ship pitching in head seas, where the lines of wave crests are perpendicular to the ship's direction of travel as shown in Figure 4.5.4

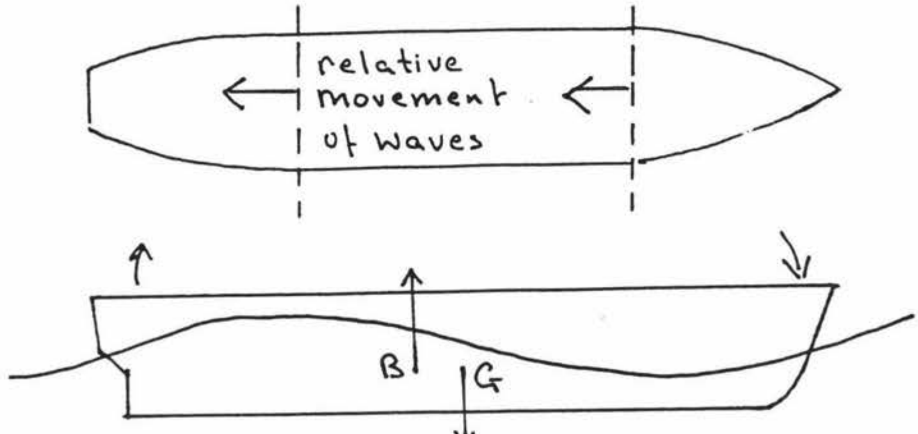


Figure 4.5.4 Pitching in head seas.

The transfer functions for pitch and heave for a cargo ship are illustrated in Figure 4.5.5. These are plotted to a base of wave length / ship length (λ / L) to provide non dimensional functions referred to as Response Amplitude Operators (RAO's)

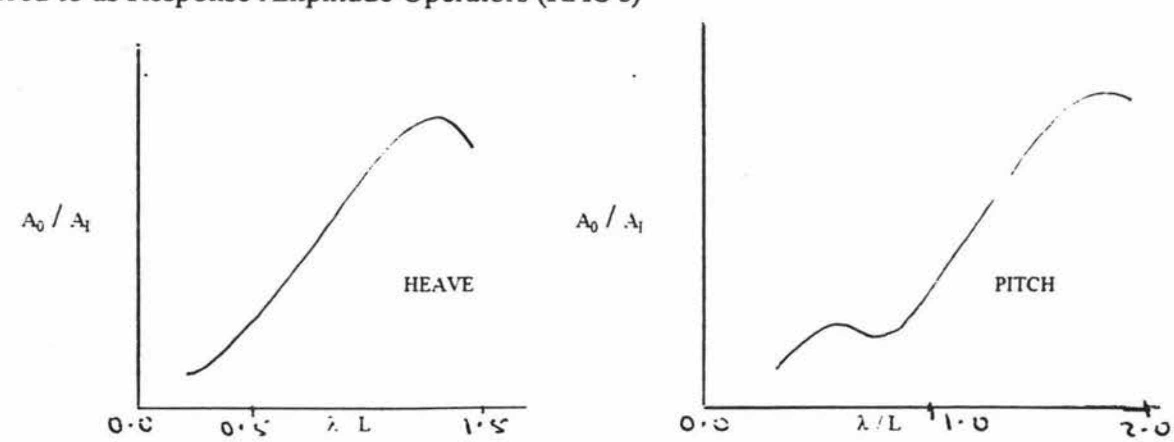


Figure 4.5.5 Response Amplitude Operators for a cargo ship.
(Hearn et al., 1991)

As with rolling there are methods available to the designer to reduce pitching. From the RAO's in Figure 4.5.5 it is apparent that the tendency to pitch reduces with an increase in ship length, and that for a ship of length more than 1.3 times the wave length, the natural pitching motion is small. A ship with a "V" shaped transverse cross section near the bow tends to pitch less than one with a fuller cross section, and the coupling between heave and pitch is smaller when the centre of flotation and centre of buoyancy are close to one another. Excessive pitching can cause structural stress, slamming and the shipping of water on deck, and the ship's master can reduce these hazards by adjusting course and speed. Lindemann (1975) produced tables showing vertical acceleration at the bow, shear forces and bending moments for a ship on various headings and speeds relative to waves. He has suggested that such tables could prove useful in selecting a suitable course and speed to avoid damage to a ship in heavy seas.

While analysis of ship motions for head and beam seas is useful in the selection of hull parameters, dangerous motions can result from seas running obliquely to a ship's heading. There is also cross coupling between motions and such effects can be taken into account in a more general model of a ship's motion.

A system of equations describing a ships motions has the form:

$$(I_i + A_{ij}).\ddot{\eta}_i + B_{ij} .\dot{\eta}_i + C_i . \eta_i = F_i \quad .. \ (4.5.1)$$

where i , j = 1 to 6

η_i displacement in direction i
I_i (for i = 1 to 3) = Mass of the ship
I_i (for i = 4 to 6) = Moment of inertia about the i th axis
A_{ij} added mass and added inertia matrix
B_{ij} damping matrix
C_i hydrostatic restoring function vector
F_i forcing function vector

A_{ij} and B_{ij} represent the components of added mass, inertia and damping induced by motion in the j th mode which effect motion in the i th mode. For a sea description built up by superposition of a spectrum of sinusoidal waves of different amplitudes and frequencies, moving obliquely to the ship's heading, the forcing function F_i is complex as illustrated for only one component of $\underline{F}$ in Figure 4.5.6. In the Figure, $\underline{u}$ represents the ship's velocity and $\underline{v}$ the wave velocity.

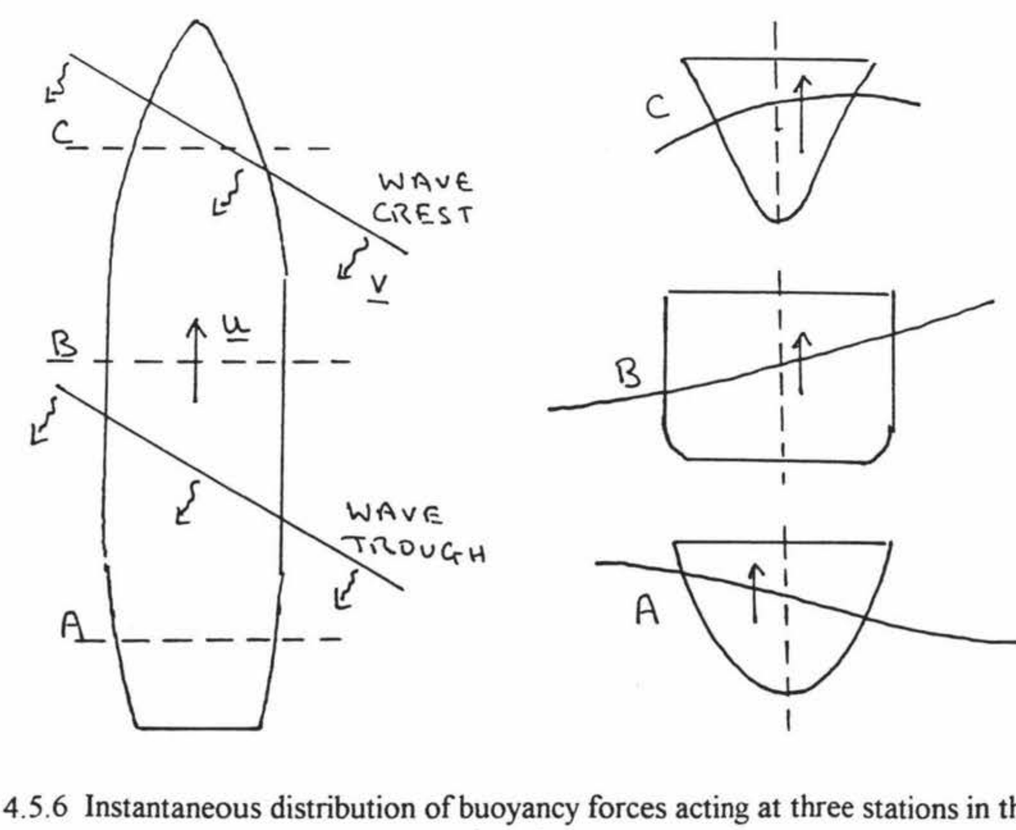


Figure 4.5.6 Instantaneous distribution of buoyancy forces acting at three stations in the ship's length

The solution of Equation 4.5.1 over a practical time interval is difficult because of the number of terms involved, and this would not be an efficient strategy when it is acknowledged that coefficients A_{ij} and B_{ij} are not known accurately for a wide range of conditions. A number of approaches use simplifications of the general equation of motion, neglecting small cross couplings, and linearising near linear terms. (Paffett, 1986). The model used by Elsimillary and Millar (1986) eliminates surge (η_1) to give five degrees of freedom, and in the system of Equations 4.5.2, pitch and heave are independent of sway, roll and yaw. It is intuitively apparent that pitching or heaving in oblique waves as shown in Figure 4.5.6 will cause sway, roll and yaw, and that those couplings are ignored by the system of equations.

$$(M + A_{33}).\ddot{\eta}_3 + B_{33}.\dot{\eta}_3 + R_3 + A_{35}.\ddot{\eta}_5 + B_{35}.\dot{\eta}_5 = F_3 \quad \text{(heave)}$$

$$(I_5 + A_{55}).\ddot{\eta}_5 + B_{55}.\dot{\eta}_5 + R_5 + A_{53}.\ddot{\eta}_3 + B_{53}.\dot{\eta}_3 = F_5 \quad \text{(pitch)}$$

$$(M + A_{22}).\ddot{\eta}_2 + B_{22}.\dot{\eta}_2 + A_{24}.\ddot{\eta}_4 + B_{24}.\dot{\eta}_4 + A_{26}.\ddot{\eta}_6 + B_{26}.\dot{\eta}_o = F_2 \quad \text{(sway)}$$

$$(I_4 + A_{44}).\ddot{\eta}_4 + B_{44}.\dot{\eta}_4 + R_4 + A_{42}.\ddot{\eta}_2 + B_{42}.\dot{\eta}_2 + A_{46}.\ddot{\eta}_6 + B_{46}.\dot{\eta}_6 = F_4 \quad \text{(roll)}$$

$$(I_6 + A_{66}).\ddot{\eta}_6 + B_{60}.\dot{\eta}_6 + A_{62}.\ddot{\eta}_2 + B_{62}.\dot{\eta}_2 + A_{64}.\ddot{\eta}_4 + B_{64}.\dot{\eta}_4 = F_6 \quad \text{(yaw)}$$

Equations 4.5.2 (Elsimillary and Millar, 1986)

Equations 4.5.2 are used to simulate a ship's motions over time for assumed sea spectra, ship speeds and angles of encounter. Although statistical methods are necessary to derive coefficients from observations and model tests, the process is deterministic. In practice ships' motions are a stochastic phenomenon and almost all parameters involved have random elements. The precision with which GM is known depends on estimates of the mass and centre of gravity of loads in a ship, the distribution of loads varies from one voyage to another, and the sea state encountered involves a large random element.

Modelling of ships motions can be used to improve ship safety in a number of ways. It enables a naval architect to assess and improve the sea keeping qualities of a ship at the design stage. Output from models may provide ship managers with data to assess the suitability of a ship for a particular trade. The output can also provide a ship's master with information about the ship's responses to the sea on different headings and speeds. And the model may also be used to provide information about the level of safety of a ship. This could be in the form of the probability of capsize, or the probability of a given level of damage for a particular ship in a given service for a stated length of time.

4.6 Manoeuvrability

Manoeuvrability is an indication of the ease with which a ship can be handled, and is relevant to safety for ships encountering traffic and when negotiating restricted waterways. The main devices for manoeuvring are a ship's rudder and engines, some ships are fitted with side thrusters, and often tugs are used to assist with manoeuvring. Although twin screw ships may be more manoeuvrable, most merchant ships are single screw with a single rudder as these involve simpler construction and are more economical than multiple screws.

A ship's manoeuvrability depends mainly on its size, engine power, hull geometry and the type and size of propeller and rudder fitted. A number of variable factors can significantly change the ship's manoeuvring characteristics:

- the condition of loading and trim
- depth of water and the proximity of other ships and obstructions in the water
- wind strength and direction relative to the ship
- flow of water around the hull

During a sea passage it should be possible to steer a straight course, and in calm conditions a ship that is dynamically stable can maintain course with few rudder movements, but a ship that is dynamically unstable tends to yaw to one side or other when going ahead with the helm amidships. Generally narrow ships tend to have greater dynamical stability than a ship with a fuller form. A dynamically stable ship is harder to turn and will have a larger turning circle than one less stable, and an attempt to avoid a hazard by making a large alteration of course is less likely to succeed. Turning circles and the concept of dynamical stability provide a basis for measuring a ship's manoeuvrability.

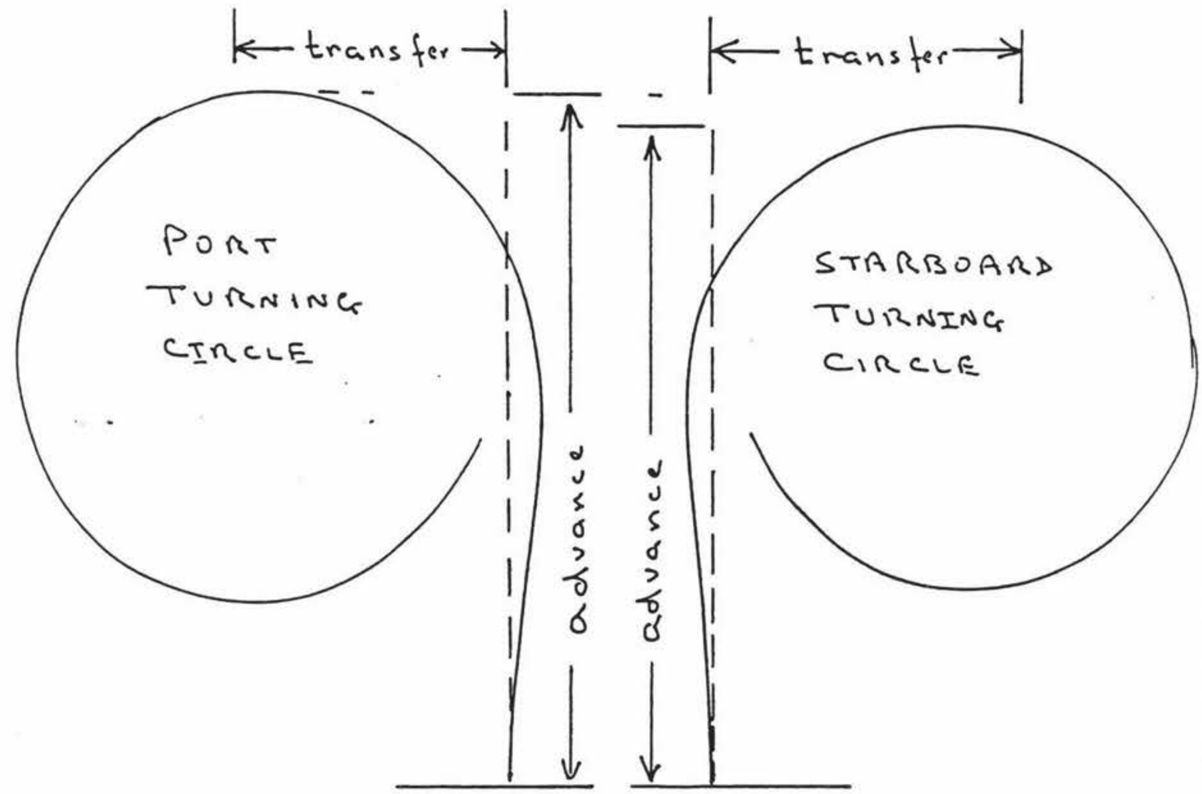
Manoeuvring tests are carried out on new ships during sea trials. Deep water and good weather are required for trials, no more than sea state 4 and wind force 5 being acceptable. The information is required for the ship in a normal loaded seagoing condition, and data is observed using a highly accurate navigational positioning system and a rate of turn indicator.

The standard manoeuvring tests are:

- speed trials
- stopping from full speed using full astern power
- stopping from full speed with the engine stopped
- turning to port and starboard using maximum rudder and at various speeds
- course changes to port and starboard using 10 and 20 degrees rudder
- tests to determine the lowest speed at which the ship can be steered

If the trials indicate that the ship is dynamically unstable then a spiral test is used to give a quantitative measure of dynamical stability. In a spiral manoeuvre, the helm angle is increased gradually and the rate of turn is measured (Det Norske Veritas, 1991).

A summary of manoeuvring information derived from trials is presented in a wheelhouse poster, and a typical poster is shown in Figure 4.6.1. Details of the ship's manoeuvring characteristics are also presented in a manoeuvring booklet, which may be supplemented when further information becomes available during operations carried out over the ship's life. The information is for guidance in ship handling, and in 1995 an IMO resolution provided minimum manoeuvring standards for new ships of over 100 metres in length, and new oil and gas tankers of any length.



TURNING CIRCLES

CONDITION		NORMAL LOAD				NORMAL BALLAST			
		advance		transfer		advance		transfer	
		DIST	TIME	DIST	TIME	DIST	TIME	DIST	TIME
FULL SPEED	PORT	780	3'43"	419	3'43	554	2'22"	295	2'22"
	STARBOARD	772	3'35"	365	3'35"	540	2'16"	257	2'16"
HALF. SPEED	PORT	749	4'19"	422	4'19"	536	2'49"	301	2'49"
	STARBOARD	726	3'49"	350	3'49"	518	2'29"	250	2'29"

(distance in metres, time: min' sec")

DISTANCE AND TIME REQUIRED TO STOP SHIP

CONDITION	NORMAL LOAD		NORMAL BALLAST	
	Distance	Time	Distance	Time
Full speed	2150	9'30"	1550	7'10"
Half speed	975	6'15"	700	4'50"
Slow speed	694	4'20"	432	3'20"

Figure 4.6.1 A typical wheelhouse poster.

A number of measures are used to define acceptable manoeuvring capability:

- the ratio of tactical diameter (see glossary) to ship's length, for merchant ships 4.5 is considered good, and ratios greater than 7 are very poor
- turning rate; generally 0.5 to 1.0 degree per second
- rate of change of heading per unit rudder angle in one ship length travelled should be greater than 0.3, and 0.2 for large tankers (Rawson and Tupper, 1994).

There are limitations on the information that can be presented in a manoeuvring booklet or poster, as data is obtained for only a limited number of conditions that affect manoeuvrability. A ship's characteristics can be very different in the light and loaded conditions, and when a ship is trimmed, manoeuvring at slow speed in shallow water with tidal stream running, the displayed information may be of little help to the ship handler. However the information is useful as a measure to compare the ship's manoeuvring performance with that of vessels of which the mariner has previous experience. A knowledge of the distance necessary to stop a ship in a given condition travelling at a given speed would influence the choice of speed in reduced visibility. The information contained in a manoeuvring booklet can be used when planning a passage in confined waters, and the improved navigation control could make a positive contribution to safety.

Manoeuvring trials can provide a great deal of data about a ship, and there is a number of ways in which such quantitative information is used to improve safety. Standard trials data has been used to identify the appropriate mathematical models of a ship manoeuvring, and to derive the hydrodynamic derivatives for the equations. Gill (1975) found that equations of the following form appeared suitable for describing ship manoeuvring behaviour over a range of forward speeds and ahead engine speeds:

$$(m^* + a_x).\dot{u}' = a_1.U'.n' + b_1.n'^2 - (a_1 + b_1).U'^2 + (X_2 + m^*).r'.v' + X_2.\delta^2.U'^2$$

$$(m^* + a_y).\dot{v}' = Y_1.v'.U' + Y_2.r'.U' - (Y_5 + m^*).u'.r' + Y_2.\delta.U'^2 + Y_4.r'.v'^2 / U'$$

$$(I^*_z + a_n).\dot{r}' + (b_n + c_n.U'^2).v' = N_1.v'.U' + N_2.r'.U' + N_3.\delta.U'^2$$

where: m^* = mass / $\tfrac{1}{2}.\rho.L^3$, I^*_z = moment of inertia about z axis / $\tfrac{1}{2}.\rho.L^5$,
a_x, a_y, a_n = added inertia in surge, sway and yaw,
a_1, b_1 = longitudinal force coefficients, c_n = speed coefficient,
n = engine speed in rpm, δ = rudder angle in radians,
u = surge velocity, v = sway velocity, U = track speed = $(u^2 + v^2)^{1/2}$,
X = longitudinal force, Y = lateral force, N = yaw moment,
r = rate of turn in radians per second, ρ = density of sea-water,
and primes indicate that a parameter has been non-dimensionalised.

Gill's equations are for three degrees of freedom; surge, sway and yaw. As discussed in Chapter 4.5, yaw and sway are strongly coupled with roll and it is appreciated that such models are necessary simplifications of a more general 6-degree-of-freedom model of ship motions. There has been advances in the modelling of ship motions which have practical benefits such as assessing a ship's manoeuvrability in waves (Ottosson and Bystrom, 1991) and using rudder to reduce rolling.

Mathematical modelling promotes an understanding of ship manoeuvrability and enables a more reliable extrapolation of data obtained from ship trials and model tests. The number of conditions of loading in which manoeuvring trials can be conducted is very limited and a suitable model can be used to derive data for a ship in the fully-loaded or ballast condition from observations about the ship in an intermediate-loaded condition.

In the same manner as described for seakeeping models, a manoeuvring model can be used to design good manoeuvring characteristics into a ship. A ship's principal dimensions are dictated by commercial considerations. and the parameters that have the greatest effect on manoeuvrability are fixed before any detailed design work is carried out. The naval architect's contribution to good manoeuvring characteristics can therefore be limited to the geometry of the stern and the size and design of the rudder. The diameter of the turning circle decreases with an increase in rudder area for rudders of area up to about 2% of the projected underwater hull area, but further increase has little effect (Clarke, 1978) A large rudder can make course-keeping more difficult and increase the stress on the after part of the ship, so the designer is working with a number of constraints. Use of a manoeuvring model at an early stage in ship design can help identify potential problems before a heavy investment of time and resources has been made.

Mathematical ship manoeuvring models are used in ship simulators and radar simulators for training mariners and pilots. For general training a mathematical model which only roughly approximates the characteristics of a ship may be adequate, and will provide trainees with an appreciation of the difference in response between a laden bulk carrier and a small fast refrigerated cargo ship for instance. Greater fidelity is necessary for a ship simulator used to train pilots in berthing a large tanker. Simulations are also used to assess channel design or upgrading of port approaches to allow larger ships to enter. Experienced pilots navigate the large simulated ships through the modified channels in order to identify constraints. The cost of a single accident could be far in excess of the cost of a simulator investigation, but a mathematical model which gives a very close approximation to the characteristics of a range of real ships is a prerequisite.

Manoeuvring models are also used to enhance the operation of ships' navigational and control equipment. Autopilots are programmed with a ship's characteristics to improve steering capabilities and to reduce wear on the rudder and steering gear. Ships' equations are also used in a Kalman filter to reduce the errors associated with position-finding equipment. Thus it can be seen that modelling a ship's manoeuvring characteristics can lead to direct improvement in ship safety; it remains to consider whether measures of manoeuvrability can be used in a mathematical model of ship safety.

Manoeuvring characteristics are not critical to safety during a sea passage in open waters and with good visibility. Course alterations for approaching ships can usually be made in plenty of time and the mariner on the bridge should be aware of the approximate stopping distance, advance and transfer on turning for the size and type of ship. In reduced visibility there is a likelihood of close quarters manoeuvres, and greater turning circle diameters and stopping times decrease safety. There is also a possibility of loss of control of a dynamically-unstable ship. In confined waters such as channels and harbours, a slow response to the helm, or the inability to control a ship when swinging, can lead to collision, grounding or contact damage. This suggests that a mathematical model of ship safety should include at least the following parameters:

- stopping distances
- diameter of the turning circle
- rate of turn for a given rudder angle
- minimum speed for helm response
- dynamical stability

4.7 Environment

The physical environment in which a ship operates has direct consequences for safety. Strong winds, rough seas, currents and tidal streams affect a ship's movement and controllability, while poor visibility makes navigation difficult and hazardous. Large changes in temperature can cause stresses in a ship's hull and, together with humidity, affects the requirement to ventilate cargo. Weather conditions can make the routine operation of a ship difficult and affects the crew's ability to carry out maintenance that may be essential to safety. Also highly significant to the safety of a ship on passage in coastal waters are the depth of water, distances from dangers and the level of vessel traffic in the area. These factors are potential inputs to a model of ship safety, and while they cannot be controlled, their effects have been observed, recorded and analysed over the years.

Wind

The effect of wind pressure on a hull and superstructure can cause a ship to heel, and will also affect controllability. The effect is greatest on ships with large freeboard and superstructure, such as passenger ships, roll-on-roll-off cargo ships, container ships and livestock carriers, and ships that are in the light or ballast condition. Wind heeling moment can be calculated, given wind strength, the projected area of the hull above the water and the centres of pressure and lateral resistance. Using assumptions about the probable maximum wind force, a wind heeling lever can be calculated and plotted on a ship's GZ curve to determine the heel and effect on dynamical stability. Controllability aspects are more problematic and strong winds can make it impossible to hold a particular course, or to manoeuvre a ship to a berth.

Wind speed is expressed in knots, kilometres per hour or by wind force on the Beaufort scale. The Beaufort scale enables wind strength to be estimated by the appearance of the sea, and is the method of observation used in ships that are not fitted with anemometers. The scale is from Force 0 for calm, to Force 12 for a hurricane wind with speeds of over 64 knots. Each wind force numeral covers a range of speeds, and is associated with a description of the sea. For example, Force 6: 22 - 27 knots, strong breeze, large waves begin to form, white foam crests are more extensive everywhere, probably some spray. (Burgess, 1978) Force 6 is associated with a gauge pressure of about 110 Pascals on a flat surface perpendicular to the direction of wind.

The general distribution of wind is given in world climatic charts and monthly routing charts. These indicate the probable direction and strength of the prevailing wind, and provide useful information about seasonal patterns, and what can be expected in a particular trading area. The wind experienced at any place at a particular time may be very different from the prevailing wind, and a regional weather forecast can provide reliable predictions for a few days. NAVTEX messages and radio facsimile weather maps provide up-to-date weather information for ships.

Waves

The Beaufort scale relates wind speed to the visual appearance of waves on the sea surface. Although the scale is useful in the absence of direct methods of observing wind speed, the wave length, amplitude and period of waves depends on the recent history of wind blowing over the sea. Waves are caused by the wind and the development of waves depends on the strength of wind, the duration of the blow, and the fetch or distance over the sea that wave generating wind has blown. Thus the sea description used in the Beaufort scale is for a fully developed sea, and for a given wind strength the sea may be different close to shore with an offshore wind, or if the wind has blown from one direction for only a short duration. Waves that are generated by a wind blowing at the time of observation are referred to as "sea", and waves that have travelled a considerable distance from the region in which they were generated are called "swell". At any place waves encountered are likely to be a mixture of sea and swell of different amplitudes, periods and wavelengths, and moving in different directions. This causes complications in attempts to describe the sea surface in precise mathematical terms.

Sea and swell waves are described by amplitude, wave length and period or frequency. Although related, in that for a given wave length there is some maximum amplitude and minimum period, the relationship is not straight forward.

The observed sea surface at any point can be represented as the sum of a number of sinusoidal waves of different amplitude and frequency.

$$h(t) = \sum_{i=1}^{n} A_i . \sin(\beta_i + \omega_i . t) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 4.7.2$$

where $h(t)$ = height of the sea surface from the mean level
A_i = amplitude of sinusoidal wave i
ω_i = angular frequency (radians per second)
β_i = phase angle in radians
n = an integer sufficiently large to give accurate representation of the surface.

Wave observations lend themselves to statistical analysis and various statistical measures are used to simplify the description of a complicated phenomenon. A commonly used statistic is the "significant wave height", which is the mean of the 1/3 highest waves observed. This is a useful parameter because it is correlated to the mean wave period (Perakis and Papadakis, 1988). Thus, given the frequency distribution of significant wave height, other wave parameters can be deduced. The probability associated with a given significant wave height can be represented as a continuous distribution as illustrated in Figure 4.7.1.

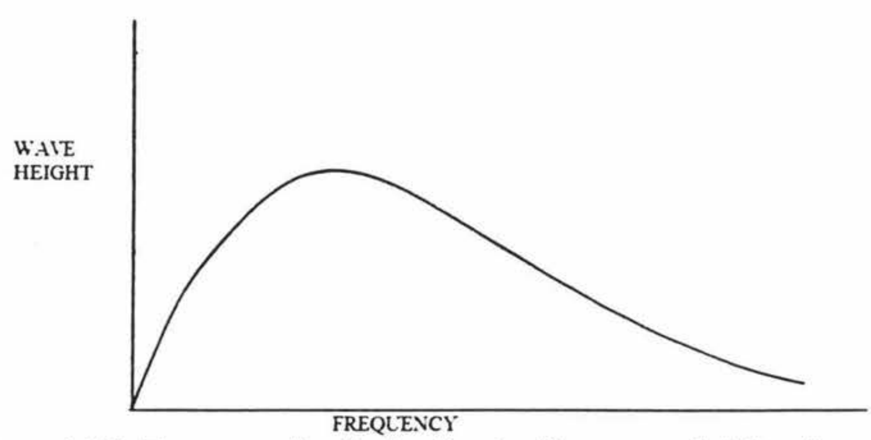


Figure 4.7.1 Frequency distribution for significant wave heights observed at a given place.

Another measure used to simplify the description of the sea surface is the "sea state", and this is related to intervals on the real line relating to significant wave heights as shown in figure 4.7.2

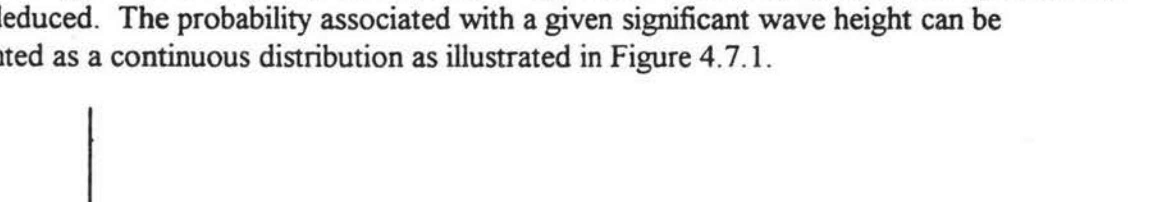


Figure 4.7.2 Sea state and significant wave height (Burgess, 1978).

Over the years, millions of observations of ocean waves have been recorded, and tables of wave periods, lengths and heights are available for the parts of the sea most frequently used by shipping. In applying this mass of data to ship safety, some gross simplification is necessary, and one approach is to use standard distributions to represent the probability distribution of significant wave heights under various conditions. Hoffman and Karst (1975) note that many investigators have found the Rayleigh distribution to correctly represent observed short-term distributions of the heights of sea waves and related phenomena such as ship motion and bending moment response.

The Rayleigh distribution has properties that can be used easily in a mathematical model, the main one being ease of integration so that time consuming numerical methods of integration are not necessary.

The Rayleigh distribution is defined by the probability density function:

$$f(x) = \begin{cases} \dfrac{x}{\alpha^2} . \exp(-x^2 / 2.\alpha^2) & \text{for} \quad x > 0, \ \alpha > 0 \\ 0 & \text{for} \quad x < 0, \ \alpha > 0 \end{cases}$$

From the density function we can obtain the distribution function F(x) which gives the probability that the random variable X is less than a specified real number x (Hoffman and Karst, 1975):

$$\Pr | X < x | = F(x) = \int_{-\infty}^{x} f(t).dt = \int_{0}^{x} \frac{t.\exp(-t^2 / 2.\alpha^2).dt}{\alpha^2}$$

$$F(x) = \begin{cases} 1 - \exp(-x^2 / 2.\alpha^2) & \text{for} \quad x > 0 \\ 0 & \text{for} \quad x < 0 \end{cases} \qquad \dots \quad (4.7.3)$$

Assuming that the probability of encountering waves of a given height is specified by the Rayleigh distribution for any region, wave characteristics for the region can be represented by the variable α. Figure 4.7.3 illustrates the distribution for various values of α. Given α, the probability of encountering waves of height " x " can be calculated directly from equation 4.7.3

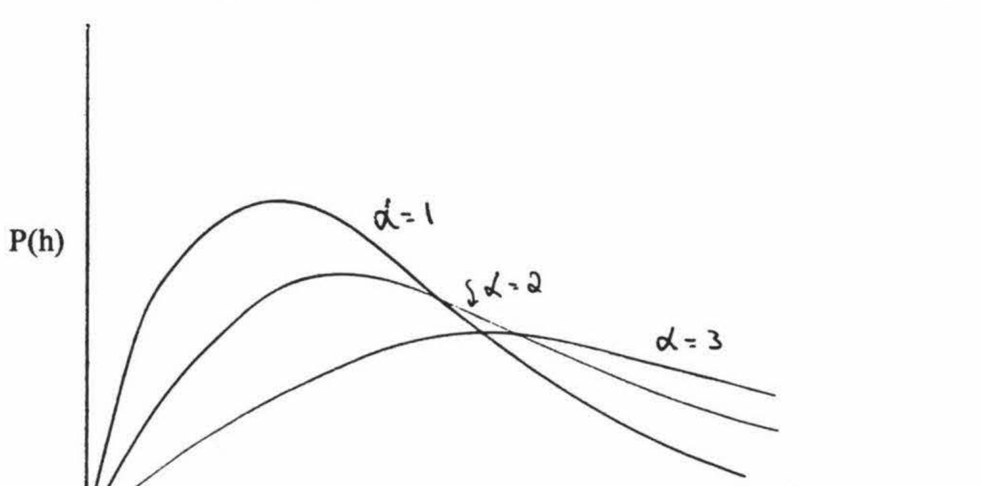


Figure 4.7.3 Rayleigh distribution for significant wave heights.

The method for determining the probability of encounter with waves of a given height is used in the computer model described in Chapter 6. A pre-requisite for the use of this model is to fit Rayleigh distributions to the wave data for each region, so that the seasonal or monthly wave probability distribution for a region is represented by a single variable α.

Currents

Surface currents are the horizontal flow of water generated by frictional drag of the wind, and modified by the Coriolis force and topographic features of the oceans. The strength and direction of currents can vary from day to day, depending on the recent history of winds and storms in a region. The vector mean of currents flowing at various positions is plotted to give a general circulation which is presented in current atlases and monthly routing charts for the oceans. According to the Mariners Handbook there is probably no part of the open ocean where currents do not reach the rate of 1 knot at times, and currents of 2 to 3 knots are found in a number of regions. Currents of more than 3 knots are confined to very restricted regions and the strongest currents observed had rates of up to 7 knots (The Hydrographic Office, 1989).

A ship's movement over the ground is the vector sum of its movement through water (course, speed) and the current (set, rate). Before the availability of electronic navigation equipment giving a continuous indication of position, an allowance for current was necessary when estimating a ship's position between observations. In practice the data available about the set and rate of current was not accurate enough for an estimated position to be used with confidence, and the allowance was rather one of acknowledging that a ship could have drifted several miles downstream from the dead reckoning position. In ships fitted with GPS (global positioning system) or other suitable navigational system, information about position is available continuously and the safety implication of degradation in navigational accuracy due to current is not significant.

Another aspect relevant to safety is that a navigator can use currents to reduce passage times even though this may reduce safety. Shipping traffic may become concentrated along the axis of a current such as that through the Florida Strait, thereby increasing the danger of collision. Also ships may navigate in areas that should be avoided, such as off the east coast of South Africa where ships heading south sometimes use the dangerous waters along the edge of the continental shelf to achieve maximum speed in the current, and ships heading north keep close to the shore to use the counter currents. Although such practices are ostensibly caused by the existence of strong currents, it may be more appropriate to consider the effect on safety from the point of view of navigation, human involvement and economic pressure, rather than as a physical phenomenon.

Tidal streams

Tidal streams are the horizontal flows of water caused by the rise and fall of the tide. The direction and rate of tidal streams change rapidly over a few hours and information is given for specific positions in navigational charts and pilot books. The rate depends on the range of tide and the topography. Tidal streams are only significant near land, and in many areas can reach speeds that makes navigation impossible except during periods of slack water. Strong tidal streams are a hazard when ships are manoeuvring in restricted waterways, but assessment of the level of risk associated with a tidal stream is complicated because it depends on the nature of the area in which the ship is being manoeuvred, the existence of dangers, the width of navigable channels, the ship's manoeuvring characteristics and the knowledge and skill of the mariner. If all such factors could be considered constant, the level of hazard could be related to the rate of tidal stream as illustrated in Figure 4.7.4.

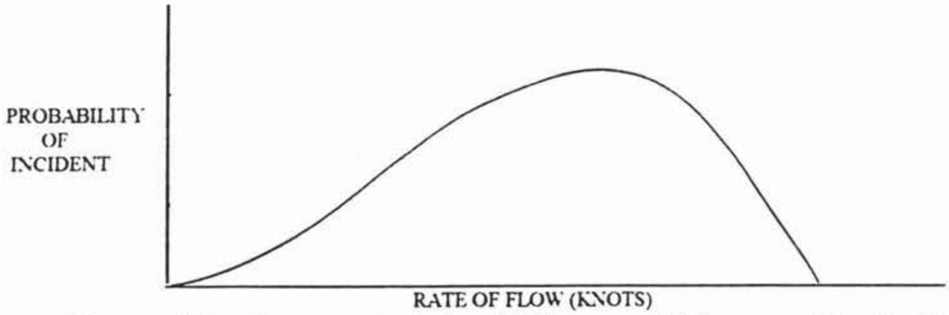


Figure 4.7.4 Suggested relationship between tidal rate and level of hazard.

In Figure 4.7.4 at zero rate there is no danger associated with tidal stream. As rate increases the level of hazard increases as the square of rate, in proportion to the energy imparted to the ship by the movement of water. There are other considerations besides energy, a small tidal stream could be helpful when berthing a ship, but opposing this there is some loss of position certainty. As rate increases, the mariner becomes more cautious and takes additional precautions such as using tugs to assist with berthing. Eventually the rate reaches a level that manoeuvring is too dangerous and the ship is obliged to wait until the time of slack water. Data to support the suggested relationship could be obtained from trials in a ship handling simulator, and conceptual relationship of this type may be presently used by port authorities to set limiting conditions under which ships may enter or leave harbour.

Fog, mist and rain

Monthly routing charts provide information about the probability of fog and reduced visibility over the oceans, but the incidence of restricted visibility is extremely variable and local area weather forecasts are necessary when there is a likelihood of fog. Restricted visibility increases the risk of collisions and groundings, and marine qualifications include a study of methods for predicting fog. In ships that are not fitted with an electronic navigation system, restricted visibility makes navigation difficult, especially when approaching land. However the main danger in restricted visibility is from other vessels, and the increased likelihood of collision in areas with high levels of vessel traffic.

Vessel traffic

There is no comprehensive source of information for the probable levels of vessel traffic that may be encountered on a passage from one port to another. Since collisions with other ships account for about 20 percent of ship losses, the level of vessel traffic is a significant variable in an assessment of ship safety. Vessel traffic includes all craft using navigable waters, including commercial ships, ferries, fishing boats, pleasure craft, military ships and a variety of miscellaneous craft such as dredgers, barges, supply ships, incinerator ships and research vessels.

The concentration of vessel traffic is extremely variable. A ship crossing an ocean may go for several days without sighting another ship. On approaching the coasts of industrial countries many large merchant ships will be sighted at all times of year, large numbers of fishing boats may be encountered, either engaged in fishing or travelling to or from fishing grounds. During summer months and particularly at weekends there will be yachts and pleasure boats cruising or racing. The movement of these vessels is largely uncoordinated and various attempts to measure vessel traffic levels have met with difficulty. The most successful traffic surveillance studies are those carried out for a particular locality such as the approaches to a major port where the arrivals and departures of commercial ships are well established and visual or radar surveys can be conducted to count the number of craft in the area. Extensive studies have been carried out in European and Japanese waters, but even in those areas there is little quantitative information available to the mariner or for use in a model of ship safety.

Apart from variation in numbers there is a great variation in the size of vessels. The level of risk to a medium size ship on encountering a 300,000 tonne tanker is greater than that associated with a small cargo ship, a fishing boat or yacht. Therefore the number of vessels in a unit of sea area is not useful without some qualification about size and type. Attempts have been made to weight vessels according to size, waterplane area, and by other subjective criteria (Easams, 1977) but there are difficulties in establishing suitable weightings, one being that different parameters are used to indicate vessel size; gross tonnage, deadweight, displacement, container capacity and length are quoted for various types of ships. Mass and volume are not suitable indices for vessel traffic units as can be seen by comparing the risk involved when approaching an area of say 100 square miles occupied by a single 100,000 tonne ship or one hundred 1000 tonne ships.

Fuji (1979) analysed traffic flows in the approaches to major Japanese ports in a study to determine the capacity of fairways. He found that when all ships involved in collision were counted, the risk of collision per trip is about proportional to the number of ships in a channel multiplied by their lengths. When risk of collisions is measured per ship-year, or when ships suffering only slight damage are excluded, the size dependency is not so simple. Fuji and other researchers have explored a concept of ship domains which are the areas surrounding ships into which each navigator would attempt to prevent other ships from entering. Estimates indicate that the area is oval, extending 6.4 ship lengths forward of a ship and 1.6 ship lengths astern and to each side, with area $6.4.\pi.L^2$. This implies that channel capacity is inversely proportional to the square of ship length.

Traffic lanes and separation zones have been established in many areas of high traffic density. In studies carried out by the University of Hamburg, Kwik (1979) developed a mathematical model to evaluate the collision rate for individual ships. The model was applied to traffic densities and distributions of speed, course and passing distances determined by traffic surveillance in the Dover Strait. Kwik calculated the collision rate to vary in near linear proportion to the ratio of ships' turning circles. The rate also depended on speeds, with a minimum collision rate at about 19 knots, and increasing for speeds slower and faster than 19 knots. He found that if all ships used the traffic routing system the collision rate reduced to approximately half the rate without routing. If it is assumed that the radius of the turning circle is proportional to ship's length, the risk of collision would be in proportion to the length of vessels involved, which agrees with Fuji's (1979) observations.

Although vessel traffic data on a world-wide scale is not available, there seems no reason why traffic information for particular routes could not be gathered, given co-operation from shipping companies and watch-keeping officers. Surveys could request ships' officers to record the numbers of vessels observed during a passage; arrival and departure information is available from port authorities, and a series of observations could be made in port approaches. In the computer model described in Chapter 5 of this study, the traffic index used is based on the number of ships which enter a circle of fixed radius centred on the ship, during each day of a sea passage.

4.8 Propulsion, steering and auxiliary machinery

A modern ship is totally dependent on its machinery for propulsion and steering. Other machinery important to ship safety are electrical generators, boilers, bilge or ballast pumps and fire pumps. The efficiency and reliability of such machinery is essential to safety, and an investigation by a team of shipping industry experts found that machinery related problems had contributed to 30 percent of tanker losses during the years 1976 to 1994. The team observed that complexity, with the existence of a large number of critical components, was significant to the vulnerability of propulsion machinery (Marine Engineers Review, April 1995, page 12).

Propulsion machinery accounts for about 20 percent of the initial cost of a ship, and the outlay on fuel is about 20 percent of voyage costs. In a competitive market, the ship owner will balance the total cost of propelling a ship with the efficiency and reliability of the method of propulsion. Early steam ships were driven by reciprocating engines powered by coal-fired boilers. Coal was replaced by oil, and reciprocating engines by steam turbines which were reliable, but not as efficient for manoeuvring as reciprocating engines. Steam plant is efficient for high power output, and some large tankers and large, fast container ships are fitted with steam turbines. As diesel engines became more economical and reliable, they displaced steam, and at present most merchant ships are powered by single slow-speed diesel engines.

Slow-speed diesel engines are reasonably reliable, and are economical to install and operate. The engines use low grade bunker fuel for sea passages, and diesel oil which is more expensive and less viscous while manoeuvring. A disadvantage compared with higher-rated medium-speed diesel engines is that the larger components are more difficult to handle during maintenance and repairs. The slow-speed engines are more reliable, and involve less moving parts and fuel pipes, but redundancy can be achieved by installing more than one of the smaller medium-speed engines (McGovern, 1978).

A high degree of reliability is essential when a ship is fitted with a single engine which drives a single screw, as the failure of one component may lead to total loss of propulsion. Most ships have the capability to carry out engine repairs, and an engine breakdown at sea need not lead to further consequences. In bad weather, near the coast, in heavy vessel traffic or when manoeuvring in port, a failure of the propulsion system can lead to an accident and even the loss of a ship. In January 1993, the tanker MV Braer grounded on the coast of the Shetland Islands, and was lost as a direct result of failure of the propulsion system.

Manufacturers supply a wide range of diesel engines, and the selection of an engine to suit particular needs involves the consideration of initial cost, fuel consumption, size, maximum and continuous output, familiarity of staff with particular makes and types of engines, and the availability of technical assistance and spare parts. An engine is expected to last for the life of a ship, and during that period of 20 to 25 years there will be developments which could make the initial choice less than ideal. An engine is dependent on its associated systems for the supply of fuel, cooling water, lubrication, starting air and control. The inclusion of these systems means that there is a great deal of diversity between the plant layout in different ships. When the different conditions of service encountered by ships is taken into account it may be extremely difficult to evaluate the level of reliability associated with the propulsion plant of a particular ship. However, the general principle for determining the reliability of engineering systems is well established.

Figure 4.8.1 is a simplified block diagram of the systems associated with ships' propulsion machinery. The operation of the main engine is dependent on the operation of each of the

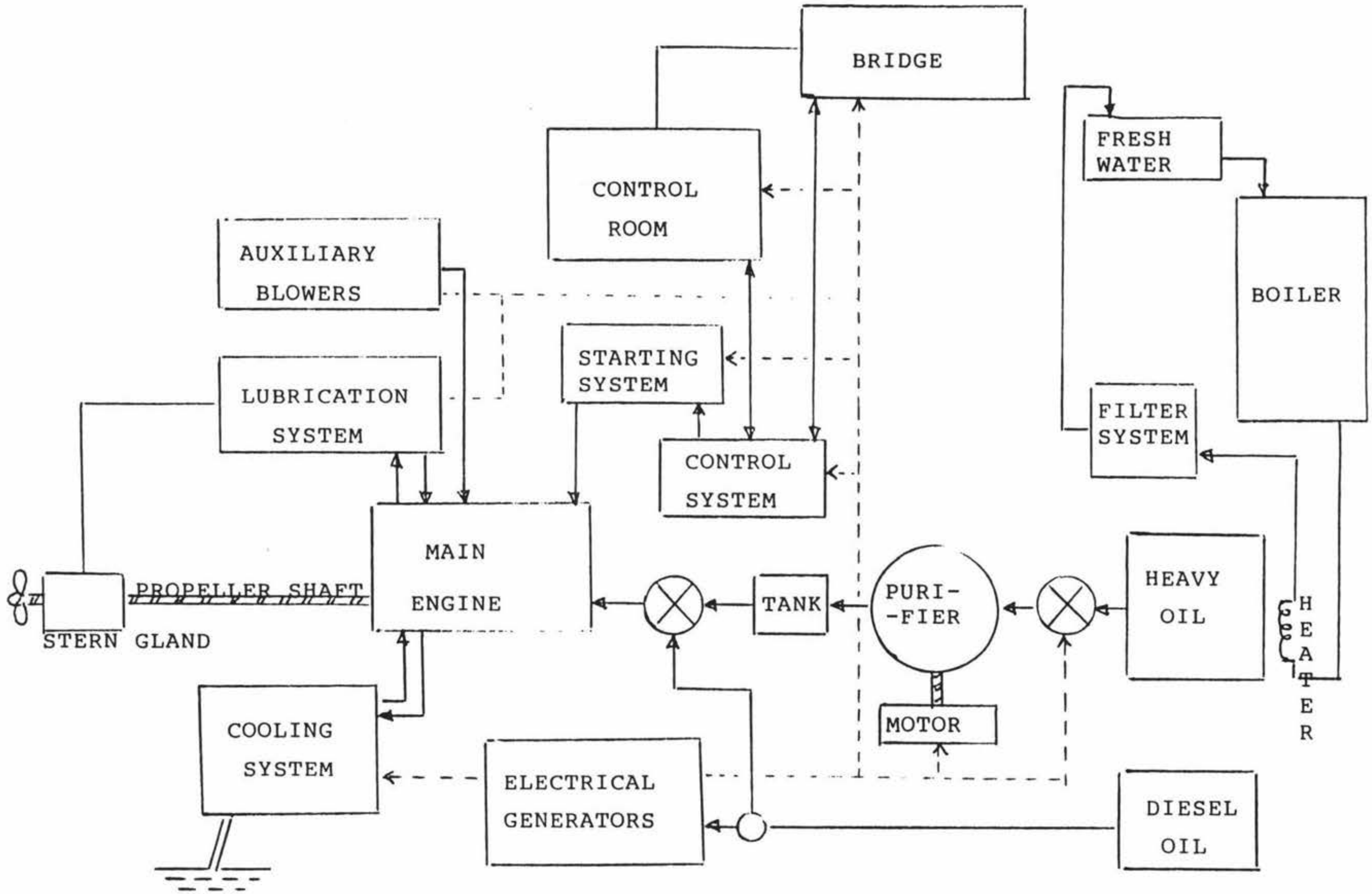


Figure 4.8.1 Main engine and associated systems

associated systems, and most of these systems incorporate some redundancy. For example, the starting system may consist of two motor driven compressors supplying air to two air reservoirs. Since each compressor can feed both reservoirs, and either reservoir can provide enough air to start the main engine about ten times, the failure of one compressor, reservoir or pipeline will not prevent the engine from being started. The consequence of failure of electrical power is such that a ship may have three generators in parallel, and an emergency generator located outside the engine room. Some components of a system may not be duplicated, for instance only one boiler may be fitted, so if it fails an alternative means of heating heavy fuel is required, or the engine may run on diesel oil for a length of time determined by the quantity of diesel carried.

Because of the dependency of the main engine on all systems being operational, Figure 4.8.1 may be simplified further to show dependent systems in series and duplicated subsystems in parallel. Using a layout such as that in Figure 4.8.1, a probabilistic method can be used to determine the reliability of the propulsion system for a ship.

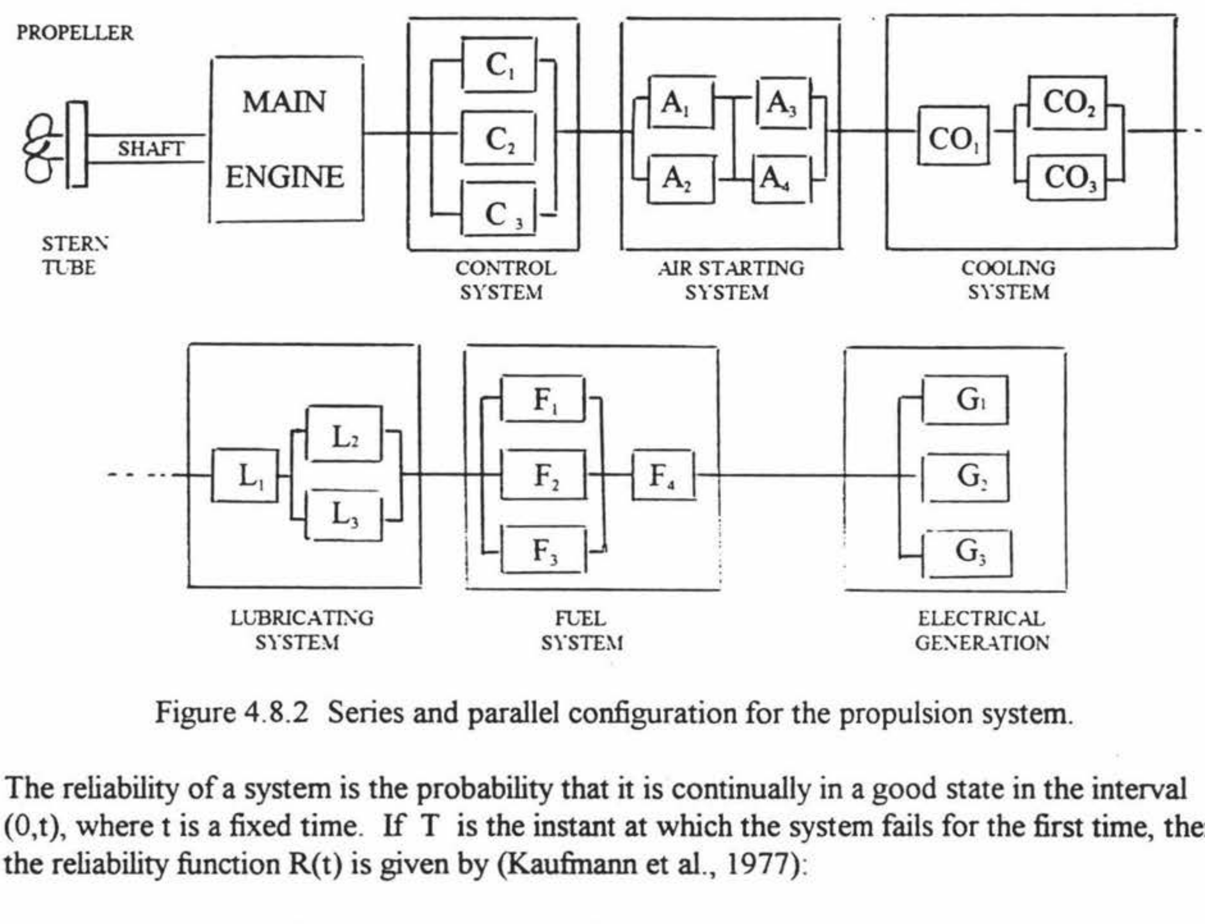


Figure 4.8.2 Series and parallel configuration for the propulsion system.

The reliability of a system is the probability that it is continually in a good state in the interval (0,t), where t is a fixed time. If T is the instant at which the system fails for the first time, then the reliability function R(t) is given by (Kaufmann et al., 1977):

$$R(t) = pr\{ T > t \}$$

In engineering applications, an exponential reliability function is assumed, so that

$$R(t) = \exp(-\lambda.t)$$

where λ is the failure rate of the system, which may be related to the mean time between failures (MTBF)

$$\lambda = 1 / MTBF$$

In series configurations, the reliability of the total system is found by multiplying reliabilities of the sub-systems:

$$R(t) = R_1(t) \cdot R_2(t) \ldots R_n(t) = \exp(-\lambda \cdot t)$$

$$\lambda = \lambda_1 + \lambda_2 + \ldots + \lambda_n$$

For redundancy, where systems are duplicated or in parallel configuration, system reliability is the probability that all components in parallel do not fail during the defined time interval t. If R(t) is the probability that a system will not fail during t then the probability of failure is 1 - R(t).

The probability that two systems will fail during t is therefore

$$(1 - R_1(t)) \times (1 - R_2(t))$$

and the reliability of the total system is

$$1 - (1 - R_1(t)) \times (1 - R_2(t))$$

$$= R_1(t) + R_2(t) + R_1(t) \times R_2(t)$$

The reliability of two identical systems giving 100 percent redundancy is

$$R(t) = 2 \cdot R_1(t) - R_1^2(t)$$

$$= 2 \cdot \exp(-\lambda_1 \cdot t) - \exp(-2 \cdot \lambda_1 \cdot t)$$

i.e. total reliability is less than twice the reliability of each system on its own. Similarly, the reliability of a system with n systems in parallel can be calculated using the binomial theorem:

$$R(t) = n.R_1(t) - \frac{n.(n-1)}{2!} \cdot R_1^2(t) + \frac{n.(n-1).(n-2)}{3!} \cdot R_1^3(t) - \ldots$$

Thus if the reliability of each sub-system in the main propulsion system is known, the total reliability of the system can be determined.

The probabilistic approach may be developed to analyse the consequences of engine failure. Whether engine failure leads to further consequences, including the possibility of the ship becoming a total loss, depends on where the ship is and the conditions that exist at the time of the failure. It is assumed that MTBF applies to operating time only, and time when the main engine is not in use (such as when a ship is alongside a berth or at anchor) is excluded.

Suppose that the total system has a MTBF of 5000 hours, and that the average utilisation of the main engine is 0.6, then the reliability of the propulsion system over a period of one month is for 432 operating hours:

$$R(432) = \exp(-432/5000) = 0.917$$

Thus the probability of a total system failure during the month is 0.083.

Three stages of a voyage are considered; suppose that a ship is:

- manoeuvring in confined waters for 0.02 of the time (8.6 hours)
- navigating near the coast or in vessel traffic for 0.15 of the time (64.8 hours)
- well clear of land and dangers for the remaining 0.83 of the time (358.6 hours)

Then the probability of a failure occurring during each of these phases can be calculated

PHASE	HOURS	P (failure)
confined waters	8.6	.002
coastal waters	64.8	.013
open waters	358.6	.069

This initial approach relates probabilities only to time at risk, and does not take into account other factors dependent on the stage of voyage that influence the probability of failure. For instance, after a long ocean crossing the fuel supply is changed from heavy to diesel oil, so that there is a change in the conditions of operation that may lead to a failure. While in port, machinery may be overhauled, possibly increasing the reliability of the propulsion system, or alternatively, if the overhaul was not carried out correctly there may be a decrease in reliability at a critical time. Such influences are subtle and complex, and their probabilities could only be estimated after a close examination of total system reliability for a large range of service conditions.

Supposing that the probability of failure in each stage of a voyage has been estimated, the next step is to relate failure to the probability of consequential damage or loss. Whether a ship is damaged or lost as a result of engine failure depends on the proximity of hazards, environmental conditions, the ability of mariners to handle the ship, and the availability of assistance and tugs.

The most straightforward situation is in open waters, where the only significant danger is from bad weather. A ship without propulsion is difficult to control in heavy seas, and although there are measures such as rigging drogues or sea anchors such procedures are difficult, and possibly ineffective and dangerous in large ships which may not have suitable materials at hand. It is reasonable to assume that for a given ship the likelihood of foundering increases with the severity of wind and waves. Figure 4.8.3 shows a family of curves for the probability of foundering in ships of different size and type. The frequency spectrum for sea state in the area and month is also shown by the dotted curve, and the probability of foundering (P_f) is the product of the curve p_g for the ship and p_s for the sea state.

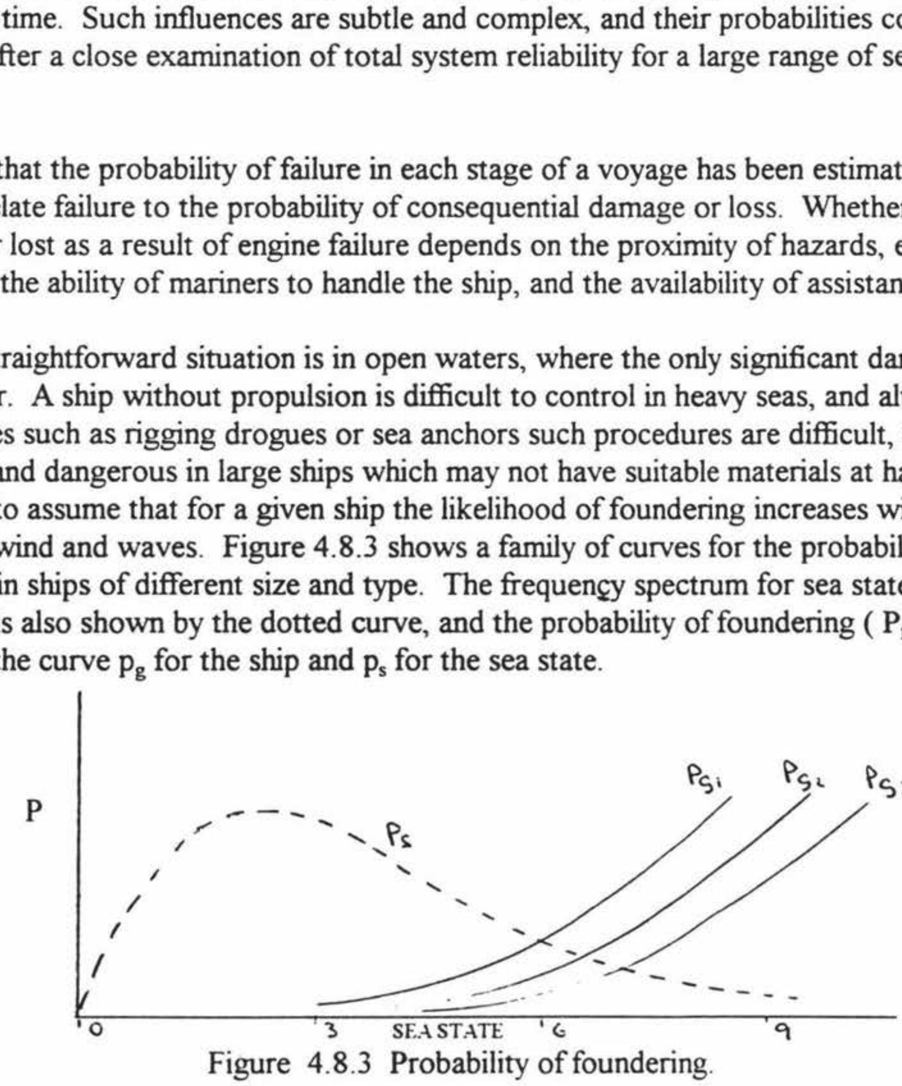


Figure 4.8.3 Probability of foundering.

$$P_f = \int_{\text{SEA STATES}} p_g \cdot p_s \, .dS$$

The sea states associated with the total loss of a ship are at the open tail end of the spectrum where observations are increasingly rare. Data on which to base the family of curves for p are also difficult to obtain as the causes of many incidents where ships may have foundered is not known (Bishop and Price, 1991).

A propulsion machinery failure can be more hazardous for ships in coastal waters and operating in heavy vessel traffic. Weather conditions and the length of time necessary for repairs are highly significant, but other factors such as currents, tidal streams, the proximity of dangers, and whether the sea bed will enable anchors to hold are also involved. Tugs, rescue services or the assistance of other vessels may or may not be available, depending on the location and time of the incident.

In confined waters the consequence of propulsion failure can be immediate. The demands on the system are also higher, with the necessity for frequent starting and stopping, and the inability to stop engines through a fault in the control system can be even more dangerous than loss of propulsion. Because of the extreme variability of the situation in which a ship may find itself after failure of the propulsion system, it is unlikely that probability distributions of the type shown in Figure 4.8.3 could be meaningful in either the coastal or confined waters situation. A direct approach such as simply weighting the probabilities of system failure to reflect the relative risks in the different stages of a voyage may be more appropriate.

Ship safety is also dependent on the reliability of the steering system and auxiliary machinery. Although most ships have a single rudder, hydraulic control machinery is very reliable, and it is usual for steering motors and control systems to incorporate redundancy. Usually there are three electrical generators and at least three general service pumps that can be used for bilge or fire pumping. An emergency generator and fire pump are located outside the main machinery space so that they can be used in the event of an engine room fire. The reliability of such machinery depends very much on its regular operation and maintenance, and on the quality of organisational and human involvement; these topics are discussed in Sections 4.9 to 4.13.

4.9 Fire safety

About twenty percent of ship losses are the consequence of fires and explosions. The proportion of ships that suffer damage from fires is probably much higher, and an observation made in the UK Department of Trade study of human elements in shipping casualties is that the fire fighting responses of ships' crews is generally successful (DOT, 1991). Fire casualties occur at sea and in port, with a significant number on ships undergoing repairs. There is a variety of causes, from human carelessness to instances of ships being struck by lightning as happened to the tankers Princess Irene and the Kriti Sun (Cashman, 1977). An analysis of fires on ships in New Zealand ports showed that the main causes were (New Zealand Marine Notices A 16):

- Burning and welding
- Smoking
- Accidental ignition of oil or fat spillage
- Faulty or misused electrical equipment
- Inflammable cargoes

Measures to minimise the risk and consequence of fire are necessary at all stages in the life cycle of a ship. Responsibility for the fire safety of a ship is shared by designers, builders, ship management and mariners. Standards for fire safety contained in national ship construction and fire appliances regulations have been upgraded several times to take account of new technology, new hazards and the requirements of the international safety conventions. The general principles behind the fire safety standards set out in the International Convention for the Safety of Life at Sea 1974, applicable to ships constructed after 1 July 1986 are (IMO, 1992 a):

.1 division of ship into main vertical zones by thermal and structural boundaries;
.2 separation of accommodation spaces fom the remainder of the ship by thermal and structural boundaries;
.3 restricted use of combustible materials;
.4 detection of any fire in the zone of origin;
.5 containment and extinction of any fire in the space of origin;
.6 protection of means of escape or access for fire fighting;
.7 ready availability of fire-extinguishing appliances;
.8 minimisation of possibility of ignition of flammable cargo vapour.

The degree to which each of these principles is observed in a particular ship depends on the type of ship and the potential fire hazard involved. Stringent adherence to all possible fire safety precautions is necessary in tankers and gas carriers where the potential hazard is extremely high. Passenger ships have extensive accommodation spaces with furnishings, ventilation and service ducts, and the comfort and privacy of passengers imposes constraints. Passenger ships are divided into zones by fire-retarding bulkheads, and are fitted with fire detectors, alarms and sprinklers. Roll-on-roll-off cargo ships carry vehicles with petrol in their tanks and are fitted with fire detectors and high volume sprinkler systems in the cargo decks. General cargo ships and bulk carriers carry a wide variety of cargo and the fire characteristics of specific cargoes carried may not be known at the design stage. From time to time, new cargoes with previously unknown hazards evolve with changing trade patterns and technology (Bolton Maritime Management Ltd, 1983).

A naval architect has to consider the intrinsic fire safety of a ship being designed. Non-combustible material should be used whenever possible, that is material that will not burn nor give off sufficient flammable vapour for self-ignition when heated to approximately 750° C. Fire-retarding bulkheads and doors must be capable of passing standard fire tests in which heat is applied to one side, and the rise in temperature over time is monitored on the other. Design must take account of the location of heat and ignition sources, such as engines, generators, boilers and electrical equipment in relation to fuel tanks and piping. There must be means of escape from compartments in which fire can break out, and means of closing ventilation from positions outside each compartment. Lack of attention to detail at the design stage can lead to potential fire hazards that remain for the entire life of a ship.

Attention to detail is also necessary during construction. Materials must be as specified in the plans, the quality of welds for fuel tanks and pipes, and the standard of electrical wiring, must be acceptable. Commercial ships are built under supervision of a classification society surveyor, and extensive testing of bulkheads, tanks, closing devices and machinery is carried out during and after building. The fire safety properties of paints, adhesives and surface facings are important as the wrong surface materials can promote the rapid spread of fire.

Ships' fire appliances include detectors, alarms, fixed installations such as pumps, hydrants and gas or foam smothering systems, and portable equipment such as fire extinguishers, firemen's outfits and breathing apparatus. There are also means of shutting off fuel to machinery from a remote location, and of closing ventilators to reduce the supply of air in the event of fire. Such devices require regular use and servicing. A damp, salt-laden atmosphere promotes corrosion and, without regular attention, fire dampers become seized, small apertures blocked and metal fittings corroded. Equipment is checked during statutory safety equipment surveys, but it is the responsibility of management and the ship's master to ensure that fire appliances are serviceable and ready for immediate use.

As well as maintaining fire appliances, ships' crews should be familiar with the location and use of equipment. Fire drills conducted at regular intervals should produce familiarity with the systems and training in their use. Shipboard training is complemented by fire-fighting courses held ashore which use replicas of parts of a ship so that the problem of fighting a ship fire can be simulated. A particularly important aspect of fighting a fire is the organisation of personnel. Fires that may have been controlled have resulted in total losses through poor co-ordination and inefficient use of personnel and equipment, and shipboard emergency plans need to be rehearsed during drills (Bayley, 1977).

A number of shipboard fires have been attributed to careless habits; smoking in bed, placing cargo lights or heaters near combustible material, and insufficient care with heat sources such as galley ranges and welding equipment. A high level of awareness of fire hazards is necessary amongst mariners, and constant vigilance is required at sea and in port when stevedores and repair personnel are on board. Many ships carry out regular fire patrols, and the crews of tankers and passenger ships are usually very aware of the dangers. But the consequences of lapses in vigilance are great, and shipboard fire remains a significant hazard.

Modelling fire safety

From the above account it is apparent that fire safety is the outcome of a complex process, with many variables, that are not easy to model. Action to reduce the likelihood of fire in a ship includes careful design, building, management and operations, with involvement at all levels. The UK Department of Trade study of the human element in shipping casualties suggests that a chain model is an appropriate description of fire safety (DOT, 1991). Figure 4.9.1 illustrates a set of relationships that could provide the basis of a chain model of fire safety.

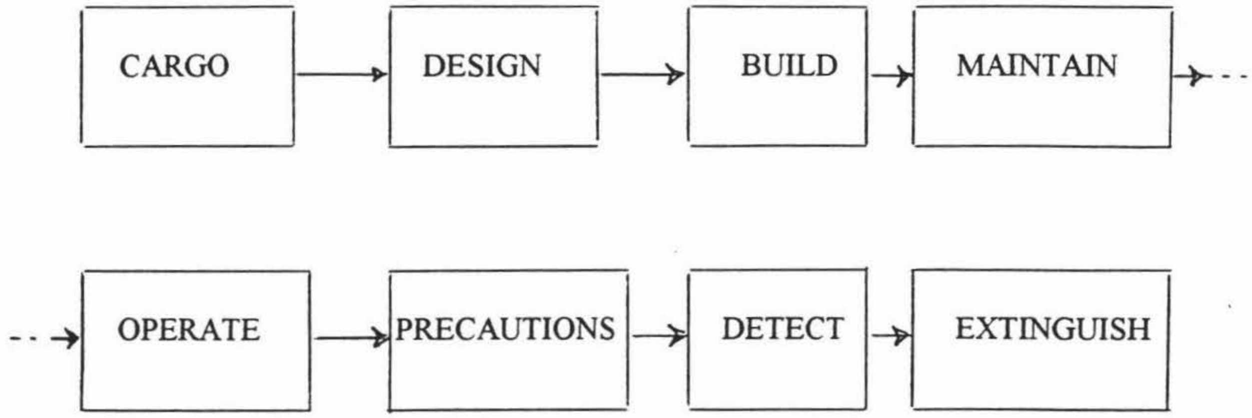


Figure 4.9.1 Chain model of fire safety.

A ship is designed to carry a range of cargoes, and although the designer may lack full knowledge of cargoes that will be carried over the ship's life, assumptions must be made about fire risk characteristics of the cargo. The cargo, fuel and combustible material in a ship are potential fire hazards that may be characterised by their ignition temperatures and calorific values.

Heat and oxygen are necessary for combustion, and part of the designer's task is to isolate heat and ignition sources from combustible materials. Design is a complex intellectual process that involves knowledge of principles and technical ability as well as creativity. It is therefore likely that any determination of the intrinsic fire safety of a ship will have a subjective element. Assessment using a fire model based on probabilities of ignition and the speed at which a fire will spread to compartments containing flammable substances could be used, and the vulnerability of a range of designs could be compared.

The quality of building, fitting-out and maintenance are determined by the design, personnel carrying out the work and those supervising or controlling quality. Maintenance, routine operation of fire appliances, the general fire safety awareness and precautions taken are closely related and very much dependent on the organisation and manning of the ship. Variability of all these factors makes a reliable evaluation of total fire risk using the chain model unlikely, and it may be necessary to limit consideration to a less ambitious model based on the rate at which fire may spread and the level of risk involved.

Figure 4.9.2 is a hypothetical relationship of the severity of fire as a function of time. Fire starts at time $t = 0$ and spreads away from the source of ignition. If the fire spreads in three dimensions the severity of fire, as determined by the volume of burning material, increases as the cube of time; similarly a two-dimensional spread increases in severity with time squared. It is assumed that unrestricted spread may be between these values, and $f(t^2)$ and $f(t^3)$ are assumed lower and upper bounds for the severity of fires. Maximum severity is limited by the amount of combustible material. The horizontal lines E_1, E_2, E_3 represent the effectiveness of various fire appliances, for example E_1 could represent a portable fire extinguisher, E_2 a mobile foam unit and E_3 a total flooding system. The figure illustrates the consequence of delay in using fire appliances. Similarly the height of the horizontal line D represents the severity of a fire necessary to activate a fire detector, and the interval $t_{E3} - t_D$ is the maximum time available between detection and activating the E_3 level fire appliance in order to successfully extinguish a fire.

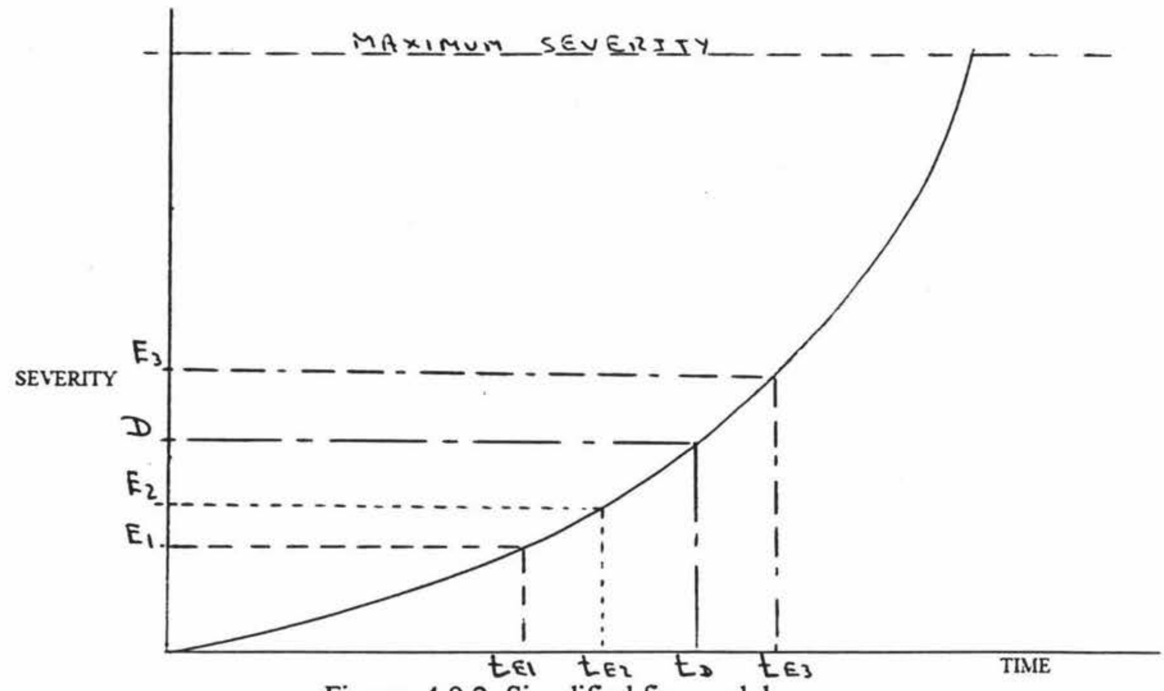


Figure 4.9.2 Simplified fire model.

Figure 4.9.3 shows developments of the simplified fire model The horizontal line at height B represents a fire barrier such as a fire-retarding bulkhead which has a delaying effect on the spread of fire. Vertical line T represents a catastrophic event, such as the sudden failure of a fire barrier, or the breach of a fuel tank resulting in an explosion. A model of this type can be developed for each likely ignition source in a ship using existing records of fires. Given an estimate of the probability of a fire starting at each source, an indication of the total fire hazard in a ship could be derived and used in a mathematical model of ship safety.

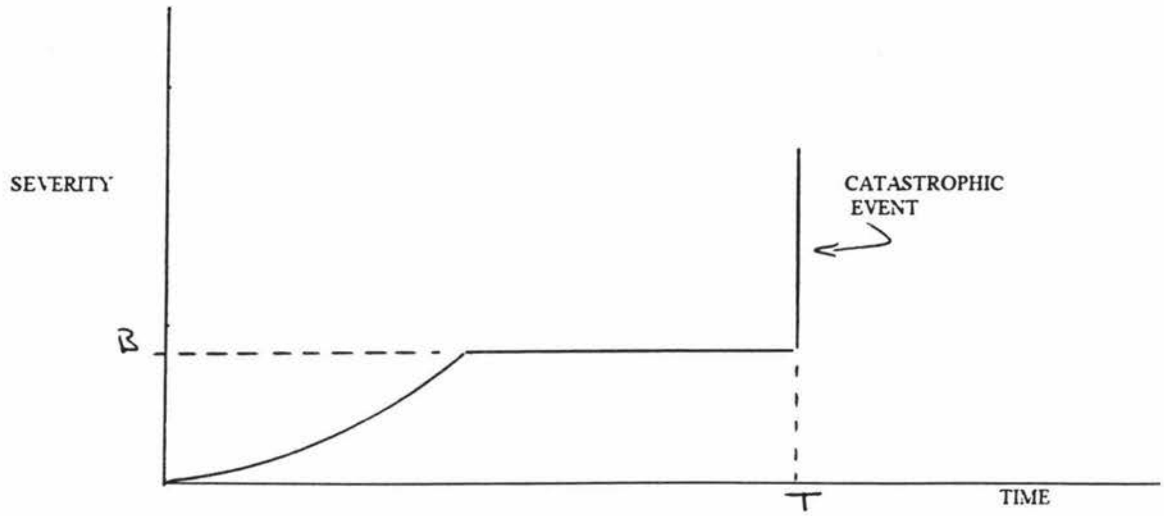


Figure 4.9.3 Elements of a fire model.

4.10 Ship operations

Ship operations are the processes necessary for a ship to carry out its commercial function. For a cargo ship this includes:

- preparation to receive cargo
- loading
- preparation for a sea passage
- unberthing and departure from port
- navigating the ship from one port to the next
- arrival and docking
- preparation for cargo unloading
- discharge

This chapter examines the relationship between routine ship operations and safety.

Cargo work
The routine preparation before loading includes a thorough inspection of cargo holds while they are empty. After loading commences, access to parts of the holds will be restricted if not impossible, and it is necessary to carry out all safety checks and tests between the completion of discharge of one cargo and the start of loading for the next. Items affecting ship safety that are checked and, where appropriate tested, include the internal structure which could have been damaged by cargo handling equipment, bilge wells, bilge suctions, sounding pipes, access covers, cargo temperature sensors, smoke detectors, fire extinguishing systems, overboard discharge pipes and storm valves (Isbester, 1993). There is often limited time to carry out such safety checks together with hold cleaning and maintenance, and this is a critical period in the trade-off between safety and commercial considerations.

The detailed information required to plan the stowage of cargo depends on the type of commodities being carried, with relatively little information required for bulk or unitised cargo compared with a mixed cargo. Safety considerations when planning the cargo stow are:

- transverse and longitudinal stability during loading operations, on completion of loading and for the duration of the voyage
- stresses on the ship's structure and the maximum permissible loading of holds, tank tops and decks
- the maximum draught permissible as limited by load lines or depth of water in ports and approaches
- precautions to protect cargo from shifting
- if dangerous cargo is to be loaded, that precautions for their stowage and segregation are observed in accordance with the International Maritime Dangerous Goods Code.

For a ship on a regular service the preparation of a stowage plan may be straightforward, but when the master and deck officers are not familiar with the type of cargo or the practices of the loading and discharging ports, some research may be necessary. Lack of available information and advice can increase the level of uncertainty and hazard associated with loading a particular cargo.

When loading starts, deck officers monitor cargo operations to ensure the cargo is loaded according to plan. It may be necessary to transfer ballast to keep the ship upright and reduce excessive trim, and vigilance is necessary to ensure the ship's structure is not over-stressed and that there is sufficient stability. Since shore personnel are involved, ships' staff have to ensure against fires and accidents to persons visiting the ship.

At the same time preparations are made for the coming voyage. The ship must have adequate bunkers, fresh water and stores. Charts and nautical publications for the voyage are checked and brought up to date with the latest information available. The passage is planned and publications consulted for advice on routes, dangers, climate and legal considerations. There is often pressure to minimise the time a ship spends on port and as already mentioned in the context of pre-loading checks, hurried or inadequate planning and preparation can reduce the level of safety.

When loading is complete, cargo lashed if appropriate, hatches secured, cranes stowed, documentation completed, crew on board, visitors ashore and engines prepared, the ship will be ready for departure. A pilot and tugs may be used for the passage from the berth until the ship is in open waters, and then the sea passage begins.

Navigation

For generalisation the sea passage is divided into three phases: port approaches, coastal waters and the ocean passage. Boundaries between phases are arbitrary, but the division is based on the proximity to danger, probable traffic levels and the degree of accuracy and responsiveness necessary for safety. In port approaches the bridge will be manned by the master, a deck officer, possibly a pilot, helmsman and lookout; engines will be operating at manoeuvring speed and ready for immediate movements. In coastal waters the deck officer will be on watch, assisted by a seaman, and the master will normally monitor progress but may not be on the bridge continuously; engines would be on full sea speed and a duty engineer would be available. For the ocean passage the deck officer would man the bridge, with a seaman available on call, the master would visit the bridge less frequently and, in ships with unattended machinery space classification, the engineer would attend to routine maintenance of auxiliaries.

Navigation equipment is prescribed by flag states in accordance with the requirements of the International Convention for the Safety of Life at Sea 1974 and its protocols (IMO, 1992 a). Requirements are based on gross tonnage and the date on which ship building commenced. For ships of gross tonnage more than 1600 the basic requirements are:

- magnetic and gyro compasses
- radars (two for ships of gross tonnage 10000 and over)
- echo sounder
- speed log
- radio direction finder

Ships trading on international voyages require instruments and publications for navigation by celestial observations, but at present an electronic position finding system is not mandatory. There are economic as well as safety-related benefits of a reliable navigation system; the traditional method for ocean navigation is to take sextant altitudes of celestial bodies and calculate a point on a position line which is plotted on a navigational chart. The method has been used successfully for many years, but does have limitations. During the day a single position is determined from observation of the sun, and the method of finding position by transferred position lines requires an accurate estimate of the ship's movement relative to the terrestrial frame of reference. Multiple position lines from star sights are available for only a short interval before sun rise and after sun set when both stars and a clear horizon are visible.

Clear sky and distinct horizons are chance events so that in some parts of the world the probability of obtaining an accurate position when needed is very low.

Since the invention of radio there has been a number of radio-based methods of position finding. The earlier primitive methods of Consol and radio direction-finding were superseded by increasingly sophisticated terrestrial hyperbolic navigation systems which gave good accuracy in certain areas of the world. The Transit satellite navigation system gives accurate positions on a worldwide basis but with a varying interval between successive positions. The more recent satellite system which became available during the early nineties is referred to as the global positioning system (GPS) and provides continuous accurate positional information in all parts of the world. The accuracy, high availability and low user cost of GPS has resulted in it being fitted in the majority of commercial ships and many smaller commercial and pleasure boats. The price of a GPS is comparable with that of a good sextant.

Ships that are not fitted with GPS or navigation system for the area of operation rely on sextant observations to reach the landfall position. The limited availability of positional information and uncertainties introduced by wind and currents makes the first sighting of land after a long passage into a significant event for navigators. The possibility of fog can turn landfall into a hazardous stage of any voyage, and it is the transition between position-finding on a global frame of reference and navigation relative to land. After sighting and identifying prominent marks such as lighthouses or headlands, the coastal passage begins and the ship's position is found by visual bearings or radar observations of marks that have been identified.

All methods of navigation are subject to errors, and the accuracy of a position line by celestial observation depends on the sextant, chronometer and skill of the observer. In good conditions a skilled observer may determine position lines with an error having a standard deviation of about one mile, but errors of several miles can be expected in less than ideal conditions. Without explicit information about the error associated with a particular observation it is considered good practice to obtain at least three position lines whenever possible to determine a ship's position. Intersection of position lines close to a point provides a check against blunders; the type of fix shown in Figure 4.10.1 (A) would give the navigator confidence in the accuracy of the position.

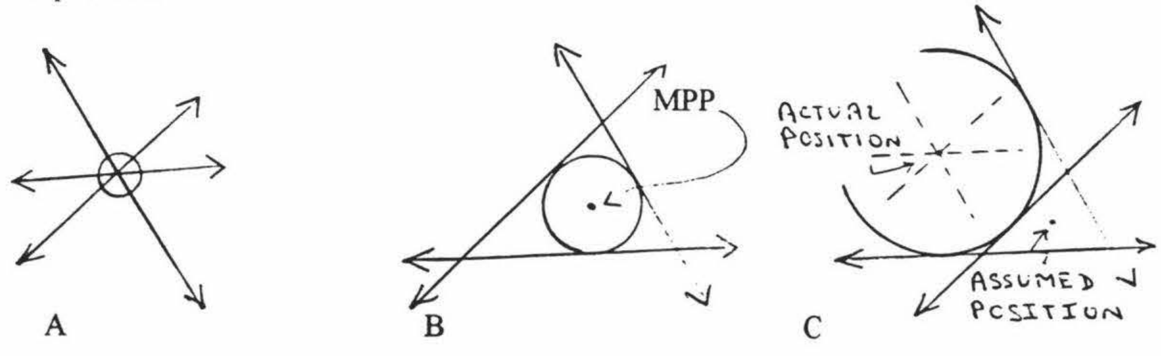


Figure 4.10.1 Position given by three position lines.

When the position lines are affected by a random error, close intersection may not be obtained, and the most probable position (MPP) is taken as the centre of the triangle formed by the three lines as shown in Figure 4.10.1 (B). However when all position lines are affected by a constant error the MPP may not be inside the triangle, as shown in figure 4.10.1 (C). Visual bearings with an accurate gyro compass or properly adjusted magnetic compass provide adequate accuracy for coastal navigation, but in a moving ship a series of bearings with errors of less than a half degree can give positions that are error by half a mile. This is shown by an example in

Figure 4.10.2 in which a ship with speed 15 knots is 2 miles from the coast and observes marks that are 2 miles apart. An error is introduced by the ship's movement in the time between observations, but the intersection of position lines at a point gives a false impression of accuracy and the ship is closer to the shore than expected.

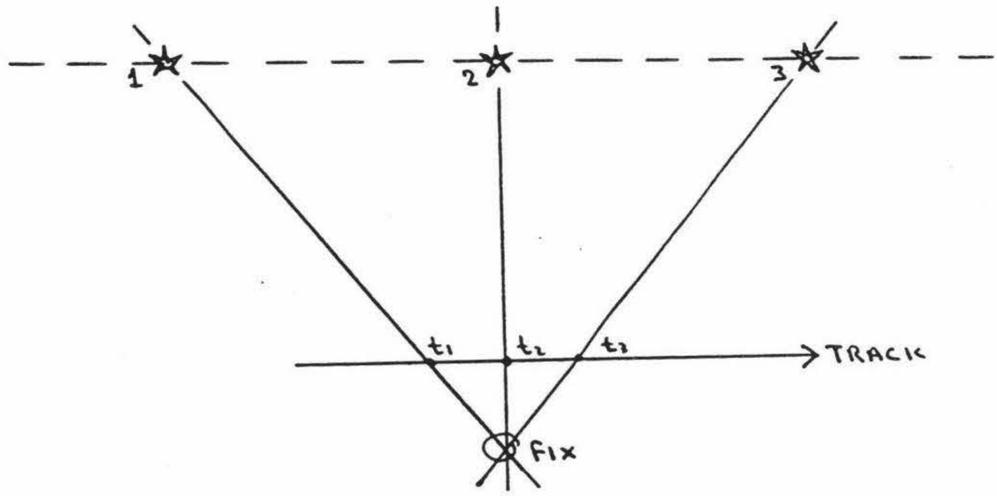


Figure 4.10.2 Error in a visual position observation.

Errors of the types indicated in Figures 4.10.1 and 4.10.2 are tolerated in coastal navigation by planning the route to give adequate clearance from danger. Another type of error is the mis-identification of navigational marks, and the consequences of such an error can be seen in Figure 4.10.3

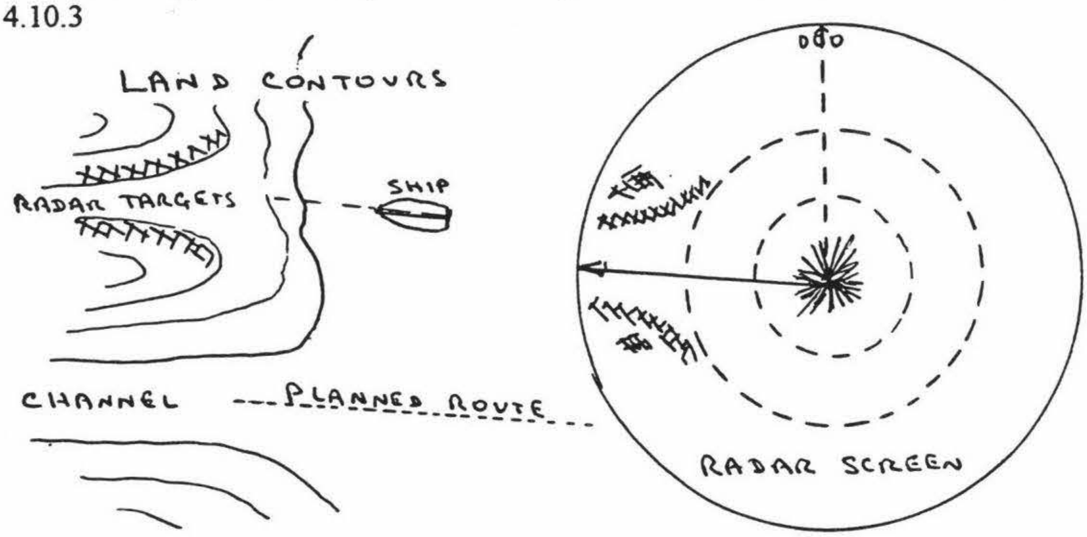


Figure 4.10.3 Error in identifying a navigation mark by radar.

The accuracy of a position-finding system should take into account both systematic and random errors, and the value of 2 standard deviations is usually given to provide an indication of the error that should be exceeded on not more than 5% of occasions. Typical static fix accuracy within the primary coverage of some radio navigational systems, in nautical miles are (Det Norske Veritas, 1991, page 24) :

Loran C 0.25 Decca 0.02 to 0.2 Transit 0.15 GPS 0.05

Positional errors quoted for GPS are well within the requirements of coastal navigation. The accuracy of GPS can be improved for a particular locality using a mode of operation called differential GPS in which a shore station in a known position receives GPS transmissions, and by comparing the known and observed positions calculates an error that is transmitted to ships in the vicinity. Claimed accuracy is in the order of 3 to 5 metres which makes the system adequate in confined waters. Thus GPS represents a single system capable of providing all the positional information required for a passage. However the following warning is given in a GPS operators manual: " WARNING: The Explorer GPS is only an aid to navigation and does not reduce the need for caution or judgement. No electronic navigation system is perfectly reliable; outputs may occasionally be incorrect. The prudent navigator should not rely solely on one device to the extent of endangering life or property."

In GPS, the mariners has a navigational system that is not only highly accurate and reliable, but is easy to use. Position is given directly as latitude and longitude, and adjustments for errors in the local reference points on which chart scales are based can be applied automatically. A ship's position, course and speed can be shown on an electronic chart display so that the navigators' function is that of decision-making, and they do not have to carry out the sometimes demanding tasks required to obtain positions by direct observation. But navigation by visual observation requires a minimum level of skill which is only maintained with regular practice, and the ease of using GPS removes much of the pressure to practise and improve such skills. This situation would leave a large ship with minimum standards of manning without an effective means of finding position in the event of a system failure, or if the US military department that provides the service closes the system down, either temporarily or permanently. Over reliance on GPS or any other navigational aid reduces ship safety as was evident in the grounding of the cruise liner *Royal Majesty* off Nantucket Island in June 1995 (Fairplay, 1995).

Modelling ship operations

Ship operations have immediate consequences for the commercial viability and safety of a ship. A ship's income is from freight received for cargo transported, and the freight received has to cover costs as well as the risk involved in loading, transportation and discharge of cargo. The hazards may be due to the nature of cargo, or the geographical extent of the voyage which determines the probability of storms, or of collision or grounding. The level of risk involved in a voyage cycle that involves loading in one port and a relatively long sea passage to discharge in another port, may be very different from one that involves a mixed cargo loaded at several ports for discharge also at a number of ports, with short coastal passages between. The latter type of voyage may involve the crew in a very heavy workload, with frequent port arrivals and departures, and the necessity to find compromise solutions for the stowage of cargo to maintain sufficient stability and trim with a part cargo on board.

Risk analysis methods may be appropriate for modelling operational safety. The probable frequency and severity of hazards could be based on experience of a trade, and on informed opinion where data is scarce. A model should take account of possible consequences of inadequate preparation for loading and for sea passages. When there is pressure exerted on mariners to complete such preparation without adequate time or resources, a knowledge of the relation between savings and probable losses could be of great value in commercial decision making.

4.11 Organisation

In shipping, as in every commercial activity, a level of organisation is necessary to set in motion and control the capital and manpower necessary to achieve a company's strategic goals. The organisation of a shipping company can be considered as two structures with very different characteristics and problems; there is the company organisation ashore involved with strategic and commercial goals, and the organisational structure on board each ship which is primarily concerned with the efficient operation of the ship. There is great diversity in shipping companies, from those that operate a single ship, to large commercial institutions with hundreds of vessels under their control. The commercial purpose of shipping companies differs; some are in business to make profit by providing shipping services, others own or charter ships to transport their own products, and still others own ships as assets to be traded for profit.

The pattern of ship-owning has changed dramatically. In 1900 the United Kingdom owned and operated nearly half the world's tonnage. The percentage of ships registered in Europe declined throughout the century, while the world's merchant fleet expanded. The establishment of open registers in countries that do not impose citizen qualifications on owners and offer tax advantages resulted in a massive increase in the fleets of these nations. At present the largest fleets are registered in Liberia and Panama although owned by USA, Greek and Japanese interests. The changing structure of international shipping has in many cases weakened the organisational links between the ownership and management of ships. The Rochdale Inquiry into shipping noted that "A ship may be beneficially owned in one country, directly owned by a company resident in another country, registered under the flag of a third country, managed by a company in a fourth country, be on a long-term charter to interests in a fifth country and even be sub-chartered to interests in yet another country" (Goss, 1977). Under such a situation the links between executives setting strategic goals and managers making operational decisions can be extremely tenuous.

Reason (1990) has analysed the relation between the flow of resources, information and motivating factors in complex systems. Figure 4.11.1 is his summary of the factors that contribute to fallible, high-level decision-making. He points out that the factors reinforcing production goals are much stronger than those reinforcing safety goals. The relationship is likely to be more unbalanced with an increase in the distance between ownership and management. In situations where organisational deficiencies lead to accidents, national authorities are limited in the action they can take against persons responsible for the conditions that brought about a situation and often punitive action can be taken only against a ship's master.

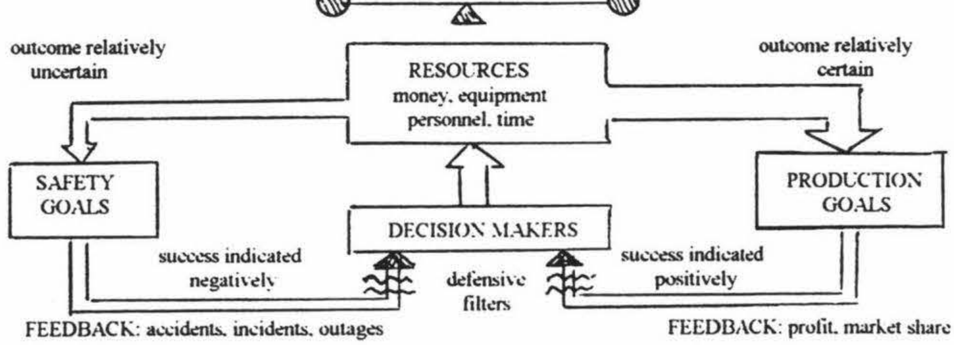


Figure 4.11.1 Factors contributing to decision making (after Reason, 1990).

Provided that a company has sufficient finance, there are few barriers to owning and operating a ship, and many entrants into the shipping industry have little experience in managing ships. At present there is no certificate of operator competency equivalent to that in the airline industry, but the International Maritime Organisation and other institutions that include ship-owners, classification societies, and protection and indemnity clubs have introduced safety management codes for ship operators. The codes recognise the need for commitment of senior management and for the establishment of a safety culture that encourages continuous improvement in safety. Companies using ship management codes have to define and document the responsibility, authority and interrelation of all personnel who manage, perform and verify work relating to safety (ICS and IFS, 1993).

While there is great diversity in the shore establishments of shipping companies, the hierarchical organisation on board ships has remained almost unchanged, apart from the reduction in numbers of personnel and the integration of some functions. Ships' masters are promoted from the deck department, having served as chief mate and deck watch-keeping officer. The master is legally responsible for the operation and safety of a ship, and communicates with the shore establishment through the company's superintendents or fleet manager. The organisational structure includes deck, engine and catering departments, though there are a number of schemes to integrate deck and engine departments, and some ships carry dual purpose officers and integrated ratings capable of carrying out deck and engine functions. Traditional functions are reinforced by statutory training and qualification requirements.

While the structure has remained virtually the same, the nature of seafarers' employment has changed. Large shipping companies recruited trainee officers as school leavers or from shore training schools, and a career was possible within a shipping company with many mariners spending their entire working lives in the employ of one company. Dynamic changes in the pattern of shipping has led to employment on a basis of short term contracts, often for one voyage. In many cases the entire crew of a ship is supplied by an agency and master and crew have no direct contact with the shipping company. If a company does not know the personnel it employs and the personnel know little or nothing about the company, there must be a relatively high level of uncertainty about a company's requirements and the individual's ability to carry them out. The problem caused by short-term manning policies has been recognised and some ship management companies have been successful in retaining good personnel within their fleet (Pressly, 1991).

Holt (1991) defined the function of management as to: set objectives, organise, motivate, communicate and to measure performance. Training establishments run courses in ship management which incorporate these principles. Together with safe management codes and the formation of professional ship operating companies, ship management may progress towards a disciplined knowledge based profession which could be beneficial to ship safety. Thus there are developments that may improve the influence of company organisation on ship safety. These influences are subtle and difficult to measure, and their long term influence on safety cannot be known with certainty, which makes it difficult to consider how to include the organisational influences into a mathematical model of ship safety. However it may be possible to model some aspects of the safety information system within an organisation, based on a scheme outlined by Reason (1991), the elements of which are summarised in Figure 4.11.2.

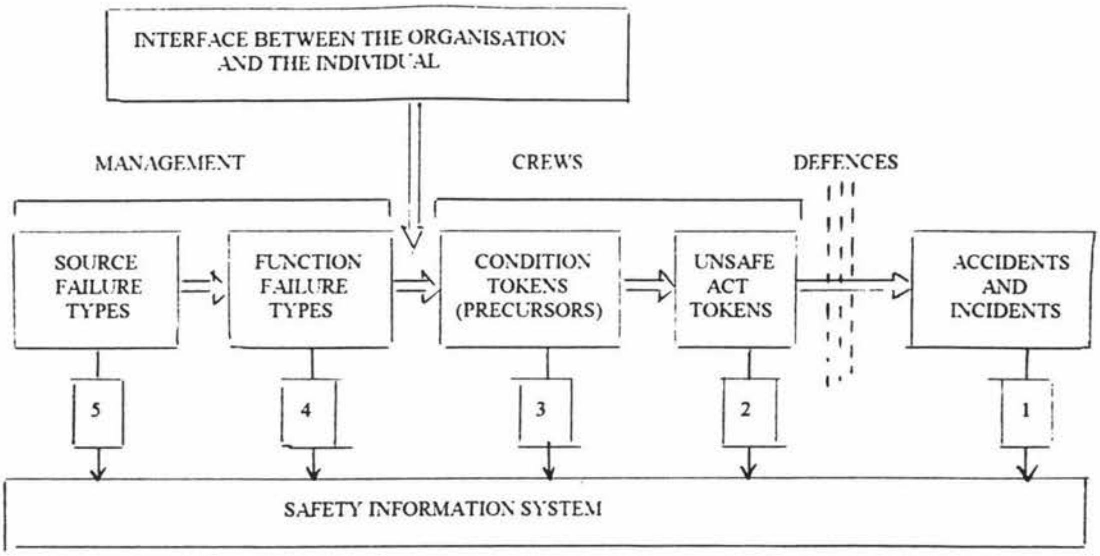


Figure 4.11.2 Elements of a safety information system (after Reason, 1991).

Reason (1991) suggests that effective safety management can only be achieved if managers are aware of the safety state indicators for the organisation. The scheme shown in Figure 4.11.2 is based on a hierarchy of measures for the vital signs that reveal the intrinsic safety health of an organisation. The most basic level involves the organisation simply reacting to accidents. Although this can improve particular aspects of safety, it is not seen as cost-effective. As an organisation's management of safety becomes more sophisticated, the time horizon for changes becomes longer, and a more strategic approach to safety is taken. A fully-developed safety information system requires elements at different levels in the scheme, and it may be possible to assess an organisation's safety culture based on this scheme. A rating system could be used in which a fully-developed system in an organisation with a high level of safety culture could be seen as close to 1, and an organisation with few systems in place for managing safety would score near zero.

Related aspects are the level of risk involved and the element of chance involved in accidents. For a low-risk operation, for example transporting harmless cargo in sheltered water which is free of vessel traffic, a sophisticated system would not be appropriate. For a company operating a fleet of gas tankers on international voyages, a fully developed system would be a necessity. The element of chance involved in accidents is problematic; an efficient organisation operating new, properly-equipped and well manned ships is still vulnerable to accidents. A slight delay in giving astern power before a ship hits the lock gates is more than a remote possibility, and even the best-run organisation can experience accidents. On the other hand relatively lax operators can enjoy long periods free from any accidents, and in an organisation with a poorly-developed safety management system, relative freedom from accidents can reduce safety awareness.

The Poisson distribution is used as a model of the random nature of accidents. If x is the number of accidents and P(x) is the probability of x accidents in a given time, then

$$P(x) = \frac{\mu^x \cdot e^{-\mu}}{x!}$$

where μ is a measure of how accident-prone an organisation is

The nature of the Poisson distribution suggests that companies with effective safety management systems are represented by distributions having low values of μ, and companies where safety management is less effective have higher values of μ. This is illustrated in Figure 4.11.3.

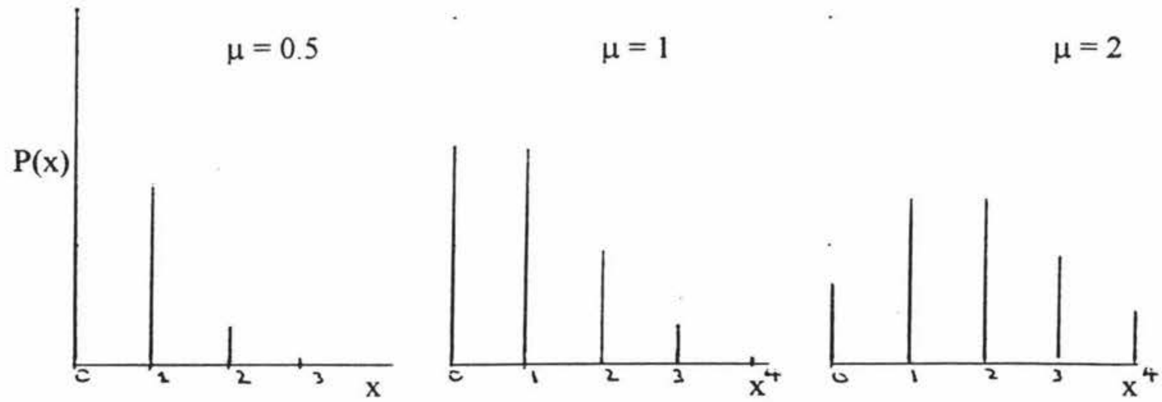


Figure 4.11.3 Poisson distribution for accidents.

The Poisson distribution is concerned with the number of accidents, and it would be useful to be able to model the severity of accidents using continuous distributions. Let the severity of an accident be represented by the variable y, and let the probability that an accident of severity less or equal to y <u>will not occur</u> be represented by the area under the curve Q(y) up to the abscissa through y. The assumption that the probability of a minor accident is greater than that of a major accident will give distributions skewed towards the origin such as Rayleigh distributions. Using Rayleigh distributions, companies with effective safety systems are represented by lower value of μ than companies with less effective systems, as illustrated in Figure 4.11.4

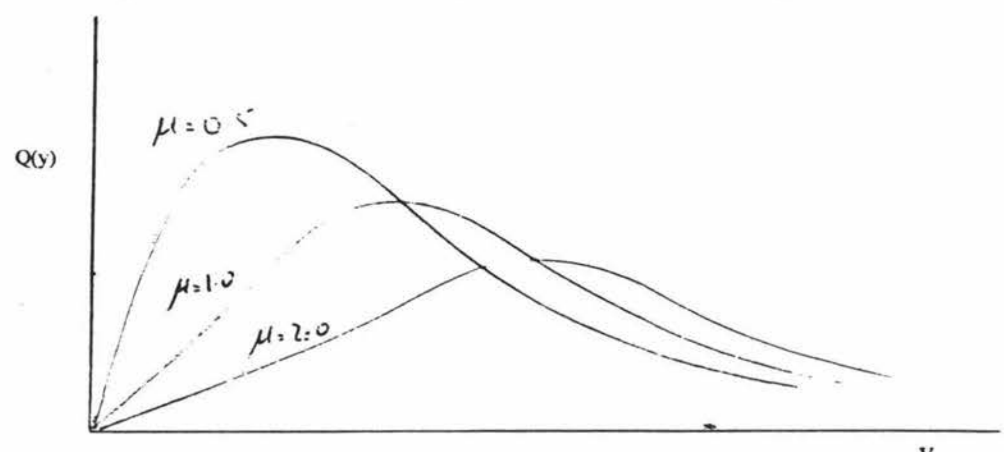


Figure 4.11.4 Rayleigh distribution for severity of accidents.

Although the shape of the Poisson and Rayleigh distributions may be correlated to the rating of an organisation's safety management system, there will be problems in obtaining the necessary data. Most organisations in a competitive industry such as shipping are reluctant to release data about accidents, and only those involving major accidents such as ship losses are generally available. From the distributions, it is apparent that major accidents are a poor indication of the safety management of a company. Goss (1977) estimated that the number of lives lost in shipping accidents is of the order of ten times that given in available statistics which consider only lives lost in major accidents.

4. 12 Human involvement in ship safety

Ships are the largest mobile structures built by man, and are under human control more or less throughout their working lives. It is therefore to be expected that the judgement, decisions and actions taken by human designers, builders and operators are basic to the safety of ships. This chapter explores the mariners' involvement in safety, for in the operation of ships, humans are closely involved with the other elements of ship safety discussed in this study. The aim is to determine whether the ways in which humans perform safety functions can be incorporated into a mathematical model. In the context of human involvement, the term performance denotes how well the mariner carries out these functions, and human reliability (or reliability) means the probability that the human will carry out a specified task, under specified conditions, during a specified time (this definition has been adapted from Kaufmann et al., 1977).

Operator involvement - the ship's crew

The nature of human involvement in running a ship has changed dramatically in recent decades. In the 1960s it was common for a general cargo ship of 15,000 tons deadweight to carry a crew of 70 persons. There was much manual work, usually for short critical periods such as arriving and departing port, and during a sea passage large crews provided plenty of manpower for watchkeeping and shipboard maintenance. The number of persons in crews aboard merchant ships has reduced over the years, and at present the majority of cargo ships and tankers of over 15,000 tons and on international voyages have a total crew of 18, with some such ships manned by as few as 12 persons.

The reduction in manpower needed to operate a ship has been achieved through a combination of automation, simplification of functions and rationalisation of procedures. Ships built after the second world war were fitted with derricks, and had hatches fitted with beams and covered with wooden hatch-boards and tarpaulins. Sufficient persons were needed to operate such equipment manually. In the engine rooms the main engine and auxiliaries had to be monitored continually, and required frequent overhaul. In a modern ship, a crane can be operated by one person, hatch covers are operated by hydraulic rams, and machinery is installed that is reliable enough to require only scheduled maintenance by a shore based team of fitters. Many ships have unattended machinery spaces (UMS) which do not require engine room watchkeepers. Reduction in the deck and engine departments has enabled further reduction in personnel, fewer people to feed, and smaller accommodation requires fewer catering and house-keeping personnel. Also, with modern radio equipment which is easy to operate, a specialised radio operator is not required.

The reduced manning of ships has several implications for ship safety. Since there are fewer souls on a ship, an accident should result in fewer injuries or deaths. The general increase in the size of ships means fewer lives expended per tonne mile of cargo carried than in the past, so there are apparent beneficial effects of reduced crews. On the other hand, there is concern that the reduction in manpower may have gone too far, and that ships may have too few persons to carry out all necessary monitoring and control functions, and to be able to take necessary action to save the ship in an emergency (Drahos, 1992). Associated implications are that there is greater reliance on key personnel and fewer training opportunities in a situation where every person on board is necessary for the normal operation of a ship.

The variability of tasks and of humans makes it difficult to determine the number and quality of operators necessary to run a ship. Human factors involved in ship operations can be considered in terms of; knowledge, experience, judgement, skill, the ability to use equipment, to read displays and operate controls, and to interact with other human operators in an appropriate manner. The multi-dimensional nature of human involvement and the variability of humans has led prominent researchers to question whether human operators can be modelled in a realistic way (Sanders and McCormick, 1987). Given the central importance of human operators in ship safety, the inability to include humans into a model would seriously reduce the feasibility of developing a realistic mathematical model of ship safety. However, a number of studies have used mathematical techniques to analyse, and even predict human response to particular situations (Dyer Smith, 1991), and the possibility of including the human operators into a mathematical model should not be dismissed.

Serious attempts have been made to measure human reliability and to use the data collected to assess and improve control and display panels. In 1962 the American Institute for Research developed a human reliability data base called "Data Store" that has been used in the aerospace and nuclear power industries. The data bank enabled estimates to be made of human reliability in selecting the correct control on a panel, in reading different types of display and in using check lists properly. Such tasks are relatively predictable compared with the variety of activities and decisions involved in running a ship, but the concept of measuring and applying estimates of human reliability is the same.

The human operator has been modelled in a control situation using the methods of control theory (Garner, 1966). The operator is treated as a transfer function and, given assumptions about delays, gain, noise and non-linearity, the output for a given input can be found as shown in figure 4.12.1

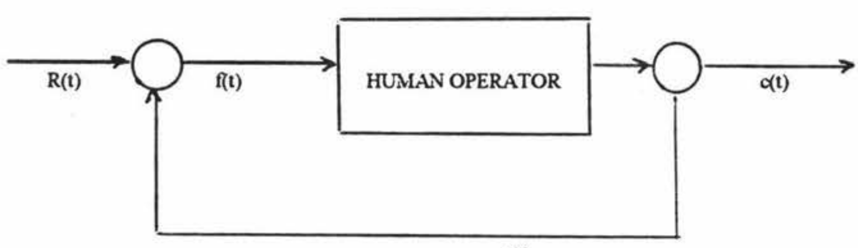


Figure 4.12.1 Transfer function of a human operator.

It may be unrealistic to try to develop transfer functions for the range of tasks to be included in human involvement in ship safety. An alternative approach is to attempt to build a model of the processes necessary to form an efficient ship's crew. A potential advantage of this approach is that the extreme variability exhibited by individuals from one day to another may be reduced when the group of individuals is treated as a team. Using a root-mean-square concept of variability, for a crew of 16 persons the variability of reliability of the whole crew should be only one quarter the variability of the variability of individual members. However this concept cannot be taken very far because great reliance is put on individuals during certain stages of a voyage.

If $\quad x \quad$ is the expected reaction to a stimulus

$\quad x_i \quad$ is the actual reaction to the stimulus by a particular person on a particular day

$$\text{let} \quad V_I = \left\{ \sum_{i=1}^{\infty} (x_i - \bar{x})^2 \right\}^{1/2}$$

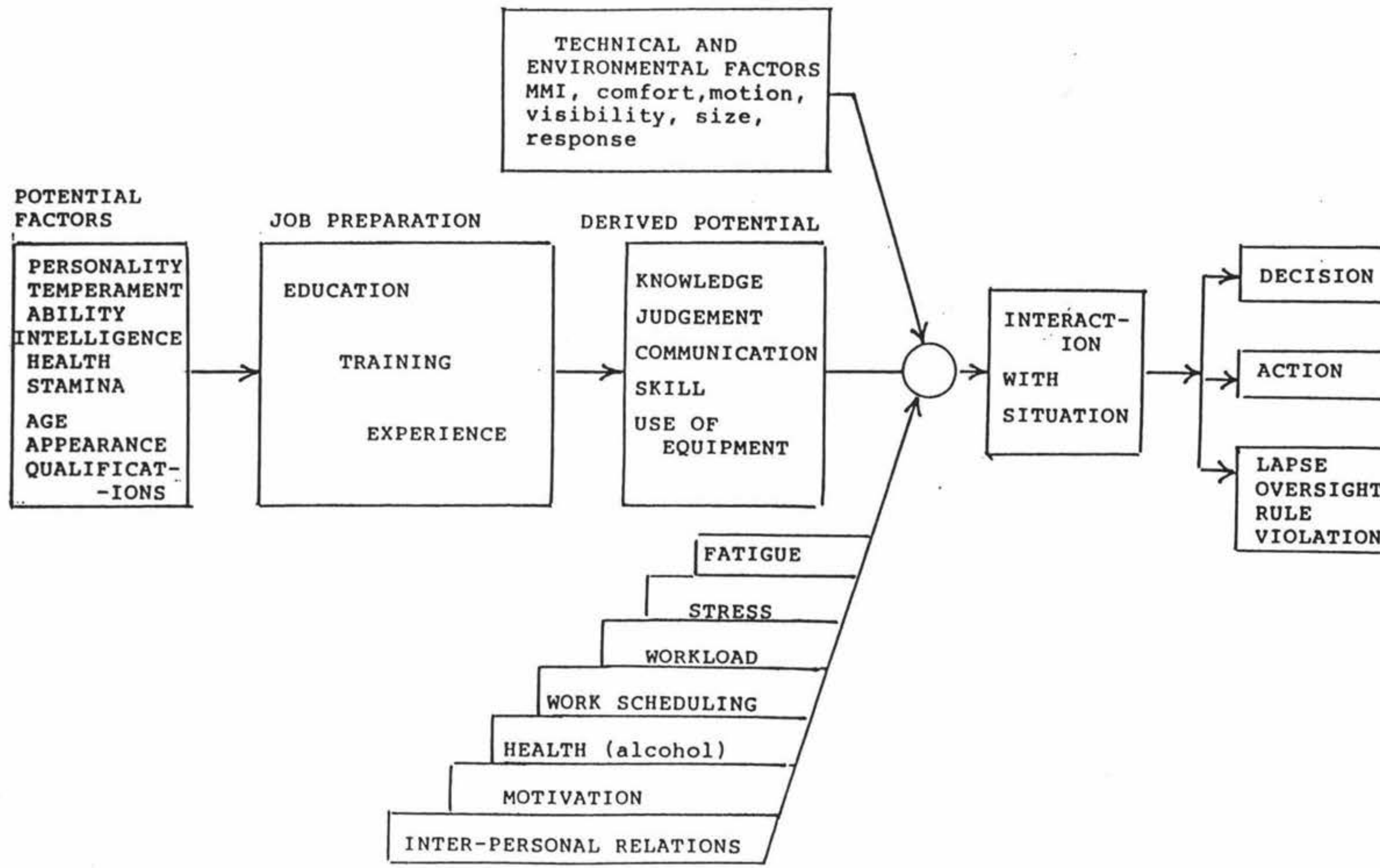


Figure 4.12.2 Human involvement in ship safety.

$$V_C = \frac{1}{16} \left\{ \sum_{n=1}^{16} \sum_{i=1}^{\infty} (x_i - \bar{x})^2 \right\}^{1/2} \simeq \frac{1}{4} . V_I$$

Figure 4.12.2 is an attempt to summarise factors that affect the reliability of a ship's crew. Although flexibility is an attribute that makes the human operator essential to the running of a ship, individual persons may have only a limited flexibility, and need to be selected as being suitable for the functions they will perform. In practice selection is a complex process involving some degree of self-selection by the individual, so that unsuitable persons are less likely to be candidates for a job. Selection by a personnel manager may be rather arbitrary, and depend more on appearance and paper credentials than on the ability to perform essential tasks. A third level of selection occurs during training where unsuitable candidates are dismissed, leave of their own accord, or fail to qualify.

Job preparation includes a blend of education, training and experience. There are circumstances in which human involvement will be essential to the safety of a ship, but which are encountered so infrequently that without a broad base of knowledge a candidate will be poorly prepared for specific situations. The outcome of job preparation is for the candidate to have appropriate knowledge and skills, so as to enable good judgement to be exercised and suitable action to be taken in a range of circumstances that the candidate is likely to encounter. It is apparent that job preparation is an open- ended process which is unlikely to be completely satisfied. However, if training is carried out in a logical manner, preparation for the most probable circumstances is carried out before preparation for the less probable circumstances, and there are decreasing returns to extended job preparation.

Figure 4.12.3 is a tentative model relating human reliability to selection and job preparation. This model is an application of the concept of investment in human capital described in chapter 9 of the book: Labour Economics (Fleisher and Kniesner, 1984). In the figure, S_{H0} represents reliability prior to job preparation and is a function of factors used in selection. Referring to Figure 4.12.2, the selection factors are themselves complex functions of various human attributes. Research into selection factors is far from conclusive and much depends on matching the personality of candidates to the socio-technical environment in which they will have to perform. Reeve (1987) compared the personality profiles of successful and less successful groups of merchant navy personnel. The successful group shared the following attributes; highly intelligent, stable, realistic, serious, prudent, conscientious, cautious, self sufficient and resourceful. Obviously any attempt to estimate values for S_{H0} can be little more than crude approximations. Nonetheless, subjective ordinal evaluations of S_{H0} are made on a daily basis when one candidate for a job is chosen rather than another.

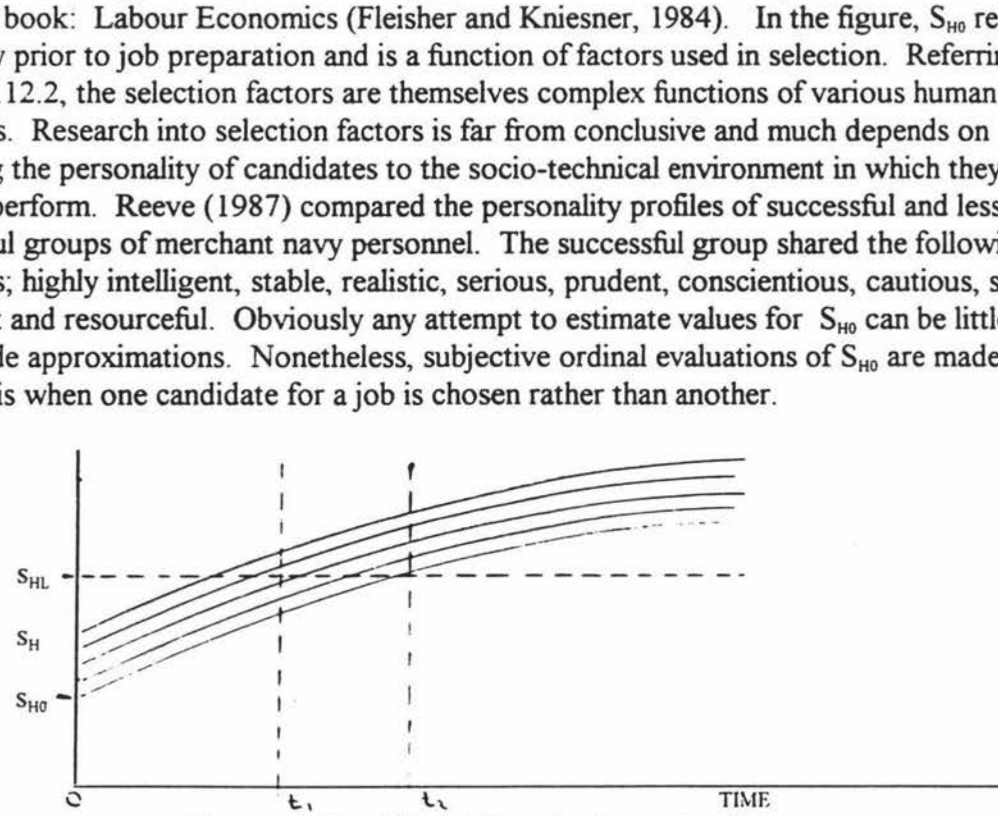


Figure 4.12.3 Model for selection and training.

It is assumed that candidates with high S_{H0} will benefit more from job preparation than those with lower S_{H0}. This assumes that poor training and experience does not demoralise candidates with high potential. In Figure 4.12.3 the value S_H increases with time spent in job preparation and S_{HL} represents the lowest acceptable level of reliability necessary to become a successful member of a ship's crew. In Figure 4.12.2 selection and job preparation result in a derived potential for reliable reactions in a given situation. This potential is one of four factors which influence the outcome of human involvement in a particular situation. The other factors influencing human reliability shown in Figure 4.12.2 are operational and technical factors, and the physical environment.

Operational influences

It is normal practice for ships, as capital intensive commercial ventures, to be operated continuously. Stoppages are usually due to outside influences, such as delays caused by congestion in ports, through cargo being unavailable, or through shortage of labour to work cargo. The crew is confined to the ship most of the time and social interaction must influence motivation and work attitudes, and in turn this will effect safety. It seems likely that a ship will be a safer place when morale is high and there is good communication between crew members. The management style of the company and senior officers will have a strong influence on the reliability of crew members, and must have a strong influence on safety. However such influences are complex and subtle, and unlikely to be included in a realistic way into any mathematical model of ship safety.

A factor that has received much attention in recent years, particularly since the grounding of the tanker Exxon Valdez, is occupational fatigue. The International Maritime Organisation has define fatigue as: " ... degradation of human performance, slowing down of physical and mental reflexes and impairment of the ability to make rational judgement through prolonged periods of mental or physical activity, inadequate rest, adverse environmental factors, physiological factors, stress or other psychological factors" (Parker, 1991). The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 (STCW Convention) provides that "The master of every ship is bound to ensure that watchkeeping arrangements are adequate for maintaining a safe navigation watch," and that, "The watch system shall be such that the efficiency of watchkeeping officers and watchkeeping ratings is not impaired by fatigue." Similar provisions are made for engine room watchkeeping (IMO, 1978).

The measurement of fatigue presents a problem in industrial accident research. According to Surry (1969), the term fatigue includes physiological fatigue, performance decay and a subjective feeling of tiredness. Physiological fatigue does not correlate with the degradation of performance and a highly-motivated operator can maintain a very high level of performance even when physically tired. However, performance frequently does decline with prolonged periods of work, possibly due to decreased motivation and boredom. Shipping companies tend to rely on self monitoring by the individuals concerned: "You're tired if you say you are." However commercial pressures and lack of extra personnel to take over tend to increase the incentive for individuals not to report fatigue until it has reached a dangerous level.

Drahos (1992) maintains that fatigue is affected by three basic mechanisms:

- the number of hours worked,
- inability to get regular and uninterrupted sleep, and
- exposure to stressful conditions.

Other relevant factors are the time of day or night and the level of mental and physical stimulation to which the operator is subjected. A common situation is for a watchkeeping officer to work many hours in port before the ship sails so that he is tired when he takes over the watch that night. After the fast pace of work in port, he is alone on a dark bridge on a peaceful night, with little to do besides monitor the ship's progress and keep a lookout for dangers. The STCW Convention provides that: "Duties shall be so organised that the first watch at the commencement of a voyage and the subsequent relieving watches are sufficiently rested and otherwise fit for duty."

The relationship between number of hours worked and operational reliability is not obvious. There are large variations between different persons working at the same task as well as variations for one person working at a range of different tasks, or at one type of task in differing circumstances. Experiments to establish a relationship between the length of time worked and performance have been limited to operators working at clearly defined tasks where measures of performance can be established. For example the performance of an observer detecting signals on a radar screen can be measured by the percentage of signals detected. Performance at repetitive or monotonous tasks tends to decrease linearly with time, and the rate of deterioration becomes greater as the interval between demands placed on the operator increases (Sanders and McCormick, 1987).

A navigational watch is essentially a monitoring activity. A visual lookout is kept for dangers which could be approaching ships showing navigation lights, unlit floating objects, rocks or shoals. The ship's course is checked, the radar, echo sounder and navigational equipment may be used briefly, the ship's motions, sea state and wind force and direction are noted, and a watch is kept over the securing arrangements for cranes and deck cargo. This involves a wide range of activities compared with those involved in the monitoring functions described by Sanders and McCormick (1987), and so the decrease in performance should not be so significant. However, prolonged periods of watchkeeping are likely to diminish performance; it is proposed here to assume that human reliability decreases linearly over time as shown in Figure 4.12.4.

At the beginning of a period of duty, the watchkeeper attains a level of reliability R_0 which is determined by his job preparation and influences that occurred in the period before the watch. A short amount of time is necessary for the watchkeeper to take over, to become familiar with the situation and for dark adaptation at night. After taking over the watch it is assumed that performance declines steadily over time. This will not be the case for a well-motivated person on a coastal passage where there is a relatively high level of mental stimulation, but in a situation where the watchkeeper is demoralised by factors such as the length of continuous sea service and poor relations with senior personnel, it is likely that an uneventful watch will induce a steady decrease in reliability over time.

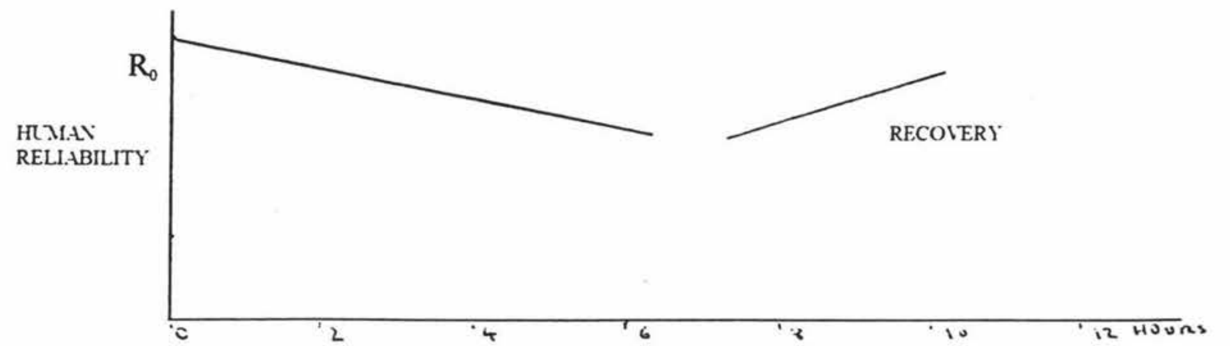


Figure 4.12.4 Reliability of watchkeepers.

A well-motivated person can recover rapidly after a prolonged period of watchkeeping, but when conditions are not conducive to rest, recovery will be slow. Aboard a ship with high levels of vibration and noise, especially in rough seas, it may be difficult to get adequate rest. The size of a ship and its seakeeping qualities are significant to rest and recovery. A linear recovery rate is assumed here, with a lag of about one hour between the end of a period of duty and the beginning of recovery.

Besides watchkeeping there are several other functions that are critical to a ship's safety. The master does not normally keep a watch but his performance is important to safety at critical times such as port arrivals and departures, navigation in restricted visibility and in high traffic density. The employment of unreliable watchkeepers will add to the master's burden so that his own reliability may be diminished. Similarly the engineers in a ship with unattended machinery spaces may be called to work long periods in difficult conditions after a problem with main or auxiliary machinery.

A model for assessing crew reliability must take account of which functions are carried out on a continuous basis by watchkeepers, as well as those carried out on an intermittent or occasional basis by both watchkeepers and non-watchkeeping personnel. The US National Research Council approached the problem of minimum manning levels by developing a functional model for activities necessary for the running of a ship. Their model takes into account vessel type, voyage profile, level of technology and operating conditions (Seaways, April 1991 , pp 5 - 8).

Figure 4.12.5 is an example of a task synthesis for functions carried out by key personnel on board a ship. The personnel involved are the master, three deck officers, three engineer officers and five general purpose (deck or engine room) ratings. The figure shows times when all personnel are actively involved, times of normal watchkeeping at sea and in port, and critical periods such as when navigating in reduced visibility, or when engine repairs are being carried out. Watchkeeping personnel have additional duties that can only be carried out when off watch. Many of these additional duties are important to safety and require a high standard of human reliability. Examples include: passage planning, correction of charts and navigational publications, stability and stress calculations, checking that cargo, hatch covers and cranes are properly secured, checking hold temperatures, bilge soundings and the maintenance and testing of safety equipment such as lifeboats and fire appliances.

The proposed human reliability levels in Figure 4.12.4 can be combined with the task synthesis in Figure 4.12.5 to generate time-dependent human reliability estimates for individual personnel. Given indicative values for each crew member, it may be possible to produce a reliability index for a ship's crew as a whole. Although individual reliability will change from one voyage to the next, comparison of different crews over a standard set of circumstances that may be encountered in a standard voyage will give an index that allows crews to be compared. The index QCREW used in the computer model described in Chapter 5 makes use of this idea.

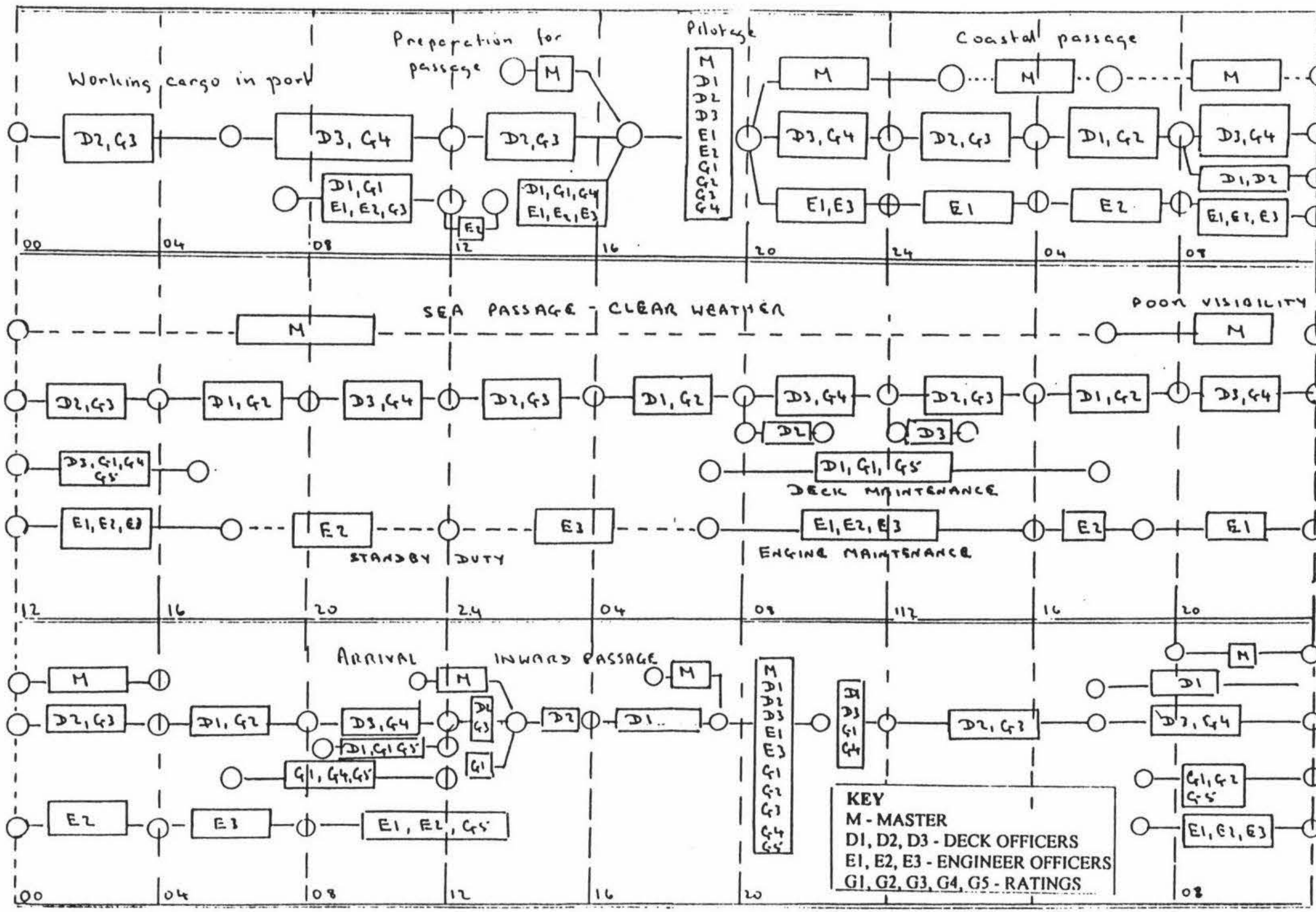


Figure 4.12.5 Task synthesis

The reliability of the crew is a function of the reliability of individual members. During different phases of a voyage, the whole or part of the crew (subsets of the crew) act as a team. This implies that the reliability of the crew depends on the reliability of individuals in the context of the particular teams in which they are involved. The following relation is suggested:

$$QCREW = \sum_{j=1}^{m} \sum_{i=1}^{n} K_{ij} \cdot R_{ij}$$

$$\text{where} \quad \sum_{j=1}^{m} \sum_{i=1}^{n} K_{ij} = 1$$

m: number of subsets of the crew that operate as teams
n: number of persons in each team
K_{ij}: weighting for member i when operating in team j
R_{ij}: reliability of member i when operating in team j

Weightings K_{ij} depend on the teams as well as the members involved. Greater weighting is expected for teams involved in activities where there are greater consequences if something goes wrong. The hierarchical structure of the ship's crew is also reflected in the weighting system, with the person in charge of an operation typically receiving a higher weighting. The makeup of various teams is shown in Figure 4.12.6.

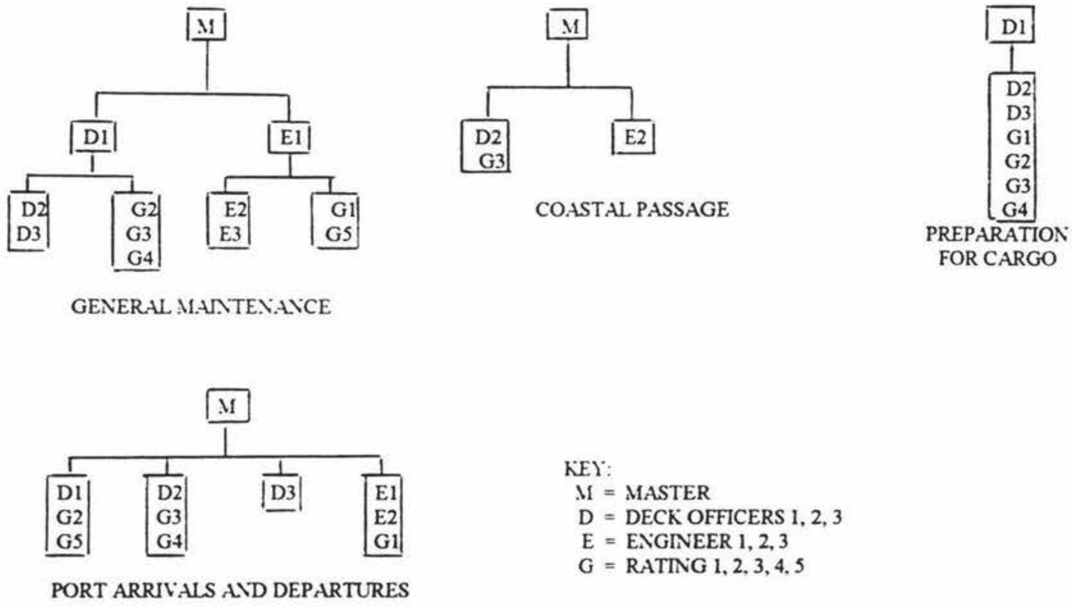


Figure 4.12.6 Subsets of the crew involved in team tasks.

The influence of technical factors

The master and crew of a ship live and work in a man-made environment, and the technical design of a ship and its equipment have an important influence on the performance of its personnel. Design considerations for commercial ships are dominated by economics; a ship is built to transport cargo efficiently and a design objective is to maximise earnings from cargo carried, within constraints imposed by the requirement for intrinsic safety outlined in this study. The gradual evolution of ships since the introduction of steam propulsion has provided naval architects with feedback about operational problems, but there are instances of ships where operational considerations have not been allowed for and the adaptability of the crew has been stretched to accommodate design limitations. Consideration of human factors and the ship environment is now an integral part of the qualification of naval architects and ship designers, and design objectives include that a ship is easy to operate and maintain. This section considers the complementary question of how a ship's design influences the performance and reliability of its human operators.

Maintaining a good look-out is an essential part of safe navigation, and the efficiency of the look-out function is diminished by obstructions. A 360-degree uninterrupted view from the look-out position is ideal but seldom achieved, so watchkeepers are obliged to continually change position to ensure adequate coverage. This activity may help to promote alertness, but such benefit has to be compared with the increased probability of not seeing a danger. Obstructions to the view from the bridge are dangerous when a ship is berthing or manoeuvring in confined waters, and the UK Merchant Shipping Notice M1264: Navigation Bridge Visibility, published in 1987, sets standards to be taken into account by the designer. The Code of practice for ships' bridge design, published by the UK Department of Industry in 1977 provides general principles for the selection and layout of instruments and displays, but even within the recommendations of this and similar codes there is much scope for individuality. This means that even experienced operators need time to become familiar with the bridge and other control stations after joining a ship. As part of a study of ships' bridges, Lowry (1994) interviewed mariners and pilots about their reactions to various bridges. Lowry defined an effective bridge as " a bridge that can be used without placing limitations on the decision making process". The effectiveness of a bridge depends on factors common to a variety of situations, factors related to the tasks being carried out and factors determined by the individuality of the mariners and pilots that use the bridge. The assessment of any individual is influenced by his particular experience, and there is a strong subjective element in any such rating system.

Lowry's definition of an effective bridge may provide a basis for incorporating the influence of the bridge technology on the human operator into a mathematical model of ship safety. A bridge is used by various subsets of the ship's crew, and its effectiveness may be related to the limitations it places on each of these teams. The bridge teams could be asked to rate various functions on a scale 0 to 1, where 0 indicates that the function is impossible to carry out on that bridge, and 1 indicates that the bridge places no limitation on the team's ability to carry out that function. Examples of functions to be carried out are:

- Look out; by day, by night and in restricted visibility
- Use of radar; by day and by night, plotting approaching ships
- Assessing the relative bearing of an approaching ship
- Monitoring steering, course, engine rpm, propeller pitch
- Change over to hand steering
- Use of radio
- Internal communications
- Fixing the ship's position and use of navigation and pilot charts

Weighted averages may be used to give an approximation of the effectiveness of the bridge. Assessments of workload have been carried out using such interviewing techniques, and the effectiveness varies inversely with the work load imposed by a particular design. In a study of the integral total control of the bridge, navigation training simulators were used to simulate passages using different bridge configurations. The data was summarised as a quantitative rating of work load (QRWL) and a subjective rating of work load (SRWL), and the results indicated that bridge design can have a significant effect on work load, and thus operator performance (Kristansen et al., 1989). QRWL and SRWL could provide useful indices for the influence of bridge technology on the performance of bridge teams.

An increasingly important technical influence on the mariner's performance is the ship's response to rudder and helm movements. Information about a ship's characteristics for standard manoeuvres is displayed but this information has serious limitations, especially for manoeuvring in shallow waters, and a number of maritime organisations are presently conducting research into more appropriate methods of measuring manoeuvrability. (Blanchardi and Dellino, 1991) A ship's safety depends not only on manoeuvrability, but the mariners' and pilots' ability to anticipate the ship's response. Similarly in heavy weather, experience of other ships may not prepare a mariner to judge the limit of safe operation, and a large ship may suffer structural damage before the ship's personnel are aware of the severity of forces acting on the ship (Bishop and Price, 1976).

Technological influence on the work carried out by a ship's crew includes the extent to which labour-saving machinery and equipment are used. The advent of the global positioning system has reduced the effort required to fix a ship's position in all stages of a voyage. Similarly the use of hydraulic and pneumatic controls has eliminated much of the physical effort required to work a ship, modern engines being fitted with a network of sensors and actuators which can automatically monitor and adjust settings, while some shipping companies use robots to help with heavy routine maintenance tasks. Over the years, traditional methods of working are used with increasing difficulty, and the safety of a ship will depend to a greater extent on the overall reliability of the operator and the ship's technical systems.

The influence of environmental factors

Living organisms react to the environment through their senses, and the environment affects a person's moods, performance and the ability to work. There seems little possibility of including subtle environmental influences which are only intuitively understood into a mathematical model of ship safety, but some of the more obvious effects must be considered. The weather has a dominant influence on ship operations, and its effect on a ship's physical safety has already been considered. Other environmental influences include the time of day, levels of noise and vibration, temperature and the area of operation with regard to traffic levels and dangers to navigation.

Rough seas and poor visibility have significant influence on human performance. Work is difficult when a ship is rolling, pitching and heaving; the accelerations make it difficult to carry out physical tasks when the operator has to brace himself and anticipate the motion when carrying out a task that requires physical dexterity. There is also the physiological effects of the ship's motion that makes it difficult to concentrate and brings on nausea. But humans are adaptable and can change work practices in rough weather, part of a mariner's seamanship training being preparation for heavy weather. Mariners can acclimatise to a ship's motions and the worst deterioration in performance is likely to be when a crew joins a ship after a long period of shore leave, and experiences heavy weather soon after their ship leaves port.

There have been attempts to measure the degradation of human performance due to motion. The significant parameters are acceleration and frequency. One method based on experiments where a number of persons reported their reactions to movements gave an empirical formula for the subjective magnitude (SM) of the effects of motion (Rawson and Tupper, 1994):

$$SM = (30 + 13.53.(\ln f)^2).a^{1.43}$$

where: a = acceleration / g
g = acceleration due to gravity
f = frequency in radians per second

Figure 4.12.7 shows curves of constant SM plotted against frequency and acceleration. The relationship shown in the figure agrees with observations that the degradation of performance is greater on board small ships with higher frequency motions, and at the extremities of large ships where linear accelerations due to pitching are greater. The practice of siting accommodation and engine rooms close to the stern increases the probable degradation of human performance. It is expected that human reliability will have an inverse relationship to SM as illustrated in Figure 4.12.7.

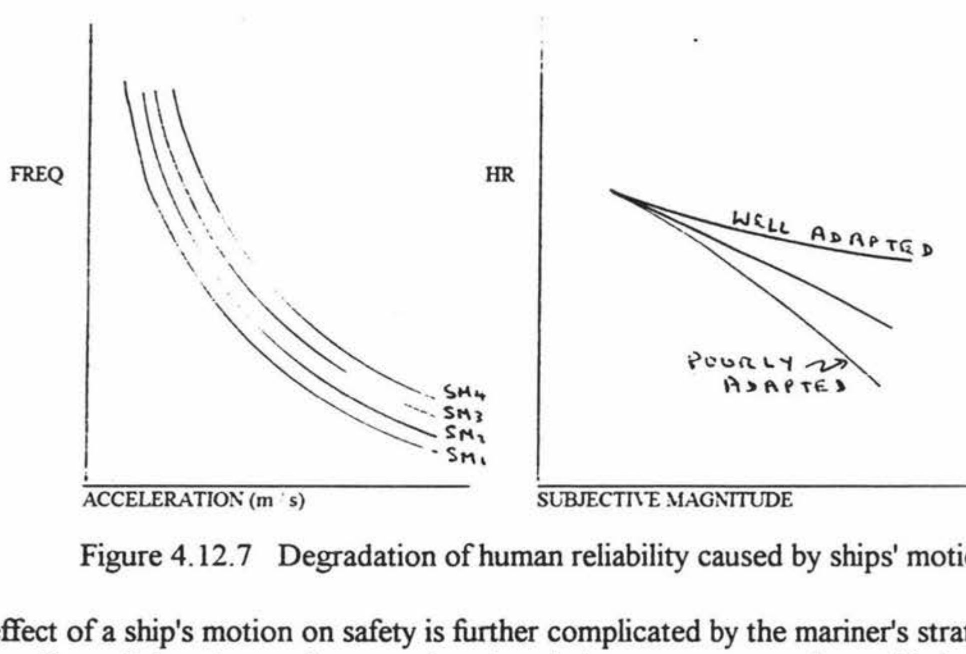


Figure 4.12.7 Degradation of human reliability caused by ships' motion.

The effect of a ship's motion on safety is further complicated by the mariner's strategy for coping. On realising that performance is reduced, the operator may change his behaviour, for example by staying further from dangers than normal, by reducing speed or by allowing more time for tasks that are critical to safety. A UK Protection and Indemnity Club analysis of claims reported in the shipping magazine Fairplay gave the percentage of collisions that occur in different weather conditions (Fairplay, March 1994, page 27):

SEA CONDITION	PERCENTAGE
calm	37
slight	38
moderate	19
rough	6
	100

Although the figures cannot be properly interpreted without knowing the frequency of rough weather for ships at risk, the percentages do not suggest a strong correlation between rough weather and collisions.

Poor visibility increases the risk to shipping, particularly for large or fast ships, or when there is a high density of traffic. The International Regulations for Preventing Collisions at Sea require ships to proceed at a safe speed, based on a full appraisal of conditions, but a long period in fog puts great stress on the master, navigators and other personnel, in that order. The additional stress is caused by concern for safety and the extra vigilance necessary, the monotony of watching and listening for approaching ships, monitoring radar, plotting approaching ships and keeping track of the ship's progress. The engineers would be ready to stop or reverse engines at short notice, while the fog signal sounds a prolonged blast at intervals of not more than two minutes, making it difficult for anybody on board to relax. The Protection and Indemnity Club analysis of collisions in different conditions of visibility are as follows (Fairplay, March 1994, page 27):

VISIBILITY	PERCENTAGE
good	56
fair	6
poor	38
	100

As before, interpretation is difficult without knowledge of the frequency of vessels at risk in each condition of visibility. The UK Meteorological Office (1967) publication "Meteorology for Mariners" provides maps showing the percentage distribution of fog over the oceans in January and July. For most coastal regions the frequency of fog rarely exceeds 1%, the exceptions being the North Atlantic and North Pacific in summer, and the Baltic in winter. Taking into account that the highest shipping traffic densities are in north west Europe, the eastern seaboard of the USA and around the coast of Japan, an estimate of the frequency of ships operating in fog is about 2% , and possibly up to 5% for ships navigating in poor visibility. Thus 5% of the ships at risk are responsible for 38% of collisions, which indicates a positive correlation between poor visibility and collisions.

The incidence of collision or grounding in poor visibility is significant, and should be included in a mathematical model of ship safety. This requires information about voyage itinerary, the frequency of fog for the season in which a ship will be operating in each area, and the traffic distributions in such areas. The likely duration of poor visibility is also an important parameter as it affects the master's navigation strategy and the degree to which the reliability of ships' personnel will be reduced. If fog is expected to lift within a few hours, the appropriate action would be to wait, whereas if fog is likely to persist then stopping the ship or an excessive reduction in speed lengthens the time at risk and will reduce the master's and watchkeepers' performance in avoiding dangers to navigation.

Time of day affects human reliability, particularly for work such as monitoring where vigilance is necessary. The body's circadian rhythms follow a daily cycle so that mental alertness and bodily signs fall into a pattern which becomes synchronised to cues such as sunlight, meals and sleep (Bryant, 1987). The need for continuous operation means that some personnel are expected to be sufficiently alert and reliable when their bodily signs are unfavourable. Given sufficient time, a watchkeeper will adapt to a new pattern of behaviour such as keeping the 12 to 4 watch in a system of 4 hours on, followed by 8 hours off duty, however, as shown in Figure 4.12.5 this pattern is frequently interrupted. Degradation of performance through working routines that are out of step with a watchkeeper's circadian rhythms is more significant on board ships operating with only two watchkeepers. If there are 5 watches over 24 hours, i.e. one of 4 hours and four of 5 hours duration then the pattern is repeated over a two day cycle and the periods of duty are regularly out of step with the body's natural cycle. Although the phenomena of circadian rhythms is well known, the level of deterioration of human reliability would have to be established to incorporate its effect into a mathematical model. Relevant questions are: how well can the body adapt to irregular patterns of activity? and, is there long term deterioration? There may be a strong connection between cyclical changes in human reliability and the high rate of casualties in small ships with minimal manning and short voyages.

Modelling human involvement in ship safety

It seems unlikely that a mathematical model could fully reflect the complex and subtle nature of human involvement in ship safety. An important reason for human involvement is to detect failures in mechanical systems and to take corrective action, and for this reason most accidents which follow mechanical failure also involve human error. In an analysis of 100 accidents recorded by the Dutch Shipping Council, 2250 underlying causes were identified, 345 of which were forms of human error, and yet only 4 accidents occurred without any preceding human error (Wagenaar and Groeneweg, 1987).

A model of human reliability for a ship's crew may take account of the relationships shown in Figure 4.12.2, so that a potential level of performance is determined by selection and job preparation. Reliability is degraded by various influences, such as long work periods, monotony, poor design of the work station and unpleasant ship motions. But as mariners find their own reliabilities or those of other crew members have fallen to unacceptable levels, they take extra precautions to avoid unnecessary risk. These measures should result in a limiting level below which the human reliability of a crew is unlikely to fall.

4.13 Surveys, maintenance and repairs

There are both legal and commercial reasons for regular surveys of ships. A ship of gross tonnage 500 and over, registered in a country that is party to the international safety conventions, is issued with survey certificates after passing inspections carried out by organisations recognised by the government of that country. Ships may also be checked from time to time by inspectors employed by the ship's flag state, or a port state that the ship is visiting. A prerequisite for the issue of convention certificates and for insurance cover is usually a valid certificate of class issued by a classification society. In addition, surveys may be carried out by protection and indemnity clubs, charterers and cargo shippers. Thus there is a complex industry involved in the survey an certification of merchant ships.

Before a ship is built, plans are approved by a maritime authority or a classification society. During construction, surveyors attend the ship from time to time to check that it is being built according to plan, to verify that materials are acceptable, and to carry out tests. Requirements for ship construction and survey are contained in national regulations based on international conventions, and the classification societies have developed rules through long experience and research. The rules for hull scantlings, ships' machinery and equipment are complicated, with details contained in many documents, and expert system software has been developed to guide designers and surveyors through the information.

After construction and fitting-out are complete, and a ship has been surveyed and has completed sea trials, the following safety certificates are issued:

- International Safety Construction Certificate to cover the hull, propulsion and auxiliary machinery

- International Safety Equipment Certificate to cover lifesaving and fire appliances, lights, signals, stability information and navigational equipment

- International Safety Radio Certificate to cover radio communication, direction finding equipment and emergency beacons

- International Load Line Certificate to cover freeboard, load line markings, water tightness and access.

When a ship is in service, periodical surveys are carried out at specified intervals, and intermediate surveys during intervening years. At periodical surveys the ship is dry-docked, and the hull cleaned and examined before painting. A thorough examination is made of the external hull including the rudder and propeller, and of the internal structure and systems. Holds and tanks are normally empty for dry-docking, except for fuel tanks in use and ballast necessary to give the required trim while docking. The extent of a periodical survey is governed by the age and general condition of the ship and by the judgement of the surveyor (The Shipping (Survey) Regulations, 1989). An alternative to periodical surveys is the method of continuous survey of hull, machinery and equipment, under which the examination of the entire ship is carried out over the period of five years.

Most merchant ships are constructed of mild steel, and the marine environment promotes the corrosion of steel. From the time of construction, continuous effort is necessary to control corrosion, and usually the new structure is shot-blasted and painted. Paint serves to separate steel from oxygen, some paints also inhibit corrosion by chemical reaction, reduce electrolytic action, inhibit marine growth on the underwater hull, and give an appearance that is more attractive than rusty steel. Good surface preparation is necessary before the structure is painted, and when the paint coating is damaged, local corrosion occurs that can be more damaging than general surface rust. Paint coatings are regularly damaged during normal ship operations (contact with wharves, barges, floating logs and ice) and is often damaged when working cargo. When a ship flexes during loading, or in waves, the movement can damage the paint coating, and in ballast tanks and around the propeller and rudder, electrolytic action will take place when the coating is removed. Heavy pitting and lines of corrosion can weaken a structure, and excessive localised corrosion can go unnoticed in ballast tanks and parts of the structure that are normally inaccessible. Also fittings such as pipes, flanges and bolts that may be critical to the water tightness of a hull can corrode at rates far in excess of the general rate of corrosion.

Movable steel fittings, such as closing devices for hatches and watertight doors and fire dampers, become seized if not operated and greased regularly. A regular programme of inspecting, operating, cleaning, oiling, greasing and repairing can reduce the need for replacements and repairs. With the general reduction in ship board manpower and pressures for quicker voyage cycles, such programmes are hard to sustain, and more immediate requirements take precedence. Some of the older maintenance routines were effective when ships carried large crews, but possibly were not very efficient in that some tasks were carried out more often than necessary, while others may have been neglected. Some companies have introduced planned maintenance schemes, the basis of which is to give every item of equipment, structure and fittings the maintenance it needs to ensure its continued efficient operation (Isbester, 1993). The planned maintenance system is built around a schedule and records which enable a mariner to identify the work that needs to be done during each period, and assigns responsibility for carrying them out. Plans have to be sufficiently flexible so that maintenance is not carried out when conditions are unsuitable.

Ship maintenance is dictated by economics, operational requirements and safety considerations. Without regular maintenance a ship's structure and equipment deteriorates, and eventually major maintenance or repair will be necessary. Routine maintenance consumes resources, but so does response to crisis such as when cargo hatch covers will not close, or when a ship is detained in port because it is considered to be unseaworthy. Sufficient finance spent properly can promote smooth running and lessen the probability of crisis, but there may be other considerations such as cash flow problems, short term charters, or the expected sale or scrapping of a ship. The need for measures such as port state control inspections may stem from pressure to reduce spending on maintenance in a depressed freight market.

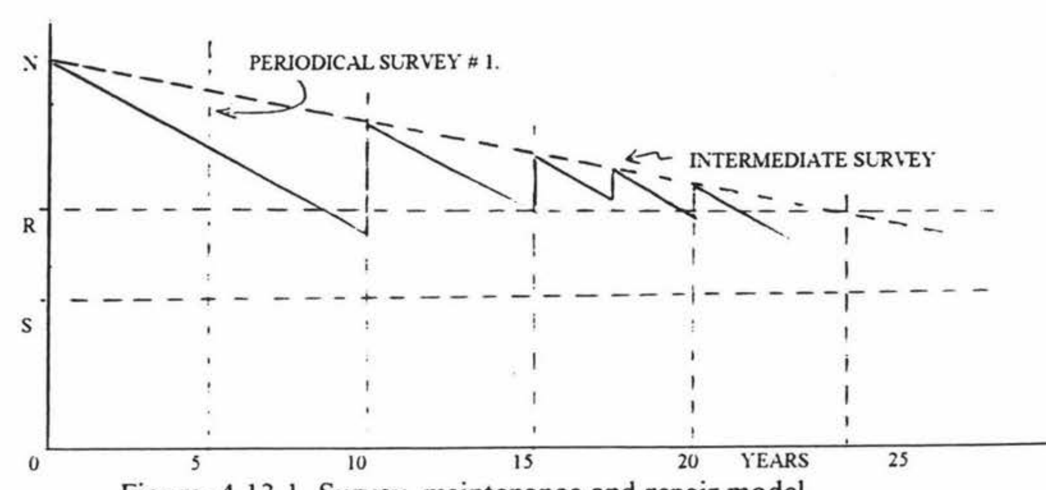


Figure 4.13.1 Survey, maintenance and repair model.

Figure 4.13.1 is a model of survey, maintenance and repairs, in which the horizontal axis represents time for an assumed ship's life of 25 years. The vertical axis is a hypothetical measure of the ship's structural reliability, where OS is the reliability of a structure which will fail under the normal stresses to which the ship is expected to be exposed. OR represents the minimum standard necessary to comply with survey requirements and ON represents the standard to which the new ship is built.

Two rates of deterioration are shown, one being a global rate that applies to the entire structure and is shown by the downward sloping dashed line. The other, shown as a full line, is the maximum rate of deterioration of part of the structure that is critical to overall strength. The two rates represent lower and upper bounds, and the actual rate at which any individual member should deteriorate lies between them. Because the dashed line represents a minimum rate of deterioration, and applies to the entire ship, it is not possible to reverse this deterioration economically by additional maintenance or repair. The maximum rate applies to a limited number of elements, for example lines of pitting in ballast tanks, or cracking near hatch corners. The local structure can be repaired or replaced, but it is assumed that this restores the structure only to the condition represented by the vertical height of the dashed line. Both rates are functions of the quality of care given to the ship, and of the forces and impacts which the ship is subjected to.

Periodical surveys are carried out every 5 years. If the structural reliability exceeds the minimum OR then there is no compulsion to make repairs, and the structure continues to deteriorate until the next periodical survey. In Figure 4.13.1, the structural reliability is below the minimum required at the time of the second periodical survey, and structural repairs are carried out. The same occurs at the third periodical survey, but it is apparent that the structural reliability is not going to remain adequate for another five years, and an enhanced intermediate survey is necessary mid-way between periodical surveys.

The model described is a gross simplification of the many subtle and interactive processes which occur when a ship ages, and represents the reliability of an entire complex structure with a single parameter. Events described by the model reflect reality to the extent that a ship's structure and equipment do deteriorate, and that ships between 10 and 15 years old often require structural repairs as a result of deterioration. Chapter 5 of this study develops this model to take account of the stochastic nature of stresses contributing to structural deterioration, and of shipping company policies for maintenance.

4.14 Lifesaving appliances and safety communication

In the event of a major ship failure, the final objective is to save human life, and the International Conventions for the Safety of Life at Sea prescribe minimum standards for lifesaving appliances carried in ships. Requirements are upgraded from time to time as new technology becomes available, and the equipment specified depends on the size of ship, date on which building commenced and whether the vessel is a passenger ship, cargo ship or a tanker. The lifesaving appliances provided in non-passenger ships are:

- lifeboats and rescue craft
- liferafts
- lifebuoys and man-overboard signals
- lifejackets
- distress signals
- line-throwing appliances
- immersion suits
- radio and communications equipment

In ships constructed after 1 July 1986 the usual provision is two totally-enclosed motor lifeboats which also serve as rescue boats. The boats are fitted in davits, one on each side of the ship so that they may be launched with the ship listed up to 20 degrees and with up to 10 degrees trim. Each boat has the capacity to accommodate all persons on board the ship, so that in an emergency where one boat cannot be launched the other is sufficient. Existing ships equipped under the 1960 Safety Convention need not carry totally enclosed boats, and only one boat needs to be motorised. Totally- enclosed boats provide better protection for the crew than open or partially-enclosed open boats, but can be difficult to handle and to use as rescue boats. An alternative system provided in some ships is a single free-fall lifeboat launched from a ramp at the stern, and a separate rescue boat.

Ships are provided with liferafts to accommodate all persons, and liferafts should be capable of being launched from either side of a ship. Hydrostatic release units or other suitable means are fitted so that if the ship sinks the liferafts float and inflate automatically. An extra liferaft is provided where survival craft are located more than 100 metres from one end of a ship.

Lifeboats, davits and liferafts are expensive items of equipment which require maintenance to ensure serviceability. Equipment and provisions are liable to deteriorate, though this is less of a problem in liferafts and enclosed boats. Provisions have to be replaced every five years and distress signals every three. The Safety Convention specifies weekly visual inspection of survival craft, and engines to be run ahead and astern. All lifesaving appliances including lifeboat equipment are checked monthly, and at least one lifeboat should be lowered during monthly emergency drills. Each boat should be lowered with its assigned crew and manoeuvred in the water at least once every three months. The wire rope falls used for launching survival craft should be turned end for end every 30 months and renewed at internals of not more than five years (IMO, 1992 a).

The necessity for and effectiveness of lifeboats has been challenged on occasions by both mariners and organisations involved in shipping. It is open to question whether lifeboats return benefits consistent with the resources used in their provision and ongoing maintenance, and whether these resources could save more lives if used to improve some other aspect of ship safety. Existing knowledge of the total safety function is not sufficiently developed to provide convincing answers. Opinion among mariners ranges from professional concern that lifeboats are kept in good order, to apathy and little faith in the ability of lifeboats to save lives. This latter attitude may be caused by the association of abandoning ship with extreme weather conditions which would make it very dangerous to launch the boats. However lifeboats have been used to save lives after collisions, groundings and fires which need not be associated with bad weather. Data about lives saved in lifeboats is scarce, but Gardner and Goss (1977) examined all Preliminary Inquiry reports where lifesaving appliances were used in UK ships for the period 1959-69, and found that 584 lives were saved by lifeboats and 112 by liferafts. During the 11 years, the number of UK registered ships at risk dropped from 2689 to 1900 (Goss, 1977). Casualty statistics suggest that the UK fleet had a rate of total losses to ships at risk of about half the world average. A bold extrapolation of Goss' data implies that on average at least one life is saved per lifeboat carried in ships. Crewing levels have reduced since 1969, but the approximation suggests that lifeboats provide more than a token benefit.

The UK Rochdale report recommended that cost-benefit-analysis (CBA) be applied to problems in the shipping industry, and Gardner and Goss carried out a detailed study of the costs of alternative provisions made up of lifeboats, liferafts and rescue boats. The data included capital, maintenance and survey costs, and the opportunity cost of the weight of equipment which reduces the cargo a ship can carry. This study demonstrated that it is perfectly practicable to apply the techniques of CBA so long as the relevant data is available, but the main difficulty was in quantifying benefits of the different schemes. Various qualitative statements were made comparing lifeboats and liferafts, but no conclusion could be made as to whether liferafts should take the place of lifeboats (Goss, 1977). The statements suggest that liferafts and lifeboats are not just substitutes, but complement one another. Inflatable liferafts have been used effectively on many occasions, but in strong winds have to be loaded with a sufficient weight of persons to prevent capsize. The mariner usually has little contact with the inflatable liferafts carried in ships as they are packed in fibreglass cases until inflated. Annual servicing is done ashore and for the mariner the liferaft is an unknown quantity. By comparison regular drills ensure familiarity with lifeboats, which is likely to promote confidence in the equipment, and this in itself is an important safety consideration.

Ships' lifeboats have a long history and there are records of heroic journeys of survival in small open boats (Lee and Lee, 1971). Technology has changed the emphasis from being able to survive at sea for long periods to the need for fast and efficient recovery of survivors. Wireless telegraphy is said to have contributed more to saving lives at sea than any other equipment, and the efficiency and availability of radio has improved continually. Until recently the principal means of distress communication was radio telegraphy on 500 KHz and radiotelephony on 2182 KHz. On 500 KHz the automatic alarm system in a ship is activated by a signal of 12 long dashes, and this is followed by the distress signal SOS in Morse code. The system is limited by the variable nature of the range at which transmissions can be detected, and it is likely that many ships reported missing could have transmitted distress signals that were not received.

In 1992 the Global Maritime Distress and Safety System (GMDSS) drawn up by the Internationals Maritime Organisation came into force to provide safety communication for all passenger ships and all cargo ships of gross tonnage 300 and over. The GMDSS uses satellite communication as well as medium frequency (MF), high frequency (HF) and very high frequency (VHF) terrestrial radio to provide 24 hour coverage on a world-wide basis. The system is based on an "area of operation" concept which determines the mandatory provision of radio equipment in ships.

Areas are designated A1 to A4, where:

- A1 is within 25 miles of a coast radio station providing VHF coverage
- A2 is within 100 miles of a coast radio station providing HF coverage
- A3 is within coverage provided by the Inmarsat geostationary satellites, this covers most of the sea areas used by merchant ships
- A4 is outside the coverage of geostationary satellites and coverage is provided by polar orbiting satellites.

GMDSS is designed to take advantage of existing as well as new technology and equipment. Ships in area A3 can be provided with various combinations of transmitting and receiving equipment selected from:

- Ship's earth station for satellite communication
- MF, HF and VHF transmitters and receivers
- Navtex, for navigational and safety information
- Emergency position indicating radio beacons (EPIRBs)
- Search and rescue (radar) transponders

Satellite compatible EPIRBs are fitted to float free if the ship sinks, and transmissions from EPIRBs are coded with a ship's identification signal. The location of a transmitting EPIRB can be determined by ranging from geostationary satellites, or by the Doppler frequency shift observed during the transit of a polar orbiting satellite.

A feature of GMDSS is that search and rescue activities are co-ordinated ashore. Under the earlier distress system, ships were alerted by the transmissions from a vessel in distress. The GMDSS enables transmissions to be directed at ships in a particular area, or using selective calling to a particular ship or station, and this should enable better co-ordination and use of rescue resources. However the system is still reliant on the human user, and problems experienced with the new system include false alarms, particularly from EPIRBs, some confusion with identification codes and the misuse of radio equipment (Weaver, 1995). Advances in electronics allow many ships to sail without a radio officer. Deck officers attend a two week course for GMDSS, compared with two and a half years training previously undertaken by radio operators. Many ships also participate in the vessel tracking schemes AMVER run by the US coast guard and AUSREP run by the Australian Maritime Safety Authority. Tracking systems can provide information about ships that are able to assist in an emergency.

Lifesaving appliances and safety communication systems provide a positive contribution to the safety of life at sea. Also recent improvements such as totally-enclosed lifeboats, free-fall lifeboats and the GMDSS are likely to improve safety. Such facilities provide for safety when the normal operation of ships fail, and therefore should be considered as part of the total safety function. Communication and rescue facilities are frequently used, often by small ships, fishing boats and pleasure yachts which are not being considered in this study, and this complicates the integration of this element in a model of total ship safety. Compared with the total number of ships at risk, the number of incidents in which lifesaving appliances or rescue services are used is small enough for their use to be considered statistically rare events, and so analysis is unreliable.

Chapter 5

A simple computer model of ship safety

Chapter 3 discussed the real world of commercial shipping. Thousands of ships, ranging from coasters of several hundred tonnes to tankers capable of carrying half a million tonnes of crude oil and belonging to over 200 nations, compete to carry the goods of international trade. Many ships are new, well-equipped, with good crews, and are efficiently managed, while some are over thirty years old with corroded hulls, faulty equipment and substandard manning. Shipping is a vast and diverse international industry, and not easy to describe in precise mathematical terms. It may therefore prove useful to create a model of a simplified shipping industry to serve a limited number of ports. Such a model could facilitate the study of changes to the various factors affecting ship safety.

The simple model developed here is based on four ports, which are served by five shipping companies, each initially owning ten ships. For the early stages of development, all ships are bulk carriers of 25 000 tonnes deadweight, and the complication of handling and stowing different kinds of cargo is ignored. An assumed export/import matrix for the four ports is used, with seasonal fluctuation in the volume of cargo, but initially no long term trend is proposed. Computation is on the basis that the first available ship gets the cargo, and constant freight rates are used. This is a severe limitation since there is an important relation between earnings and the amount spent on safety, but to introduce price competition at an early stage of model development would overly complicate the model.

Data about the ships is stored in the (5 x 10 x 15) matrix SHIP(NC,NS,N), where:

NC takes integer values 1 to 5 to represent five shipping companies
NS takes integer values 1 to 10 to represent 10 ships owned by each company
N takes integer values 0 to 14, to store the following information for each ship:

0	Y0	the year in which the ship was built
1	GRT	gross tonnage
2	DWT	deadweight (carrying capacity in tonnes)
3	STR	condition of the ship's structure ($0 < STR < 1$)
4	STF	fire resistance of the ship's structure ($0 < STF < 1$)
5	VOY	voyage number (integer)
6	MCY	condition of machinery ($0 < MCY < 1$)
7	NAV	condition of navigational equipment ($0 < NAV < 1$)
8	FIRE	effectiveness of fire appliances ($0 < FIRE < 1$)
9	LSA	condition of lifesaving appliances ($0 < LSA < 1$)
10	NCREW	total number of crew (integer)

11	QCREW	crew's training, qualifications and experience (0 < QCREW < 1)
12	VAL0	initial value of the ship (NZ$)
13	DOCK	month in which dry-docking is carried out (on 5 year cycle)
14	REV	net earnings of ship (income - expenditure) (NZ$)

Each company NC (1 to 5) has a maintenance policy stored in array MAINT(NC), the value of which reflects the level below which STR, STF and FIRE should not fall, subject to funds available in REV. STF is checked at the time of periodical surveys, and STF and FIRE are checked at annual surveys.

The four ports are linked by a matrix of distances and seasonal climate factors. Distances are used to compute passage times and, together with the climate factors, determine deterioration of the hull caused by dynamic (wave loading) forces. Climate factors are also used to determine the probability of heavy weather, and hence the likelihood of damage due to weather, while distances and passage times are used in determining probabilities of collision and fire.

The program starts with an initial random distribution of ships, which will be available in a given port on a given day. As the program runs, the location of each ship is stored in the matrix AVAIL(NC, NS, N), where AVAIL(NC, NS, 0) is the port 1, 2, 3 or 4, and AVAIL(NC, NS, 1) is the day on which the ship will next be available for cargo.

Each year is divided into seasons, identified by the integer variable QTR, where QTR = 1 to 4. Each season is divided into 9 intervals of 10 days, the 5 remaining days each year being ignored. At the beginning of each 10 day interval, the cargo to be transported between each pair of ports is added to a cumulative register CARGO(NPX, NPI), where NPX is the exporting port and NPI the importing port. CARGO(NPX, NPI) acts as a warehouse for cargo until the next ship becomes available. The program does not accommodate multiple ports of loading or discharge, and cargo is only shipped when there is more than a given minimum tonnage DWMIN, set at 12 000 tonnes, which is approximately half of each ship's carrying capacity.

Each pair of exporting and importing ports (NPX, NPI) are polled in numerical order and the first ship that is available during the current season (QTR) is allocated to transport up to a shipload of cargo from port NPX to port NPI. If the ship is not at port NPX, then a ballast passage is made between the port where the ship becomes available (APORT) and NPX. If the first available ship is at NPX then a ballast passage is not necessary. Sometimes this results in an unrealistic situation when two ships make ballast passages because one of them is able to make a long ballast passage to arrive at NPX a few days before the other ship completes discharging at that port, and the other ship has to make a passage in ballast to take cargo from the next NPX polled.

The allocated ship faces hazards during ballast and loaded passages. The program applies structural deterioration, and determines the probability of structural damage, collision, grounding and fire as described in the following parts of Chapter 5. In the event of damage, a ship may be lost or could need repairs, depending on the level of damage. If ship (NC, NS) is lost, AVAIL(NC, NS, 1) is set to a high number (9999) so that it is not considered for cargo. When this happens, STR is set to zero, and ships not in service can be identified by checking quarterly reports for STR = 0.0. Ships that receive slight damage are repaired and continue on their voyage, but when major damage occurs to a ship, it is diverted to the dockyard in port 3, and the day on which the ship is next available for cargo is found by adding the number of days necessary for repair (proportional to the level of damage) to the contents of AVAIL(NC, NS,1). Ships earn no revenue for voyages in which major damage occurs.

The cost of repairs, which is proportional to the amount by which STR is below the required minimum, is deducted from a ship's revenue register REV. If the ship completes its ballast passage without incident, the tonnage of cargo loaded is deducted from CARGO(NPX, NPI), and if the ship completes the loaded passage without incident, revenue is earned equal to the tonnage of cargo carried, multiplied by the freight rate FREIGHT(NPX,NPI). Earnings are added to the ship's revenue register REV, and voyage costs are deducted.

Operating costs included in the model are:

1. A constant amount per voyage to represent port dues, stevedoring charges, agents' fees and pilotage.
2. An amount proportional to the length of ballast and loaded passages, to cover the cost of fuel.
3. An amount proportional to the total time to represent wages and running costs. Wages are assumed to be proportional to the human reliablility of crew QCREW.

A report is made at the end of each season:

The first part of the report summarises the values of registers REV, VOY and STR for each ship. Where the voyage number is greater than 99, the last two digits only are shown. Ships that are not active or have been lost may be identified because the voyage number does not increase in subsequent reports. STR is shown as 0.0 for ships that have been lost.

REVENUE ⟶ 1231
VOYAGE ⟶ 15 0.68 ← STRUCTURAL SAFETY

The second part of the report shows the number of ships lost and damaged due to weather, collision, grounding or fire during the current season, and also the total numbers of such incidents since the beginning of 1995, which is the assumed starting date for the program.

The third part of the report gives the current contents of array CARGO(NPX,NPI), to show cargo remaining in each port at the end of the season. When too many ships are lost, or out of service for repairs, the quantities shown in consecutive reports will increase. A long term increase indicates that there are too few ships for the quantity of cargo to be carried.

At the end of the five year period, company statistics are summarised to show net earnings and the cost of casualties. The results of a systematic series of computer runs for a range of values of variables QCREW and MAINT(NC,NS) are discussed in Section 5.5.

5.1 Structural strength: deterioration, damage and repair

Strength analysis is concerned with determining the forces that are likely to act on a ship, and the ability of the ship's structure to resist them. The methods in use are complcated and some aspects have not been completely resolved, for instance, it is difficult to determine the minimum load under which a complex structure will fail.

In this simplified model, a real variable STR ($0 < STR < 1$) is used to represent safety of a ship's structure. STR is not a measure of structural strength or capability, but represents a probable level of safety from structural damage or collapse caused by physical means such as dynamic forces due to waves, weights in a ship, the impact of collisions, groundings or contact with other objects.

For a ship with a structure that is completely safe in all probable conditions, STR equals 1. This is not conceivable for a commercial ship so that $STR < 1$. For a fairly new ship which is well maintained and has no significant design or constructional deficiencies, a value of $STR = 0.85$ is assumed.

For a totally unsafe ship, STR equals 0. It is not likely that such a ship would continue trading as it would become a total loss within a very short period, so that $STR > 0$, and a minimum value of $STR = 0.3$ is used in the program.

A ship's owner, operator, flag state and classification society all have views about the standard to which a ship must be maintained. The minimum standards allowed by the flag state and classification society is to ensure reasonable safety from failure during the period between mandatory inspections of the hull. In this program it is assumed that hull inspections are carried out every 5 years, and that the standard of structural safety is evaluated with a high level of confidence. If STR is below the specified minimum at the time of a docking survey then the hull is repaired to bring it up to the required minimum. The cost of repairs is deducted from the net earnings stored in REV. Commercial or other considerations may induce an owner to maintain ships to a standard higher than the specified minimum and, in the program, this is implemented by company NC's maintenance policy MAINT(NC).

A ship's structural safety is assumed to diminish with time. Structural degradation is due to corrosion, localised damage, stresses imposed by vibration and loads in the ship, and by dynamic forces caused by waves and the ship's motion.

The linear component of hull deterioration due to corrosion and high frequency vibration is allowed for by reducing STR by a fixed amount in each time period. A linear degradation of 0.01 per year is assumed, and since the degradation is applied each quarter year, the value $DQSTR = 0.0025$ is used

$$STR = STR - DQSTR \qquad \dots (5.1.1)$$

Low frequency cyclic loads such as those caused by loading and discharge of cargo increase the rate of decrease in structural safety. It is assumed that the rate of degradation is proportional to the stress to which the structure is subjected. Various studies of still water bending moments (SWBM) indicate that the maximum values of SWBM are normally distributed about a mean value that is typical for a particular type of ship (Soares and Moan, 1988). The program therefore applies normally distributed values of deterioration in structural safety, generated using random numbers for each voyage.

Given two random numbers DRAN1 and DRAN2, where 0 < DRAN# < 1 , deterioration caused by low frequency cyclic loads is assumed to be given by:

$$\text{MDSTR} + \text{SDEV} \times \text{LOG}(\text{DRAN1}) \times \text{COS}(2 \times \text{DRAN1}) \quad \ldots (5.1.2)$$

(Edwards and Hamson, 1989)

where MDSTR is the mean daily reduction in structural safety, and SDEV is its standard deviation.

Since a ship may be under stress while in the loaded or ballast conditions, and while loading or discharging, the reduction in STR is applied each day the vessel is on passage or working cargo.

Medium and high frequency cyclic loads such as those caused by the ship's motion in a seaway also cause a progressive deterioration in structural safety. As with low frequency loads, it is assumed that deterioration varies linearly with loading, but not necessarily with the same constant of proportionality. The forces to which the ship is subjected vary with weather, wave length and height, and the ship's course and speed relative to the waves. For simplicity, the ship's course and speed are ignored and the rate of deterioration is based on seasonal climate factors. This may be a reasonable assumption over a long period and each ship is treated in the same manner for outward and return voyages.

For each route between ports in the model, a seasonal climate factor α is given by an integers in the range 1 to 9, with higher values of α indicating a greater probability of rough seas. The Rayleigh distribution is used to provide a relation between α and the probability of a given sea state, as illustrated in Figure 5.1.1.

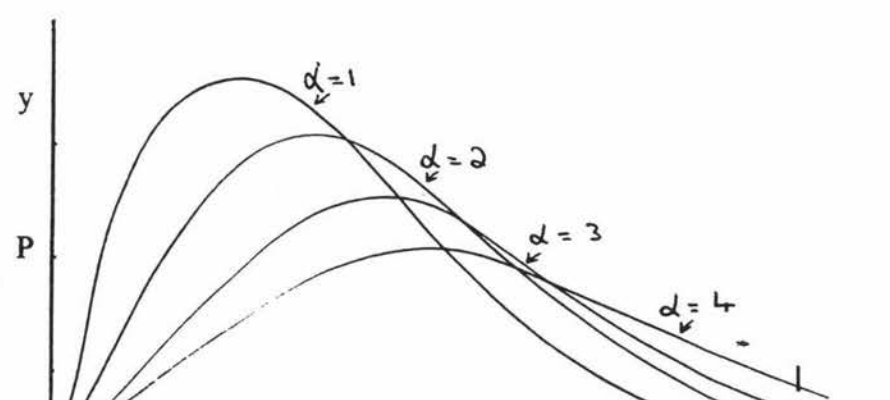


Figure 5.1.1 Rayleigh distributions for different climate factors

For low values of α, the distribution is highly skewed with maximum y occurring at a low value of x. As α increases, maximum y occurs at increasingly greater values of x. Multiplying the area bounded by the curve, the x-axis and line x = 1 by a constant to make it approximately equal to unity enables the area below the curve up to a given value of x to represent the probability of weather conditions not worse than that represented by the value of x in the range $0 < x < 1$.

For $x > 0$ the Rayleigh distribution function $F(x)$ is given by:

$$F(x) = 1 - \exp(-x^2 / 2.\alpha^2)$$

This expression is rearranged to give:

$$x = \{ -2.\alpha^2.\ln[1 - F(x)] \}^{1/2}$$

If $[1 - F(x)]$ is given by a random number RND1, where $0 < \text{RND1} < 1$, then

$$x = \{ -2.\alpha^2.\ln[\text{RND1}] \}^{1/2} \quad ... \ (5.1.3)$$

Figure 5.1.2 shows the Rayleigh distribution for a given value of parameter α. In the program, X is calculated so that the area under the curve up to x = X is equal to RND1. It is assumed that X is proportional to the expected severity of weather conditions on a particular day, and since structural deterioration is proportional to loading, the structural deterioration applied to the ship on that day is a function of X.

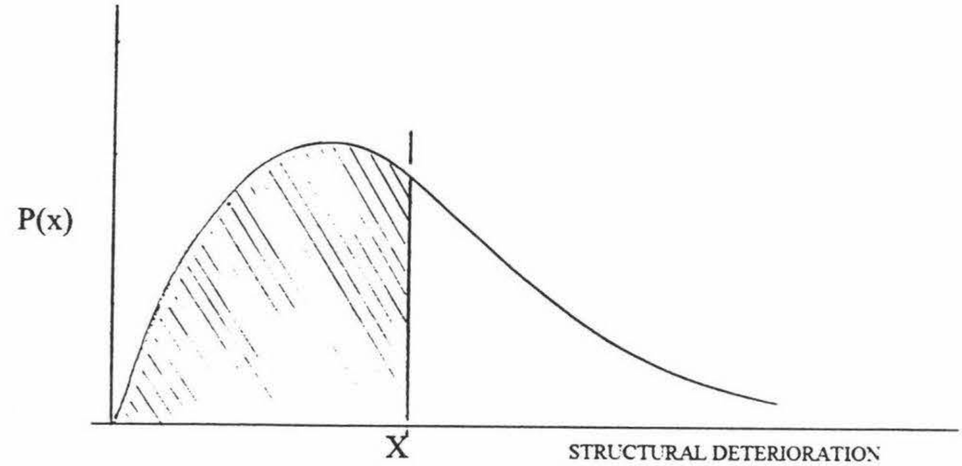


Figure 5. 1. 2 Probability of deterioration in ship's structural safety

The deterioration of structural safety due to dynamic forces is applied each day a ship is on passage, but not during loading and discharging operations in port.

Climate factors and the Rayleigh distribution are also used to simulate the probability of rough weather that can damage a ship. The probability of a ship being lost or damaged depends on the severity of the storm encountered and the current standard of structural safety of the ship. Should the forces acting on the ship exceed the ship's capacity to resist those forces, the ship becomes a total loss.

In the program, a ship's ability to resist storm damage is a function of STR. If the weather condition WFORCE exceeds the value of STR, then the ship becomes a total loss, and if WFORCE exceeds $K_D \times$ STR, where K_D is a constant, then the ship is damaged and requires repairs, the cost of which is a linear function of the amount by which WFORCE exceeds $K_D \times$ STR. After the loss of a ship, STR is set at zero, and since a ship is not accepted for transporting cargo unless STR is greater than 0.3, the ship is no longer in operation.

5.2 Collision

When two ships approach one another, there exists a probability that they will collide. The International Regulations for the Prevention of Collisions at Sea are intended to reduce this probability by standardising behaviour so that the navigator on each ship should know what action to take, and what action to expect from the other ship. Although the regulations reduce the probability of collision they cannot guarantee that both navigators will interpret the situation correctly, and take suitable action to avoid collision.

Suppose that there is an adequately trained and experienced watchkeeper on the bridge of one ship when another ship is encountered. For each type of encounter, the collision regulations specify whether each ship should give way or stand on. Provided vessels take the correct action in sufficient time, collision is avoided. However, when one of the two vessels does not take appropriate action, there is an increased probability of collision. Thus even when the navigator is adequately trained there is still some probability that the other ship will take unpredictable action which will lead to collision. If the navigator on the first ship is less well trained and experienced, the probability of collision will be greater. This justifies the assumption that when a ship is approached by another ship the probability of collision is not zero. The probability of collision is small when the watchkeeper is well trained and experienced, and increases for watchkeepers with less training and experience.

As the number of ships encountered increases, so does the probability of collision. If additional ships are considered separately, then the probability of collision would increase linearly with the number of ships. If more than one ship is encountered at a time, the watchkeepers mental workload increases, while the other ships may also interact by altering course or speed in the attempt to keep out of each others' way. This causes the probability of collision to increase in greater than linear proportion to the number of ships involved, as shown in Figure 5.2.1.

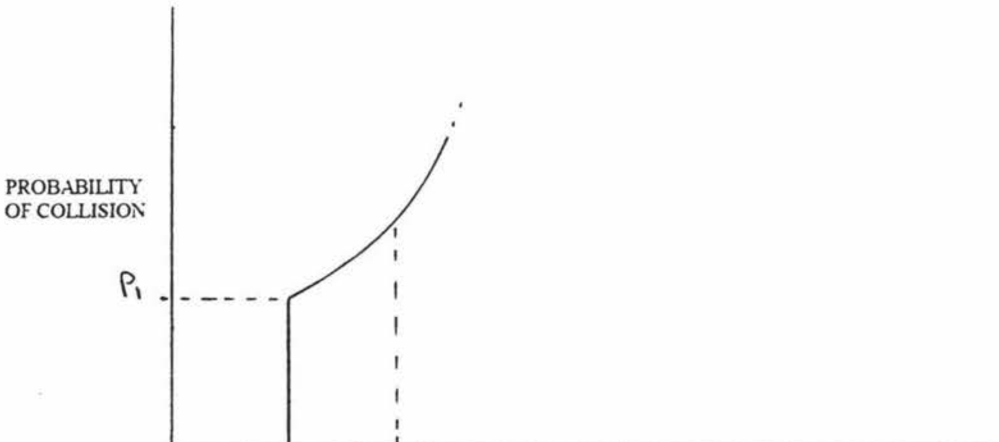


Figure 5.2.1 Probability of collision when several ships are encountered

As the rate of encounter with other ships increases, the probability of collision increases with upward curvature. But at some rate of encounter, determined by the watchkeeper's ability, another factor comes into play. The watchkeeper will realise that a dangerous situation is developing, and take some action to reduce the probability of collision. The watchkeeper may call the master who is more experienced and who will, if necessary, reduce speed, stop the ship or modify the passage plan. The shape of the probability curve should change to negative curvature, and become asymptotic to some maximum probability of collision. The curve of probability of collision will thus take the form shown in Figure 5.2.2.

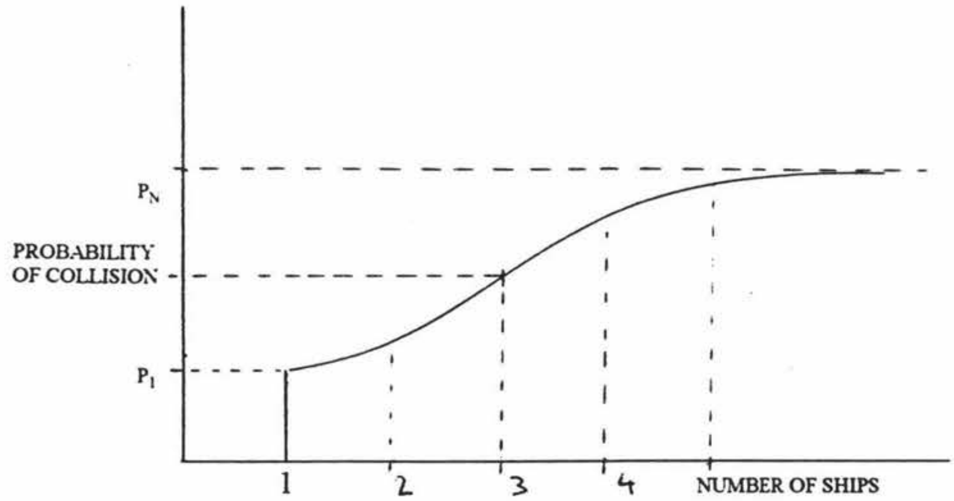


Figure 5.2.2 Probability of collision

The curve in Figure 5.2.2 is modelled using the following expression:

$$\text{PROBCOL} = \frac{\text{PN}}{[\,1 + (\,\text{PN} / \text{P1} - 1\,)] * e^{-\nu N}} \quad \ldots\ldots\ldots\ldots (5.2.1)$$

(adapted from Burghes and Borrie, 1981)

where P1 is the probability of collision when one ship is encountered, PN is the maximum probability of collision and PROBCOL is the probability of collision with one ship when N ships are encountered. ν determines the slope of the curve and the number of ships encountered at the point of inflection of the curve.

P1 and ν are related. P1 depends on the watchkeeper's training and experience, and for a very inexperienced watchkeeper this may be high, but this may be compensated for by calling the master as soon as the situation looks as though it is likely to get beyond his capability, and also by the master realising that the watchkeeper is inexperienced, and keeping alert to the traffic situation. The slope constant ν and maximum probability of collision PN depend on interaction between the watchkeeper and the master, and may be a function of the quality of organisation.

Frequency of encounter

In areas is low traffic density, the probability of encountering no ships at any particular time is high and the probability of encounter with N ships decreases with N. As the traffic density increases the probability distribution for encounter rate will change as shown in Figure 5.2.3.

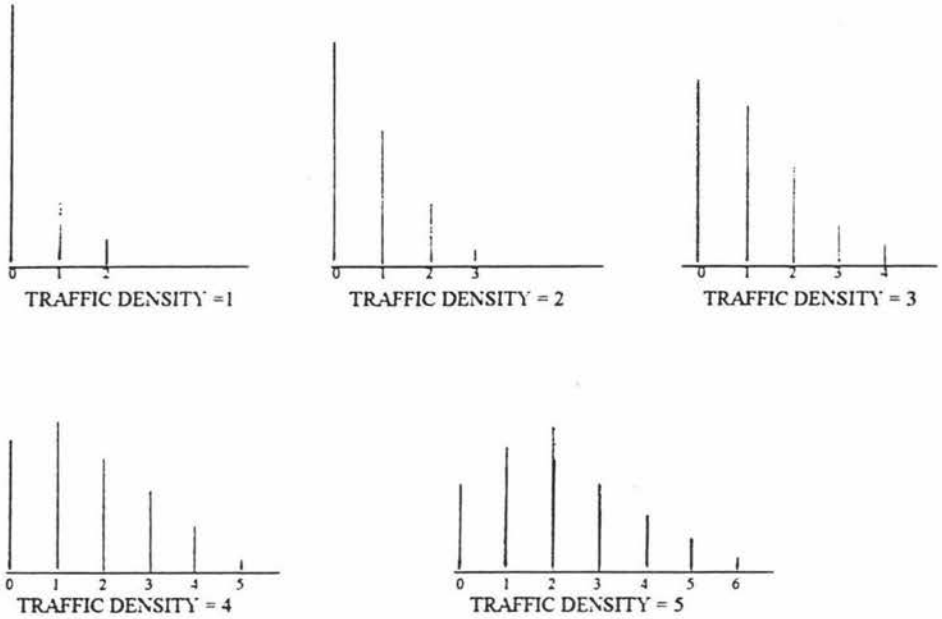


Figure 5.2.3 Encounter probabilities for different vessel traffic densities.

Some of the difficulties with defining and measuring traffic density have been discussed in Section 4.7. The problems associated with encountering different types and sizes of ships are ignored in this model, and traffic density is specified by a single parameter "N". The exact nature of "N" is not specified and there are several possible measures that could be suitable. For example, in a particular area, "N" could be the average number of ships that pass within a specified distance of a ship on a given course and speed during a 24 hour period.

In the program, integer values representing traffic density are stored in a matrix array HAZCOL(I,J) for each interval of 360 nautical miles along each route, 360 miles representing the distance travelled in 24 hours when steaming at 15 knots. Given the port at which a ship becomes available, the export port and import port, traffic density along the route for the ballast voyage and loaded voyage is read from the array. For a given average traffic density a Poisson distribution gives the probability that a specified number of ships will be encountered as illustrated in Figure 5.2.3. A random number TRAFFIC is used to simulate the number encountered, for example if the traffic density is 3 and TRAFFIC is 0.5 then 1 ship is encountered, and if TRAFFIC is 0.99 then 4 ships are encountered.

Once the number of ships encountered is found, the probability of collision PROBCOL is calculated. A random number RISKCOL is then used to decide whether a collision takes place. The level of damage due to the collision is in direct proportion to PROBCOL, and inversely proportional to QCREW and STR. The incidence of total loss and damage that necessitates repair is determined by the level of damage, and treated in the same way as damage due to rough weather.

5.3 The probability of grounding

Casualty returns show that between 20 and 30 percent of ship losses are due to grounding. The grounding of ships has resulted in relatively few lives lost, but there has been a large amount of tonnage damaged and lost, and damage by oil pollution is more likely than in other types of ship casualties. Most groundings are caused by navigational errors or misjudgement in handling ships, but some are the result of machinery or equipment failures. There have been incidents of ships grounding on uncharted shoals, but these are relatively rare and most groundings occur in well-charted waters, particularly near harbour entrances. A number of factors influence the probability of a ship running aground during normal operations, these include:

- The navigational characteristics of the area in which a ship is operating, particularly the depth of water and width of channels.

- Vessel traffic levels and the type of traffic encountered.

- The effectiveness of navigational management on board ship.

- Experience and ability of masters, pilots and navigators.

- Size and manoeuvrability of ships.

- Weather, tidal movements and the time of day or night.

To assess the probability of a ship running aground, some of these parameters must be quantified. This model uses data and observations collected by Fuji (1979), referred to here as Japanese data, and Lusted (1977), referred to here as British data. Although this data is limited and probably out of date, it is necessary for the development of the simple framework that is used in the model.

Japanese data showed that 99 percent of groundings happen within 12 miles of a coast, and British data indicates that about 55 percent of groundings were in port approaches, and a further 40 percent in coastal waters. For port approaches, the main factor is the nature of the port. In Japanese ports the frequency of groundings per 1000 port entries varied from 0.52 ± 0.3 for large industrial ports, to 0.72 ± 0.4 for medium sized ports. The frequency of grounding for merchant ships was greater at ports where there was a large fishing fleet. In this model, each port is assigned a constant PPG(I) which is proportional to the assumed frequency of grounding:

PPG(1) = 0.5 PPG(2) = 0.4 PPG(3) = 0.9 PPG(4) = 0.7

Most groundings occur because of some type of human failure. Human involvement may be direct as in the failure to plan a passage, or to take account of available information, or there may be an error of judgement when manoeuvring in confined waters. Human involvement in a grounding can be less direct, such as the failure to consider the possibility of equipment error. Occasionally groundings are caused by events that are beyond the control of human operators, such as an unexpected squall or a breakdown of main propulsion or steering at a critical phase in a voyage. In the British data, only 16 percent of groundings involved machinery or equipment failure.

The data suggests the following weightings:

Human involvement	0.84
Navigational equipment failure	0.08
Machinery failure	0.08

The availability of GPS (global positioning system) since the collection of this data could justify a smaller weighting for navigational equipment failure.

These weightings enable the probability of grounding to be related to the variables QCREW, NAV and MCY to determine a variable XGROUND used in the model.

$$XGROUND = 0.84 \times (1 - QCREW) + 0.08 \times (1 - NAV) + 0.08 \times (1 - MCY) \quad ... (6.3.1)$$

Weather and visibility

The probability of running aground increases in heavy weather and in low visibility. In the British data, 21 percent of groundings were in heavy weather and 24 percent in low visibility. The Japanese data showed an inverse relation between the number of groundings and the meteorological visibility.

In this model a seasonal visibility indicator VIS, which is an integer between 0 and 10 is utilised, with10 representing perfect visibility all the time, and 0 representing zero visibility all the time. A practical range of 9 to 3, with an average of 6, is used since no areas experience continually perfect or continually zero visibility. The following log-linear relationship is assumed between the visibility indicator and the probability of grounding.:

$$- 0.48 \times \ln(VIS / 10)$$

so that when VIS is 10, poor visibility makes no contribution to the probability of grounding, and when VIS is 6 (giving the mean probability of poor visibility), then poor visibility makes a 24 percent contribution to the probability of grounding.

A linear relationship is assumed between the probability of grounding and the seasonal weather indicator stored in the matrix array DDIST(QTR, I, J) for season QTR along the route between ports I and J. The weather indicator is an integer in the range 1 to 9, with 1 representing a high probability of fine weather and 9 representing a high probability of rough weather. A mean value of 5 is assumed so that the contribution of rough weather to the probability of grounding is given by:

$$0.21 \times DDIST(QTR, NPX, NPI) / 5$$

The effect of the weather and visibility on grounding is given by:

$$EGROUND = - 0.48 \times \ln(VIS / 10) + 0.042 \times DDIST(QTR,NPX,NPI) \quad ... (5.3.2)$$

A multiplicative relation is assumed between the contributions to the probability of grounding attributable to the port, the ship and the weather. The probability of grounding would be highest in the case of a ship manned by inexperienced personnel, working with defective equipment, approaching a difficult port in bad weather.

The probability of grounding is given by:

$$PROBGD = PPG(I) \times XGROUND \times EGROUND \quad ... \quad (5.3.3)$$

For each port entry and departure, a random number RISKGD is used to determine whether a ship will run aground during the arrival and departure passages. In reality there is a greater probability of running aground during an arrival passage, and while in the loaded condition, but in this program no distinction is been made between arrival and departure passages, nor between loaded and ballast conditions. Since some ports are predominantly exporting ports and others predominantly importing ports, the four conditions; departure in ballast, arrival in ballast, departure loaded and arrival loaded are not evenly distributed amongst ports.

If PROBGD > RISKGD then the ship runs aground. The level of damage and whether the ship becomes a total loss is determined by PROBGD and treated in the same way as damage by rough weather.

5.4 The probability of fire

Section 4.9 describes a chain model for the probability of a ship being lost or damaged by fire. The chain model involves a complex interaction of many factors and a much simpler model is considered here. The probability of loss or damage by fire depends on:

The probability of a fire starting,
The nature, quantity and disposition of combustible material,
The interval of time between ignition and detection,
The probability of extinguishing a fire once detected.

The ships considered in this model are all 25 000 tonne bulk carriers which transport identical cargoes. The fire characteristics of the cargo are not considered in the model, but the intrinsic fire safety of a ship is given by the variable STF. Initially STF is determined by the design of a ship, and depends on factors such as the protection of combustible material from heat sources and the number of fireproof bulkheads that can restrict the spread of fire. STF deteriorates with respect to time if the ship's fire protection is not given sufficient maintenance and care; fire doors and dampers corrode and can become seized, combustible material can accumulate in store rooms, fuel pipes can be damaged and if not repaired properly can leak so that fuel accumulates in engine room bilges and inaccessible areas. The rate of deterioration is a function of the quality of organisation and crew, but it is initially assumed that STF deteriorates at a linear rate with respect to time. The value of STR is reduced each quarter year by an amount equal to DSTR. As with STF, a ship's fire safety is checked at annual surveys and if below the minimum requirement, repairs are carried out which results in a cost to the ship.

The probability of a fire starting is highly dependent on the human reliability of the crew, represented by the variable QCREW in this model. A study by Japan's classification society, Nippon Kaiji Kyokai indicated that just under 50 percent of ship fires start in the engine room, and that the predominant cause is human error (MER, 1994).

The probability of a fire starting is assumed to be given by an expression of the type::

$$PFIRE1 = K_1 \times (1 - QCREW) + K_2 \times (1 - MCY) \qquad \ldots (5.4.1)$$

where K_1 and K_2 are constants and MCY is a measure of the condition of the ship's machinery. In this program, assumed values $K_1 = 0.7$ and $K_2 = 0.3$ are used.

A random number is used to determine whether a fire starts:

$$\text{IF } PFIRE > K_3 \times RND \text{ then fire breaks out}$$

where the constant $K_3 = 1200$ is set to give the expected average number of fires.

Once started, fire will spread at a rate determined by STF, and its severity will depend on the time taken to detect the fire, which is once again a function of the human reliability of the crew.

$$TIME = K_4 \times RND / QCREW$$

where $K_4 = 0.1$ is a time constant and RND is a random number ($0 < RND < 1$)

$$\text{If } \chi = 1 / STF$$

then the severity of the fire XFIRE is given by $0.8 \times TIME^{x}$, which increases exponentially with time at a rate inversely proportional to STF.

The variable FIRE represents the condition of the ship's fire appliances, and gives a measure of the severity of the fire that can be extinguished. Comparing XFIRE with FIRE, the program determines whether the ship suffers damage or is lost as a result of the fire.

5.5 Results and observations

The computer model uses a number of constants which have to be set to give reasonable results. Examples are; weather damage occurring when the force due to weather exceeds the value of the variable STR multiplied by constant K_D, and fire breaking out if the probability of fire exceeds a random number RND ($0 < RND < 1$) multiplied by constant K_3. Published casualty statistics are for total losses, but partial losses are much more frequent, and are more significant than total losses in this program. It was therefore necessary to make some assumptions that could not be supported by data in order to develop the model.

After setting the human reliability (QCREW) of each ship's crew to 0.6, and the maintenance policy (MAINT) of each company to 0.6, the program was run using assumed constants, and these constants were adjusted incrementally to give the expected number of shipping casualties for simulated five year periods. If the annual casualty rate for the world fleet is between 0.5 and 0.75 percent, then for 50 ships it is expected that one or two may be lost in five years. It was assumed that there would be approximately 50 incidents, divided about equally between weather damage, collisions, groundings and fires. Adjusting the program to give this output proved difficult because of the element of uncontrollable randomness programmed into the stochastic model, and the interaction between failure modes. For instance, adjusting constants to increase the number of collisions affects the frequency and distribution of fires, groundings and weather damage, even though the constants adjusted are not used in the routines for generating other casualty modes. As set, the program tends to generate more collisions and less fires than was intended.

The program was then run, without further adjustment of constants, to simulate the five year operating period from 1995 to 2000. The variables QCREW and MAINT were altered systematically and the cost of accidents was used as an indicator of total ship safety. The cost of a total loss was the present value of the ship, discounted from its value in 1995 at an annual rate of 10 percent. For partial losses, costs were calculated by a multiplying levels of damage by a constant (4 million dollars), with no allowance for a ship's age. These results are now discussed:

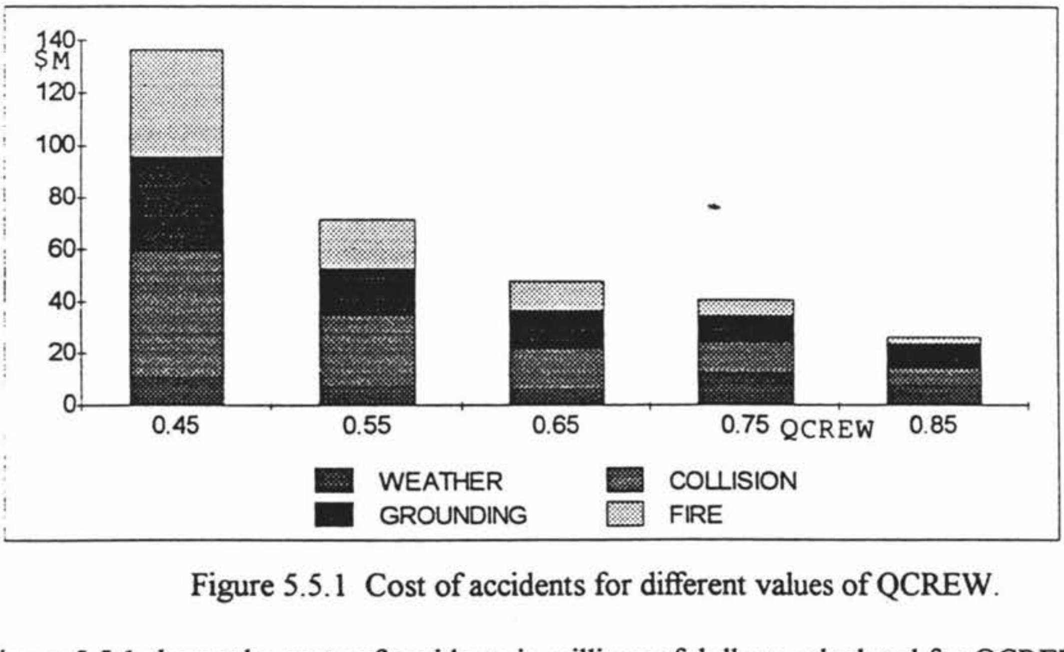


Figure 5.5.1 Cost of accidents for different values of QCREW.

Figure 5.5.1 shows the costs of accidents in millions of dollars, calculated for QCREW = 0.45, 0.55, . . . , 0.85. The figure shows that the cost associated with fires, groundings and collisions falls with an increase in QCREW, but that the cost of weather damage is not sensitive to changes in human reliability. This is expected because the variable QCREW is used in the program-routines for fires, groundings and collisions, but the possibility that ships' crews will take precautions to limit damage caused by rough seas was not taken into account.

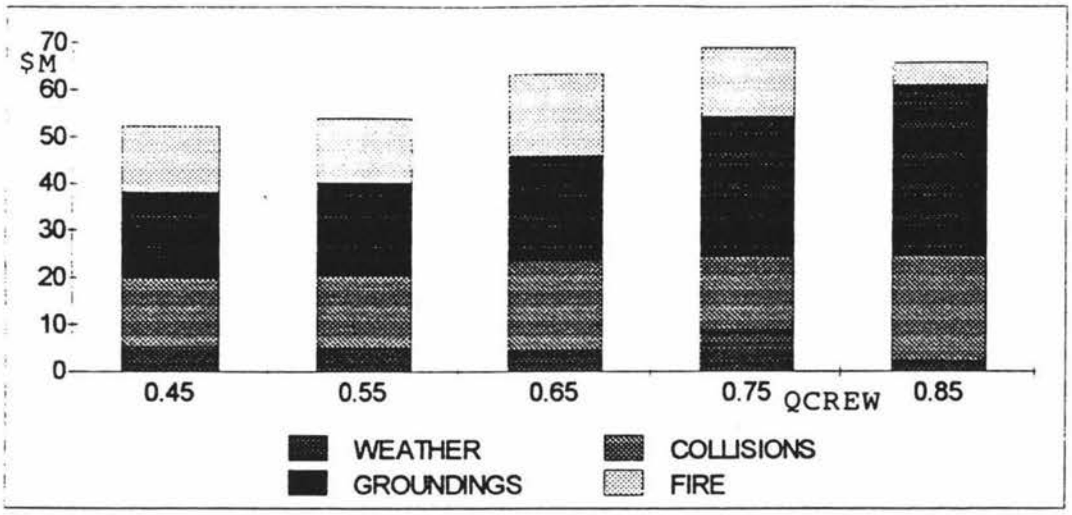


Figure 5.5.2 Cost of accidents for different values of MAINT.

Figure 5.5.2 shows the cost of accidents in millions of dollars, calculated for MAINT = 0.45, 0.55, . . . , 0.85. The figure does not indicate that the cost of accidents is sensitive to companies' maintenance policies. This is because structural safety, given by the variable STR, is checked every five years, so that the structural safety of each ship is upgraded to the standard given by MAINT only once in the simulated five year period. Each ship's fire safety STF and condition of fire appliances FIRE are checked and upgraded to the standard given by MAINT each year, in the quarter during which the anniversary month SHIP(NC, NS, 13) happens to fall. It is expected that for longer term simulation, the cost of fires and weather damage should fall with an increase in MAINT.

The model assumes that there are costs associated with increasing the values of QCREW or MAINT. A company's time-dependent costs include: recruitment, training, wages, travel, victualling, accommodation and personnel management, and in the program a ship's daily non-voyage-related cost is given by 6000 + 3000 x QCREW. Although an increase in QCREW reduces the cost of accidents, it increases a ship's running cost and thus affects the company's profits. Figure 5.5.3 shows the total profits for the five shipping companies over five years to a base of QCREW. The figure indicates that maximum profits occur for QCREW of about 0.6. Since profits are the difference between REVENUE and COST, which are both large numbers relative to profits, the large variations in profit associated with small changes in QCREW can be expected. The frequency and severity of accidents are associated with the extreme ends of probability distributions, and relatively minor changes to initial conditions can lead to large differences in outcome.

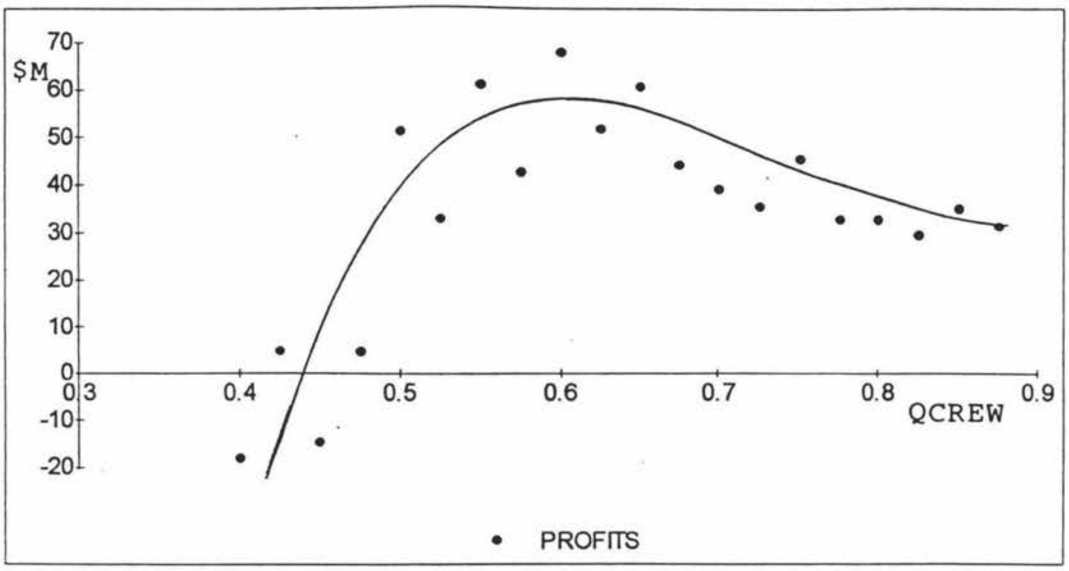


Figure 5.5.3 Total profits to a base QCREW (MAINT = 0.6).

The relationship between QCREW and profit shown in Figure 5.5.3 would not be apparent if competitive allocation of ships was introduced into the program. In this case, companies would bid down the freight rate until all profits were zero.

Figure 5.5.4 shows the standard deviation σ_{n-1} of the variation from the mean profit made by individual shipping companies. The linear regression line fitted to the data for standard deviation of company profits is 9.6 - 7.3 x QCREW showing that an increasing value of QCREW is associated with a smaller variation in profits. In Chapter 3 it was noted that income utility increases as income becomes more certain, and the effect of this is that maximum income utility occurs at a higher value of QCREW than maximum profits.

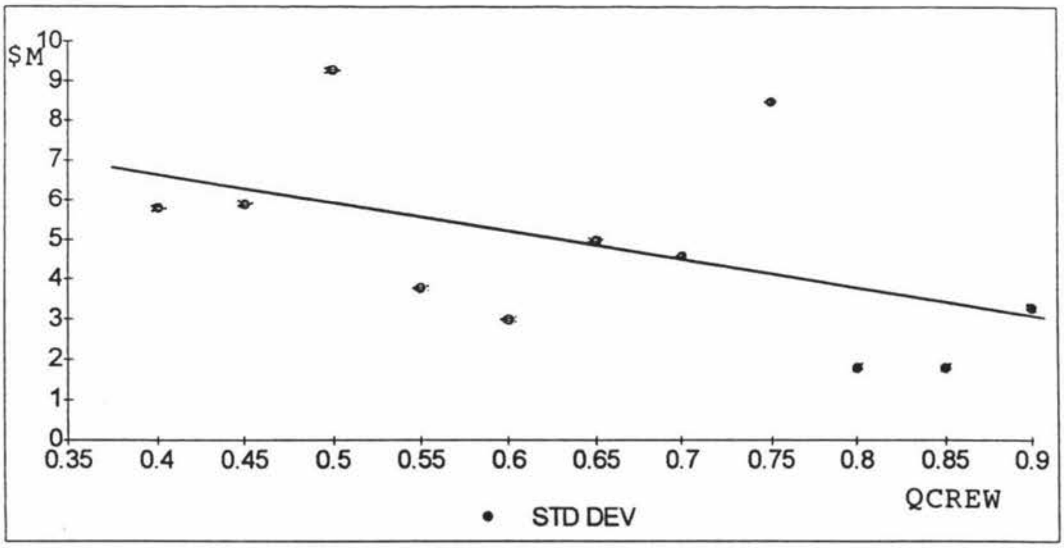


Figure 5.5.4 Standard deviation of profits for shipping companies to a base QCREW.

The increased cost associated with a higher standard of maintenance is due to repair of ships' structures at five yearly intervals when STR has fallen below MAINT, and repair or replacement of fire appliances each year when STF and FIRE have fallen below MAINT. The cost is directly proportional to the difference between actual standards, STR, STF and FIRE, and a company's policy standard MAINT. As for cost associated with improved human reliability of crews, the increased repair costs reduces company profits, and total profits for the five companies is shown to a base of MAINT in Figure 5.5.5.

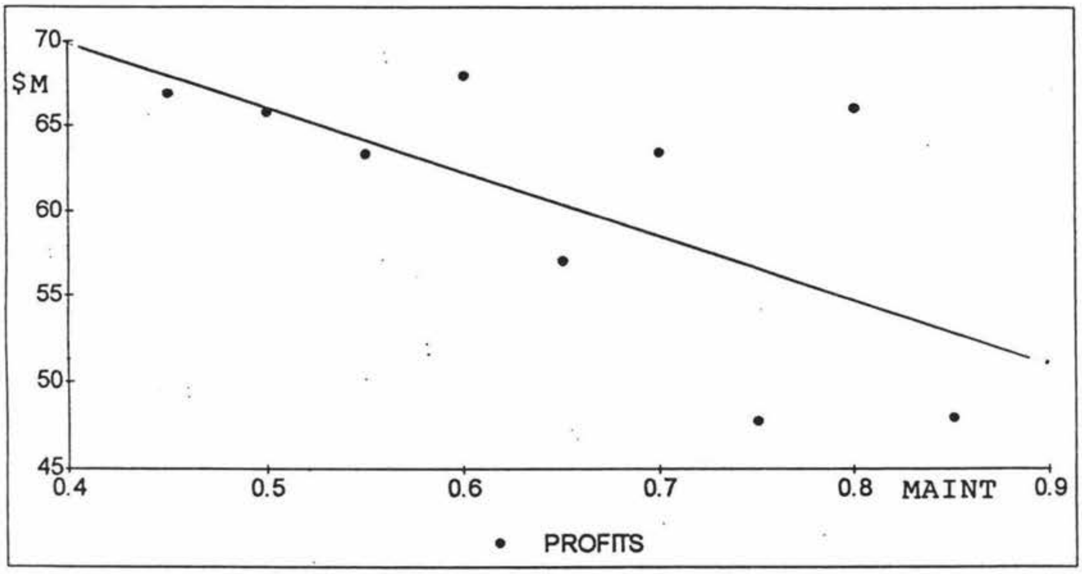


Figure 5.5.5 Total profits when to a base MAINT (QCREW = 0.6).

Figure 5.5.5 shows profitability decreasing with an improvement in standards of maintenance, and the linear regression line fitted to the data is:

$$\text{PROFIT} = 84.6 - 36.8 \times \text{MAINT}$$

The program does not relate the three components of structural deterioration (described in Section 5.1) to the present structural safety of a ship, and in practice a ship with a higher standard of structural safety should deteriorate at a lesser rate. This would reduce costs for companies with high maintenance standards. The variability of company profits σ_{n-1} increases as MAINT increases, and this reflects the greater costs of repairs carried out at one and five yearly intervals.

Although this computer model is based on hypothetical mathematical relationships and assumed constants which have not been verified, it could provide the basis of a tool for the investigation of ship safety concepts. Interactions between failure modes and the variability of costs and profits reflect what could happen in reality, although the facility to predict the results of a particular policy is very limited. Development of such models could benefit the understanding of the nature of ship safety, and may even help to assess the possible outcome of different policies with regard to standards of construction, maintenance, training and ship operations.

Chapter 6

Conclusion

Several maritime technical reports have recognised a need for scientific assessment of the overall safety of ships. Shipping professionals have become increasingly specialised, and designers, builders, owners, managers, operators, masters, engineers, surveyors and administrators each have a range of interest in aspects that make up safety. A great deal of effort and imagination has been applied to assessing particular aspects of safety, but safety crosses the boundaries between specialisations and an interdisciplinary approach is called for. Since mathematical techniques are applied to many aspects of ship safety, a mathematical model could provide a suitable link between disciplines.

The investigation addresses the question: "Is it feasible to develop a mathematical model of ship safety that will allow for the evaluation of relative levels of safety?" The initial approach was to examine the concept of ship safety in order to define exactly what was being assessed. It was apparent that there are conceptual difficulties to establishing measures of safety, and that although the term "safety level" appears often in the technical literature, statements about level of safety are subjective and depended on the experience and perceptions of the assessor. It was recognised that any measurement or quantitative assessment must refer to a well defined subset of ship safety.

The measures currently used to judge the safety performance of shipping are very limited. Two measures that are quoted in reviews of ship safety are related to the total loss of ships. These are:

Number of ships lost / Number of ships at risk
Tonnage of ships lost / Tonnage of ships at risk

The data is mainly for ships of gross tonnage more than 100, and measures based on the number of ships lost is dominated by the large number of small ships at risk and involved in casualties. Measures based on the tonnage of ships are dominated by a relatively few very large ships, for example the loss of one tanker of gross tonnage 200 000 will indicate a greater casualty rate than all ships of gross tonnage less than 2000 lost in any year.

However determined, the rate of total losses does not fully reflect the damage caused by shipping casualties and accidents. The statistical population of total losses is small relative to the loss of life, injuries, loss of property and damage to the environment caused by shipping casualties. A more appropriate approach could be to consider the overall reliability of sea transport with an index such as:

$$R = 1 - \{ \text{cost of incidents} / \text{value added by sea transport} \}$$

where the cost of incidents includes the shadow cost attached to lives lost and injuries sustained, as well as the cost of all property damage and damage to the environment.

The value added by sea transport may be a more appropriate base than the value of property at risk, and would eliminate the paradox whereby under-utilised ships appear safer than ships that are carrying out the function for which they are intended.

The elements of the above equation can be determined in principle. Techniques have been developed to calculate the value of human lives (Jones-Lee, 1976) and of the suffering due to injuries sustained in shipping casualties. The value of property lost and damaged can be estimated, and the compensation needed to repair third party damage and to restore the environment may be calculated. But in practice such estimates are extremely difficult to make, due mainly to the limited information available about marine accidents on a global scale. A thorough investigation of each incident would be necessary to establish the type of data needed, and it may only be possible to obtain the more general measures provided by the number and tonnage of ships lost and the number of lives lost.

The measures discussed so far are of safety performance, that is a determination of the level of safety by the resultant accident rate. The alternative approach is to attempt to determine the potential safety of the system, that being how well suited are ships, their equipment, organisation and personnel to meet the expected conditions. In the first type of measure, random events such as storms, poor visibility and poor human performance are implicit, while in the second type they must be explicitly stated.

Analysis of the individual elements that influence safety has been discussed in Chapter 4. If each element was independent of all other elements then the assessment of total safety could be stated as a linear function. If X_i denotes a given level of failure of a particular element, then the probability of failure of the ship is given by:

$$\text{risk} = \sum_{i=1}^{n} X_i . P (X_i)$$

where $P (X_i)$ is the probability of a failure level X_i, and ship safety can be expressed as

$$\text{safety} = 1 - \text{risk}.$$

In Chapter 4, it was seen that, far from being independent, most ship safety elements interact with other elements. A dependency matrix for ship safety elements is shown in Figure 6.1, in which N_{ij} represents the type of influence that the element in row i has on the element in column j.

and $N_{ij} = 0$ means that element i has no effect on element j
$N_{ij} = 1$ denotes an incidental or slight effect
$N_{ij} = 2$ means that i influences j, but that the effect occurs at the design or planning stage
$N_{ij} = 3$ denotes a direct influence

	STRUCTURE	STABILITY	FREEBOARD	SUBDIV'N	MOTIONS	MANOEUV'TY	PROPULSION	STEERING	AUXIL'IES	OPERATIONS	ORGAN'Z'ION	HUMAN INV	MAINT'CE	COMM & LSA
STRUCTURE	-	3	3	2	2	2	2	2	2	3	1	3	3	1
STABILITY	3	-	3	2	3	2	2	1	1	3	1	3	1	1
FREEBOARD	3	3	-	2	3	3	3	3	2	3	1	3	2	2
SUB-DIVISION	2	2	2	-	1	0	1	0	1	3	1	3	2	1
MOTIONS	3	3	2	2	-	3	3	3	3	3	1	3	3	3
MANOEUV-RABILITY	2	2	2	0	3	-	2	3	1	3	1	3	0	0
PROPULSION	2	2	2	2	3	3	-	3	3	3	2	3	3	1
STEERING	1	1	1	0	3	3	2	-	2	3	1	3	1	1
AUXILIARIES	1	3	1	1	1	3	3	3	-	3	1	3	3	3
OPERATIONS	2	3	3	2	3	2	3	2	3	-	3	3	3	3
ORGANIZAT-ION	2	2	2	2	2	2	3	3	3	3	-	3	3	3
HUMAN INVOLVEMENT	3	3	3	2	3	3	3	3	3	3	3	-	3	3
MAINTENANCE	3	1	0	0	0	1	3	3	3	3	1	3	-	3
COMMUNICAT-ION & LSA	0	1	1	0	0	0	0	0	0	2	3	3	2	-

Figure 6.1 Dependency matrix for ship safety elements

0 - no dependency from row to column

1 - dependency slight or incidental

2 - dependency at design or planning stage

3 - direct dependency

The matrix is asymmetric, for example H(4,10) = 3 and H(10,4) = 2 ; the subdivision of a ship determines the way in which the ship is loaded and this has a direct influence on the operation of the ship; while the operation of the ship does not change its subdivision, but operational aspects are considered at the design stage. The frequent occurrence of 2 and 3 in the matrix shows a high level of interaction between the different elements of ship safety. It is therefore unlikely that a linear model could provide a valid measure of total ship safety.

In Chapters 2 and 3, the influence of economic and political forces on ship safety were discussed. Changes in the level and pattern of world trade tend to reduce the general level of ship safety; a decrease in the demand for shipping services resulting in less resources being allocated to safety, and an increase in demand resulting in the employment of old ships that would have been due for scrapping in times of lower demand. Political forces influence the pattern of world trade and also the attempts by IMO and national administrations to use regulation to improve safety. The result of regulation was seen as often being unpredictable, and there was no guarantee that the reallocation of resources brought about by regulation would improve safety. Another important influence is technological development, for example the availability of cheap, accurate GPS for ships has revolutionised ocean and coastal navigation, while the provision of totally enclosed lifeboats and emergency radio beacons has improved the chance of survival after a shipping casualty. There are many positive and negative influences on ship safety which may be seen as part of a complex dynamic system illustrated in Figure 6.2. The figure is intended for illustration only as there may be numerous other influences that have not been included. Although a dynamic system can be represented by systems of equations, a great amount of preparatory work and observation would be necessary in order to develop a model of such a complex non-linear system.

Mathematical methods used in connection with various elements of ship safety were discussed in Chapter 4. The methods have been developed or adapted to solve specific problems such as to assess stress in a structure or the tendency to resist capsize. In Table 6.1 it is seen that various mathematical methods are associated with particular failure modes, and the question arises as to whether selected mathematical methods could be integrated to form a general model of ship safety.

Some of the methods were developed rigorously from basic principles but still contain an empirical element. The methods give results which are compared with results for successful ships calculated by the same method. In most cases the results cannot be related to the results for ships in a limiting condition immediately before failure, and so the methods cannot be used directly to establish the probability of failure. It is therefore apparent that most of the useful and rigorous mathematical methods for solving specific problems associated with ship safety are not compatible with one another and may not be integrated into more general models.

The stochastic nature of ship casualties suggests that a model of ship safety should be a probabilistic model. The probability of a ship casualty is approximately the sum of the probabilities of each type of casualty and thus methods to establish the probability shown in Table 6.1 could be combined to determine the probability of a casualty. An attempt to use simple models for the probability of structural failure, collision, grounding and fire was discussed in Chapter 5. The model is for a small idealised shipping industry, and although it demonstrates the use of probabilistic techniques for modelling shipping casualties, it may be difficult to validate and therefore may not have direct practical application.

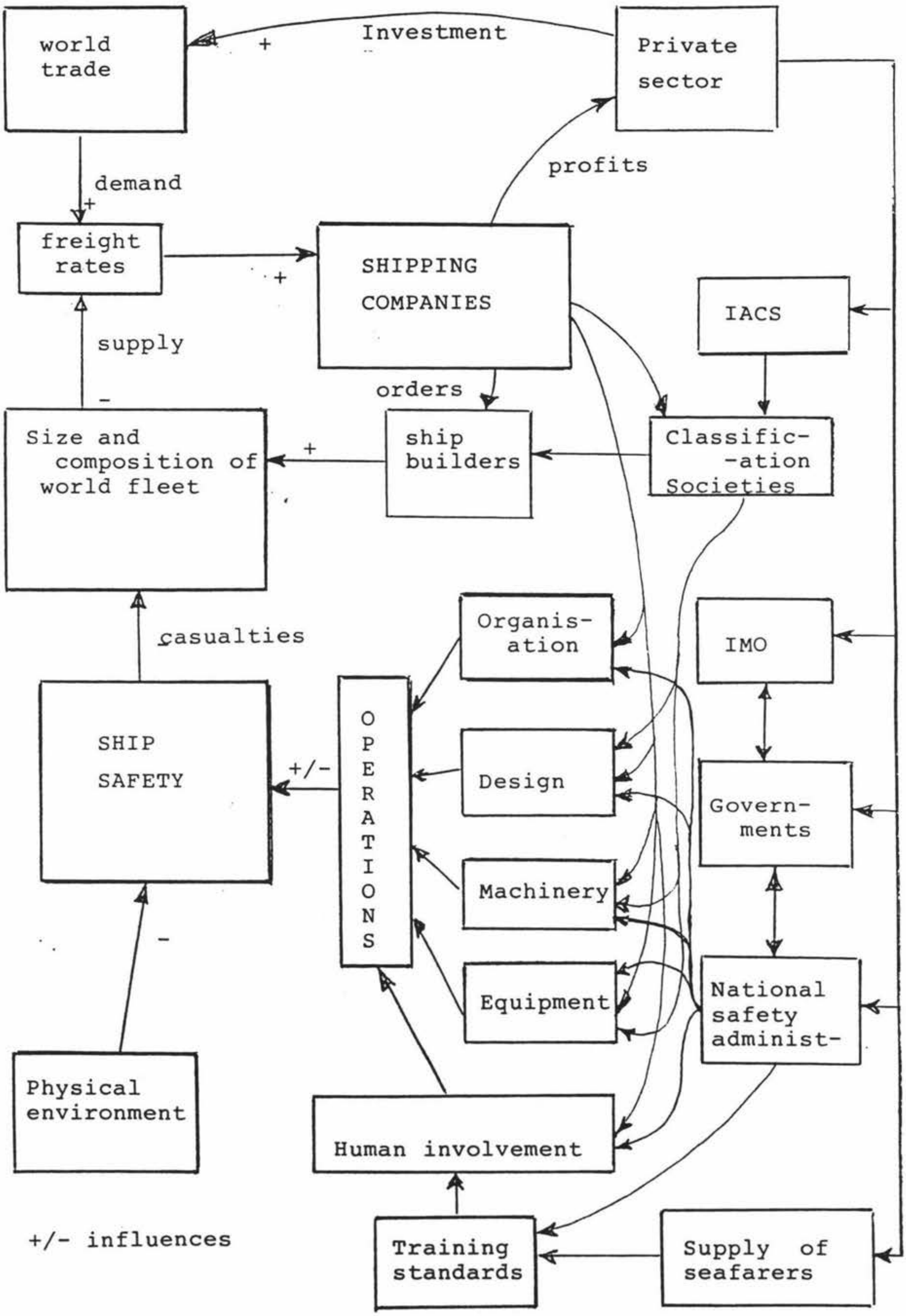


Figure 6.2 A complex dynamic system

Table 6.1 Mathematical methods and failure modes

Mechanics: beam theory, grillages Finite element method Hydrostatic analysis Response amplitude operators Structural reliability methods	Structural failure
Geometrical methods: hydrostatics Dynamical stability Modelling of ships' motions Sea spectra modelling Probability of capsize Catastrophe theory	Capsize
Empirical formulae for loading Subdivision, damage stability calculations	Foundering
Modelling ship manoeuvrability, stopping and turning Traffic modelling Ship domains Ergonomics and human reliability Probability of collision and probability of survival	Collision
Navigation error theory Modelling channel capacity Modelling ship manoeuvrability, stopping and turning Ergonomics and human reliability	Grounding and contact
Chain model for fire hazard Response time modelling	Fire

This investigation has identified the following obstacles to the development of a mathematical model of ship safety:

1. International shipping is a vast, complex and fragmented industry, which is subject to political and economic influences.

2. Technological developments can change the nature and problems associated with ship safety.

3. The factors that influence ship safety and can be only partially quantified.

4. The tendency towards specialisation of professions involved in the shipping industry has led to a better understanding of specific areas, but may have reduced the general appreciation of interactions and global effects.

5. It is difficult to define ship safety in a way that will enable realistic measurement. Measurement is therefore limited to defined subsets of ship safety.

6. The data necessary to measure ship safety performance is incomplete. Most available data are for total losses, while these are only a small percentage of the incidents causing loss of life, property and damage to the environment.

7. Some of the most important forces that determine ship safety are subtle and not completely understood. Although the literature contains much discussion about organisational and operational influences and human involvement, these forces have not been analysed mathematically to sufficient depth.

8. Simple global models of ship safety can be developed, but are difficult to validate. Restricted subsets of safety are modelled, but the results of these models are overwhelmed by effects that are external to the models.

The desire to model total ship safety is related to the need for more objective assessment of ships, their equipment and operation. Historically shipping regulations have come about in response to accidents; the load line rules were a response to the number of ships that sank because they were over-loaded, rules for minimum lifeboat capacity came about after the Titanic tragedy, and minimum training standards were prescribed because of the number of accidents which involved operator incompetence. But regulation is a blunt instrument, which can penalise safe and efficient operators, and may retard innovation. The economic forces acting in a highly competitive industry oblige ship owners to minimise costs, and where possible to reduce the cost of compliance with regulations. The imposition of extra regulations can result in a poorer allocation of resources to ship safety. In the terms of Figure 2.1, the total resources allocated to ship safety do not achieve the highest possible safety indifference curve.

The philosophical basis of ship safety is moving away from the use of prescriptive standards, and towards the development of performance standards for ships (House of Lords, 1992). If ship safety could be precisely defined and measured then a minimum standard of total safety could be set. Ship owners could achieve this standard by alternative means; one owner may favour strong construction while another may put more emphasis on watertight subdivision, or allocate more resources to developing an organisation that will ensure safe operations. The decreasing returns implicit in safety indifference curves would ensure that most operators tended towards an optimum allocation of resources. But the concept of setting an overall standard relies on having an effective means of measuring safety, and the ideal model of ship safety would allow a standard of safety to be calculated for a complete range of parameters.

From the list of obstacles to the development of a mathematical model of ship safety, it is clear that at present such an ideal is not feasible. The feasibility of developing a very useful and totally inclusive model of ship safety is small. Simple models of ship safety can be developed, as demonstrated in Chapter 5 and, although these may help in analysing and understanding safety concepts, their use in predicting specific outcomes in the real world may be limited. Specific, but not necessarily simple models of ship safety have been developed and, as discussed in Chapter 4, these can be very useful. There are also a number of models which have varying levels of generality and usefulness, such as vessel traffic models and models of ship domains. This suggests that there is a relationship between the feasibility, usefulness and generality of models of ship safety, as illustrated in Figure 6.3.

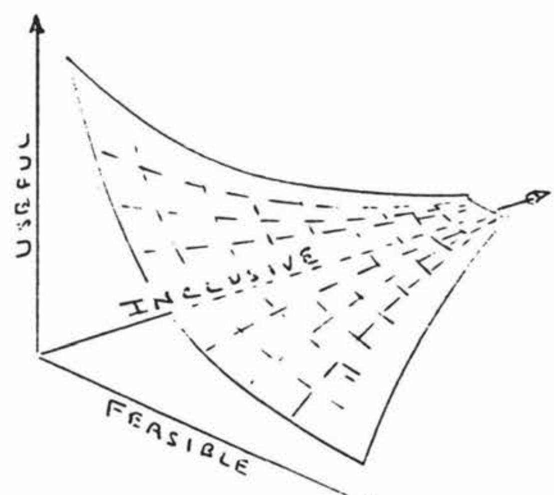


Figure 6.3 The feasibility of mathematical models of ship safety.

The surface of feasibility, usefulness and inclusiveness of mathematical models of ship safety gives the impression that the ideal, totally inclusive model may be only a remote possibility, but that less inclusive or less useful models are feasible. Extensive use is made of models for restricted subsets of ship safety, but the more inclusive models which have little immediate practical application are important for developing ideas about total ship safety, and may be essential to an understanding of the functional nature of safety, that is the expression of safety as a function of measurable variables.

In the technical literature, many professional and academic authors use the expression "total ship safety", and it is intuitively obvious that they mean the design, construction and operation of a ship so that there is a minimum risk to life, property and the environment. If safety was the prime objective then all ships would have strong construction, a high degree of subdivision, ample reserve buoyancy and stability, the best equipment, highly competent and well motivated seafarers and be operated by efficient well organised companies. But builders and designers strive to produce ships that will carry the largest amount of cargo at least cost; extra steel increases the initial cost and reduces a ship's carrying capacity, while greater subdivision may interfere with the ability to carry of cargo. Seafarers are not always competent and are often poorly motivated, while the level of organisation varies greatly from one company to another. The realities of the shipping industry turn "total ship safety" into a shadowy and tenuous concept, which is difficult to express in mathematical terms.

But although a mathematical model of total ship safety may not be feasible at present, there are potential benefits from attempts to develop one. As indicated in Figure 6.3, there are useful models of subsets of ship safety, and a great effort has been applied to developing specific techniques. Relatively little emphasis has been given to more general problems, and there is still much to be learned about interactions between safety elements. The study of these interactions crosses boundaries between different specialisations and disciplines, and here mathematical models can provide useful common ground. Although there are difficulties, attempts to further the development of a mathematical model of ship safety will provide a better understanding of the nature of ship safety, and in turn this should lead to higher standards of safety at sea.

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MER: Marine Engineering Review
RINA: Royal Institution of Naval Architects
SNAME: Society of Maval Architects and Marine Engineers
WEMT: West European Conference on Marine Technology

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Appendix

Listing of a computer program and selected output

```
'SFTMDL06.BAS SHIP SAFETY MODEL,INCLUDING WEATHER DAMAGE, COLLISION,
' GROUNDING AND FIRE

DECLARE FUNCTION DSTATIC (PASS)
DECLARE FUNCTION DDYNAMIC (PASS, ALPHA)
DECLARE FUNCTION COLLISION (RK, PASS)


DIM CEXP(4, 4, 4), SHIP(5, 10, 15), CARGO(4, 4), AVAIL(5, 10, 1)
DIM DDIST(4, 4, 4), FREIGHT(4, 4), MAINT(5), HAZCOL(6, 18), PTRAFFIC(20)
DIM MVIS(4, 4), PPG(4), COMPANY(5, 12), DAMLOSS(5, 5)

COMMON SHARED HAZCOL(), PTRAFFIC(), QCREW, STR
CLS
'CONSTANTS
'Steady quarterly deterioration of hull structure, fire safety
'and fire appliances
DQSTR = .0025: DQSTF = .0025: DQFIRE = .0025

'Input export/import matrix
FOR QTR = 1 TO 4
FOR NPX = 1 TO 4
FOR NPI = 1 TO 4
READ CEXP(QTR, NPX, NPI)
NEXT NPI
NEXT NPX
NEXT QTR


'Input ship data
NC = 1
FOR NS = 1 TO 10
FOR NP = 0 TO 15
READ SHIP(1, NS, NP)
FOR NC = 2 TO 5
SHIP(NC, NS, NP) = SHIP(1, NS, NP)
NEXT NC
NEXT NP
NEXT NS
'Adjust ship data
FOR NC = 1 TO 5
```

```
FOR NS = 1 TO 10
SHIP(NC, NS, 11) = .6
NEXT NS
NEXT NC

'Input company maintenance policy
FOR NC = 1 TO 5
READ MAINT(NC)
NEXT NC

'Input ship availability Initial distribution
FOR NC = 1 TO 5
FOR NS = 1 TO 10
READ AVAIL(NC, NS, 0), AVAIL(NC, NS, 1)
NEXT NS
NEXT NC



'Input distance matrix and climate factors
FOR N0 = 0 TO 4
FOR N1 = 1 TO 4
FOR N2 = 1 TO 4
READ DDIST(N0, N1, N2)
NEXT N2
NEXT N1
NEXT N0
'Input freight matrix
FOR N1 = 1 TO 4
FOR N2 = 1 TO 4
READ FREIGHT(N1, N2)
NEXT N2
NEXT N1

'Input traffic densities along routes
FOR I = 1 TO 6
READ K
HAZCOL(I, 0) = K
FOR J = 1 TO K
READ HAZCOL(I, J)
NEXT J
NEXT I

'Input probable distribution of ships
FOR I = 1 TO 20
READ PTRAFFIC(I)
NEXT I

' Input visibility factors
FOR N1 = 1 TO 4
FOR N2 = 1 TO 4
READ MVIS(N1, N2)
NEXT N2
NEXT N1

'Input port characteristics
FOR N1 = 1 TO 4
READ PPG(N1)
NEXT N1
```

```
' Set counters to record company performance to zero
FOR NC = 1 TO 5
FOR K = 0 TO 12
COMPANY(NC, K) = 0
NEXT K
NEXT NC

'___________________________________________________________________

'MAIN
'______   ______   _____   _____   _____   _____   _____   _

'Set counters for ships lost and damaged by weather, collision,
'grounding or fire to zero
NL1% = 0: ND1% = 0
NL2% = 0: ND2% = 0
NL3% = 0: ND3% = 0
NL4% = 0: ND4% = 0
DWMIN = 12000: ' Minimum mass of cargo that may be loaded

FOR NC = 1 TO 5
FOR K = 1 TO 5
DAMLOSS(NC, K) = 0
NEXT K
NEXT NC

FOR YEAR = 0 TO 4

FOR QTR = 1 TO 4

CLS
PRINT "YEAR: "; YEAR + 1; "  QUARTER: "; QTR
'Count number of ships lost or damaged this quarter
NLQ1% = 0: NDQ1% = 0
NLQ2% = 0: NDQ2% = 0
NLQ3% = 0: NDQ3% = 0
NLQ4% = 0: NDQ4% = 0

'Update counter for when each ship is next available
'DAYQ is the first day of the quarter
DAYQ = 365 * YEAR + 91 * (QTR - 1)
        PRINT "DAYQ "; DAYQ
FOR NC = 1 TO 5
FOR NS = 1 TO 10
IF DAYQ < AVAIL(NC, NS, 1) THEN GOTO LATERQ
AVAIL(NC, NS, 1) = DAYQ
LATERQ:
NEXT NS
NEXT NC

'Apply steady deterioration to structure and repair if necessary
'              in docking year ( 5 year cycle for docking )

FOR NC = 1 TO 5
FOR NS = 1 TO 10
STR = SHIP(NC, NS, 3) - DQSTR
STF = SHIP(NC, NS, 4) - DQSTF
fire = SHIP(NC, NS, 8) - DQFIRE
IF STR < 0 THEN STR = 0
IF STR > .3 THEN GOTO USESHIP
```

```
AVAIL(NC, NS, 1) = 9999
GOTO NSNXT

USESHIP:
YAGE = (1995 - SHIP(NC, NS, 0) + YEAR) / 5
IF YAGE - INT(YAGE) > .1 THEN GOTO NOREPAIR
BQTR = INT(SHIP(NC, NS, 13) / 3 + 1)
IF ABS(QTR - BQTR) > .1 THEN GOTO NOREPAIR
IF STR > MAINT(NC) THEN GOTO NOREPAIR
SHIP(NC, NS, 14) = SHIP(NC, NS, 14) + 100000 * (STR - MAINT(NC))
STR = MAINT(NC)
NOREPAIR:
SHIP(NC, NS, 3) = STR

'Annual check on fire safety (STF) and fire appliances (FIRE)
IF ABS(QTR - BQTR) > .1 THEN GOTO DONTCHECK
IF STF > MAINT(NC) THEN GOTO FSAFETYOK
SHIP(NC, NS, 14) = SHIP(NC, NS, 14) + 10000 * (STF - MAINT(NC))
SHIP(NC, NS, 4) = MAINT(NC)
FSAFETYOK: :
IF fire > MAINT(NC) THEN GOTO DONTCHECK
SHIP(NC, NS, 14) = SHIP(NC, NS, 14) + 10000 * (fire - MAINT(NC))
SHIP(NC, NS, 8) = MAINT(NC)
DONTCHECK:

NSNXT:
NEXT NS
NEXT NC

ZDAY = 365 * YEAR + 91 * QTR: ' last day this quarter
FOR IDAYS = 0 TO 8

'Day at begining of interval
DAY = 365 * YEAR + 91 * (QTR - 1) + 10 * IDAYS

'Deduct time dependent running costs, including wages
FOR NC = 1 TO 5
FOR NS = 1 TO 10
IF SHIP(NC, NS, 3) < .3 THEN GOTO NOCOST
SHIP(NC, NS, 14) = SHIP(NC, NS, 14) - 54000 - 27000 * QCREW
NOCOST:
NEXT NS
NEXT NC

'NPX = export port,  NPI= import port
'CARGO(NPX,NPI): Cumulative register for cargo to be shipped

FOR NPX = 1 TO 4
FOR NPI = 1 TO 4
CARGO(NPX, NPI) = CARGO(NPX, NPI) + CEXP(QTR, NPX, NPI) * 100000
NEXT NPI
NEXT NPX


Allocate:
QCARGO = 0

FOR NPX = 1 TO 4
FOR NPI = 1 TO 4
IF CARGO(NPX, NPI) < DWMIN THEN GOTO NPINEXT
```

```
FIRST = 9990
FOR NC = 1 TO 5
FOR NS = 1 TO 10
IF SHIP(NC, NS, 3) < .3 THEN GOTO SHIPNEXT
APORT = AVAIL(NC, NS, 0)
NXTDAY = AVAIL(NC, NS, 1) + DDIST(0, NPX, APORT) / 360
IF NXTDAY > FIRST THEN GOTO SHIPNEXT
IF NXTDAY > ZDAY THEN GOTO SHIPNEXT
FIRST = NXTDAY: NNC = NC: NNS = NS: AAPORT = APORT
SHIPNEXT:
NEXT NS
NEXT NC

IF FIRST > 9900 THEN GOTO NPINEXT: 'No ship allocated


'_______________________________________________________________________

' Simulate failure due to weather damage, collision, grounding or fire
' for ballast passage from port of availability AAPORT to loading port
' NPX, and then from NPX to discharge port NPI
' Failure modes are:
'    1. STRUCTURAL DAMAGE DUE TO WEATHER
'    2. DAMAGE BY COLLISION
'    3. DAMAGE BY GROUNDING
'    4. DAMAGE BY FIRE

LIGHTPASS = DDIST(0, NPX, AAPORT) / 360: LOADPASS = DDIST(0, NPI, NPX) / 360
STR = SHIP(NNC, NNS, 3): QCREW = SHIP(NNC, NNS, 11)
XGROUND = .84 * (1 - QCREW) + .08 * (1 - NAV) + .08 * (1 - MCY)
PFIRE = .7 * (1 - QCREW) + .3 * (1 - MCY)


'Light passage from AAPORT to NPX

ALPHA = DDIST(QTR, AAPORT, NPX) / 10
PASS = LIGHTPASS
IF PASS < 1 THEN GOTO PASSXI
QPASS% = 1

'Apply deterioration due to cyclic forces
SHIP(NNC, NNS, 3) = SHIP(NNC, NNS, 3) - DSTATIC(PASS) - DDYNAMIC(PASS, ALPHA)

XDAMAGE = 1.2 * SHIP(NNC, NNS, 3) ^ .2: 'Resistance of structure to damage

'Weather damage
FMD% = 1

        ND = 0
WAVELT:
        ND = ND + 1
        YD = RND
        WFORCE = SQR(ABS(LOG(YD)) * 2 * ALPHA * ALPHA) / 3.2
        IF WFORCE > XDAMAGE THEN GOTO TOTALOSS
        IF WFORCE > .8 * XDAMAGE THEN GOTO REPAIR
        IF ND < PASS THEN GOTO WAVELT

'Determine risk of collision during light passage
FMD% = 2
```

```
        RK = AAPORT + NPX - 1
        IF AAPORT = 1 OR NPX = 1 THEN RK = RK - 1
        COLSN = COLLISION(RK, PASS)
        IF COLSN > .95 THEN GOTO TOTALOSS
        IF COLSN > .001 THEN GOTO REPAIR

'Determine risk of grounding during departure and arrival in ballast
FMD% = 3
        EGR2 = .48 * DDIST(QTR, NPX, AAPORT)
        VIS = MVIS(QTR, AAPORT)
        EGR1 = -.42 * LOG(VIS / 10)
        PROBGD = PPG(AAPORT) * XGROUND * (EGR1 + EGR2)
        GROUND = PROBGD - 600 * RND
        IF GROUND > .999 THEN GOTO TOTALOSS
        IF GROUND > .001 THEN GOTO REPAIR
        VIS = MVIS(QTR, NPX)
        EGR1 = -.42 * LOG(VIS / 10)
        PROBGD = PPG(NPX) * XGROUND * (EGR1 + EGR2)
        GROUND = PROBGD - 600 * RND
        IF GROUND > .999 THEN GOTO TOTALOSS
        IF GROUND > .001 THEN GOTO REPAIR

'Determine risk of fire during light passage and loading
FMD% = 4
        FFF% = 0
        FOR NFF% = 1 TO (PASS + 3)
        IF PFIRE > 1200 * RND THEN FFF% = 1
        NEXT NFF%
        IF FFF% = 0 THEN GOTO NOFIRE0
        FTIME = 10 * RND / QCREW
        XFF = 1 / SHIP(NNC, NNS, 4)
        FDAMAGE = .8 * FTIME ^ XFF
        IF FDAMAGE > 1000 * SHIP(NNC, NNS, 8) THEN GOTO TOTALOSS
        IF FDAMAGE > 20 THEN GOTO REPAIR
NOFIRE0:

'Load passage from NPX to NPI
PASSXI:
QPASS% = 3
ALPHA = DDIST(QTR, NPX, NPI) / 10
PASS = LOADPASS

'Apply deterioration due to cyclic forces
SHIP(NNC, NNS, 3) = SHIP(NNC, NNS, 3) - DSTATIC(PASS) - DDYNAMIC(PASS, ALPHA
XDAMAGE = 1.2 * SHIP(NNC, NNS, 3) ^ .2: 'Resistance of structure to damage

'Weather damage
FMD% = 1

        ND = 0
WAVELD:
        ND = ND + 1
        YD = RND
        WFORCE = SQR(ABS(LOG(YD)) * 2 * ALPHA * ALPHA) / 3.2
        IF WFORCE > XDAMAGE THEN GOTO TOTALOSS
        IF WFORCE > .8 * XDAMAGE THEN GOTO REPAIR
        IF ND < LOADPASS THEN GOTO WAVELD

'Determine risk of collision during loaded passage
```

```
FMD% = 2

        RK = NPX + NPI - 1
        IF NPX = 1 OR NPI = 1 THEN RK = RK - 1
        COLSN = COLLISION(RK, PASS)
        IF COLSN > .95 THEN GOTO TOTALOSS
        IF COLSN > .001 THEN GOTO REPAIR

'Determine risk of grounding during departure and arrival in loaded condition
FMD% = 3
        EGR2 = .48 * DDIST(QTR, NPX, NPI)
        VIS = MVIS(QTR, NPX)
        EGR1 = -.42 * LOG(VIS / 10)
        PROBGD = PPG(NPX) * XGROUND * (EGR1 + EGR2)
        GROUND = PROBGD - 600 * RND
        IF GROUND > .999 THEN GOTO TOTALOSS
        IF GROUND > .001 THEN GOTO REPAIR
        VIS = MVIS(QTR, NPI)
        EGR1 = -.42 * LOG(VIS / 10)
        PROBGD = PPG(NPI) * XGROUND * (EGR1 + EGR2)
        GROUND = PROBGD - 600 * RND
        IF GROUND > .999 THEN GOTO TOTALOSS
        IF GROUND > .001 THEN GOTO REPAIR

'Determine risk of fire during loaded passage and discharging
FMD% = 4
        FFF% = 0
        FOR NFF% = 1 TO (PASS + 3)
        IF PFIRE > 1200 * RND THEN FFF% = 1
        NEXT NFF%
        IF FFF% = 0 THEN GOTO NOFIRE1
        FTIME = 10 * RND / QCREW
        XFF = 1 / SHIP(NNC, NNS, 4)
        FDAMAGE = .8 * FTIME ^ XFF
        IF FDAMAGE > 1000 * SHIP(NNC, NNS, 8) THEN GOTO TOTALOSS
        IF FDAMAGE > 20 THEN GOTO REPAIR
NOFIRE1:


GOTO NODAMAGE

TOTALOSS:
        AVAIL(NNC, NNS, 1) = 9999
        SHIP(NNC, NNS, 3) = 0
IF FMD% > 1 THEN GOTO LMODE2
        NL1% = NL1% + 1
        NLQ1% = NLQ1% + 1
        PVALUE = 1000000 * (1 - .1 * YEAR) * SHIP(NNC, NNS, 12)
        DAMLOSS(NNC, 1) = DAMLOSS(NNC, 1) + PVALUE
        COMPANY(NNC, 5) = COMPANY(NNC, 5) + 1
        PRINT "  SHIP("; NNC; ","; NNS; ") LOST BY WEATHER  "; WFORCE
        GOTO LMODEZ
LMODE2:
IF FMD% > 2 THEN GOTO LMODE3
        NL2% = NL2% + 1
        NLQ2% = NLQ2% + 1
        PVALUE = 1000000 * (1 - .1 * YEAR) * SHIP(NNC, NNS, 12)
        DAMLOSS(NNC, 2) = DAMLOSS(NNC, 2) + PVALUE
        COMPANY(NNC, 6) = COMPANY(NNC, 6) + 1
        PRINT "  SHIP("; NNC; ","; NNS; ") LOST BY COLLISION "; COLSN
```

```
        GOTO LMODEZ
LMODE3:
IF FMD% > 3 THEN GOTO LMODE4
        NL3% = NL3% + 1
        NLQ3% = NLQ3% + 1
        PVALUE = 1000000 * (1 - .1 * YEAR) * SHIP(NNC, NNS, 12)
        DAMLOSS(NNC, 3) = DAMLOSS(NNC, 3) + PVALUE
        COMPANY(NNC, 7) = COMPANY(NNC, 7) + 1
        PRINT "  SHIP("; NNC; ","; NNS; ") LOST BY GROUNDING "; GROUND
        GOTO LMODEZ
LMODE4:
IF FMD% > 4 THEN GOTO LMODEZ
        NL4% = NL4% + 1
        NLQ4% = NLQ4% + 1
        PVALUE = 1000000 * (1 - .1 * YEAR) * SHIP(NNC, NNS, 12)
        DAMLOSS(NNC, 4) = DAMLOSS(NNC, 4) + PVALUE
        COMPANY(NNC, 8) = COMPANY(NNC, 8) + 1
        PRINT "  SHIP("; NNC; ","; NNS; ") LOST BY FIRE "; FDAMAGE
LMODEZ:
DAMLOSS(NNC, 5) = DAMLOSS(NNC, 5) + PVALUE
SHIP(NNC, NNS, 14) = SHIP(NNC, NNS, 14) - PVALUE
        GOTO NOSHIPS


REPAIR:
IF FMD% > 1 THEN GOTO FMODE2
        DAMAGE = WFORCE - .7 * XDAMAGE
        NDQ1% = NDQ1% + 1: ND1% = ND1% + 1
        DAMLOSS(NNC, 1) = DAMLOSS(NNC, 1) + 4000000 * DAMAGE
        COMPANY(NNC, 9) = COMPANY(NNC, 9) + 1
        PRINT "WEATHER DAMAGE "; DAMAGE; "  SHIP("; NNC; ","; NNS; ")"
        GOTO FMODEZ
FMODE2:
IF FMD% > 2 THEN GOTO FMODE3
        DAMAGE = .5 * COLSN
        NDQ2% = NDQ2% + 1: ND2% = ND2% + 1
        DAMLOSS(NNC, 2) = DAMLOSS(NNC, 2) + 4000000 * DAMAGE
        COMPANY(NNC, 10) = COMPANY(NNC, 10) + 1
        PRINT "COLLISION DAMAGE "; DAMAGE; "  SHIP("; NNC; ","; NNS; ")"
        GOTO FMODEZ
FMODE3:
IF FMD% > 3 THEN GOTO FMODE4
        DAMAGE = GROUND
        NDQ3% = NDQ3% + 1: ND3% = ND3% + 1
        DAMLOSS(NNC, 3) = DAMLOSS(NNC, 3) + 4000000 * DAMAGE
        COMPANY(NNC, 11) = COMPANY(NNC, 11) + 1
        PRINT "GROUNDING DAMAGE "; DAMAGE; "  SHIP("; NNC; ","; NNS; ")"
        GOTO FMODEZ
FMODE4:
IF FMD% > 4 THEN GOTO FMODEZ
        DAMAGE = FDAMAGE / 100
        NDQ4% = NDQ4% + 1: ND4% = ND4% + 1
        DAMLOSS(NNC, 4) = DAMLOSS(NNC, 4) + 4000000 * DAMAGE
        COMPANY(NNC, 12) = COMPANY(NNC, 12) + 1
        PRINT "FIRE DAMAGE "; DAMAGE; " SHIP("; NNC; ","; NNS; ")"
FMODEZ:
        DAMLOSS(NNC, 5) = DAMLOSS(NNC, 5) + 4000000 * DAMAGE
        SHIP(NNC, NNS, 14) = SHIP(NNC, NNS, 14) - 4000000 * DAMAGE
IF DAMAGE > .1 THEN GOTO SHIPYARD
        FIRST = FIRST + 90 * DAMAGE
```

```
        IF QPASS% < 2 THEN GOTO NOFIRE0
GOTO NODAMAGE
SHIPYARD:
        AVAIL(NNC, NNS, 1) = DAY + 180 * DAMAGE
        AVAIL(NNC, NNS, 0) = 3
   PRINT "          AVAIL("; NNC; ","; NNS; ",1) = "; AVAIL(NNC, NNS, 1)
GOTO NOSHIPS

NODAMAGE:
' USE SHIP
'-------------------------------------------------------------
DWT = SHIP(NNC, NNS, 2)
IF CARGO(NPX, NPI) < DWT THEN DWT = CARGO(NPX, NPI)
CARGO(NPX, NPI) = CARGO(NPX, NPI) - DWT
IF CARGO(NPX, NPI) < 0 THEN CARGO(NPX, NPI) = 0
LOADPASS = DDIST(0, NPX, NPI) / 360
AVAIL(NNC, NNS, 0) = NPI
AVAIL(NNC, NNS, 1) = FIRST + LOADPASS + 12
SHIP(NNC, NNS, 5) = SHIP(NNC, NNS, 5) + 1
REVENUE = FREIGHT(NPX, NPI) * DWT
COST = 7500 * (LOADPASS + LIGHTPASS) + 63100
SHIP(NNC, NNS, 14) = SHIP(NNC, NNS, 14) + REVENUE - COST

NOSHIPS:
IF CARGO(NPX, NPI) > DWMIN THEN QCARGO = 2
NPINEXT:
NEXT NPI
NEXT NPX

IF QCARGO > 1 THEN GOTO Allocate

NEXT IDAYS

PRINT "QUARTERLY REPORT FOLLOWS"

CLS
PRINT "Year: "; YEAR + 1; "   Quarter: "; QTR
PRINT
FOR NC = 1 TO 5
FOR NS = 1 TO 10
PRINT USING "####### "; SHIP(NC, NS, 14) / 1000;
NEXT NS
PRINT
FOR NS = 1 TO 10
VOYAGE = SHIP(NC, NS, 5)
IF VOYAGE > 99 THEN VOYAGE = VOYAGE - 100
PRINT USING "##"; VOYAGE;
PRINT USING " #.## "; SHIP(NC, NS, 3);
NEXT NS
PRINT
NEXT NC

PRINT "              TOTAL                         THIS QUARTER"
PRINT "            LOST      DAMAGED              LOST        DAMAGED "
PRINT " WEATHER    "; NL1%; "        "; ND1%; "                  "; NLQ1%; "
PRINT " COLLISION  "; NL2%; "        "; ND2%; "                  "; NLQ2%; "
PRINT " GROUNDING  "; NL3%; "        "; ND3%; "                  "; NLQ3%; "
PRINT " FIRE       "; NL4%; "        "; ND4%; "                  "; NLQ4%; "
PRINT
PRINT "Cargo distribution at end of year "; YEAR + 1; "  quarter "; QTR; ":"
```

```
        FOR NPX = 1 TO 4
        FOR NPI = 1 TO 4
        PRINT USING "    ########## "; CARGO(NPX, NPI);
        NEXT NPI
        PRINT
        NEXT NPX

'A slight delay to scan output
'place delay here when required, or use INPUT QQQ to halt run

NEXT QTR

NEXT YEAR

        INPUT QQQ
'Summarise company performance
CLS
TOTALREV = 0
FOR NC = 1 TO 5
FOR NS = 1 TO 10
COMPANY(NC, 1) = COMPANY(NC, 1) + SHIP(NC, NS, 5)
COMPANY(NC, 2) = COMPANY(NC, 2) + SHIP(NC, NS, 14)
TOTALREV = TOTALREV + SHIP(NC, NS, 14)
IF SHIP(NC, NS, 3) < .1 THEN GOTO COLOST
COMPANY(NC, 0) = COMPANY(NC, 0) + 1
COMPANY(NC, 3) = COMPANY(NC, 3) + SHIP(NC, NS, 3)
COMPANY(NC, 4) = COMPANY(NC, 4) + SHIP(NC, NS, 11)
COLOST:
NEXT NS
COMPANY(NC, 3) = COMPANY(NC, 3) / COMPANY(NC, 0)
COMPANY(NC, 4) = COMPANY(NC, 4) / COMPANY(NC, 0)
NEXT NC

'Print summary
PRINT " COMP SHIP  VOY   REVENUE  STR  QCREW  L/D (W) (C) (G) (F) (W) (C)
FOR NC = 1 TO 5
PRINT USING " ####"; NC; COMPANY(NC, 0); COMPANY(NC, 1);
PRINT USING "  #####.###"; COMPANY(NC, 2) / 1000000;
PRINT USING "  .### "; COMPANY(NC, 3); COMPANY(NC, 4);
PRINT "   ";
FOR K = 5 TO 12
PRINT USING " ## "; COMPANY(NC, K);
NEXT K
PRINT
NEXT NC
PRINT
PRINT "TOTAL REVENUE = "; TOTALREV / 1000000
PRINT
PRINT "  NC      WEATHER   COLLISION   GROUNDING        FIRE       TOTAL"
FOR NC = 1 TO 5
PRINT USING "   # "; NC;
FOR K = 1 TO 5
PRINT USING "     ####.###"; DAMLOSS(NC, K) / 1000000;
NEXT K
PRINT
NEXT NC
INPUT QQQ
STOP

'DATA
```

```
' Export / import data in million tonnes

DATA 0,.4,.7, 0
DATA .3,0,.6,0
DATA .74, 1.0, 0, .4
DATA .1, .2, 0, 0

DATA 0, .56, .8, 0
DATA .3, 0, .78, 0
DATA .66, .88, 0, .66
DATA .3, .2, 0, 0

DATA 0, .54, 1., 0
DATA .3, 0,.76, 0
DATA .6,.9,0,.7
DATA .4, .3, 0, 0

DATA 0, .7, 1, 0
DATA .3, 0, 1.1, 0
DATA .84, 1.4, 0, .84
DATA .6, .6, 0, 0


'Ship data fields

'company 1
DATA 1980, 25000, 25000, .55, .6, 0,.55, .6, .55, .6, 20, .7, 4.17, 8,0
DATA 1980, 25000, 25000, .65, .6, 0,.55, .6, .55, .65, 20,.7, 4.17, 7,0
DATA 1982, 25000, 25000, .6,  .7, 0,.6 , .6, .55, .6, 20, .7, 4.69,3,0
DATA 1983, 25000, 25000, .7, .65, 0, .65, .62, .6, .65, 20, .7, 4.97,4,0
DATA 1985, 25000, 25000, .65, .65, 0, .7, .62, .6, .65, 19, .7, 5.58, 2,0
DATA 1985, 25000, 25000, .75, .7, 0,  .7, .62, .6, .7 , 19, .7, 5.58, 6,0
DATA 1985, 25000, 25000, .7, .68, 0, .65, .7, .65, .7, 18, .7, 5.58, 6,0
DATA 1989, 25000, 25000, .75, .7, 0, .7,  .7, .65, .7, 18, .7, 7.05, 10,0
DATA 1993, 25000, 25000, .8,  .7, 0, .7, .8, .75, .75, 18, .7, 8.9,5,0
DATA 1993, 25000, 25000, .8, .75, 0, .75, .8, .75, .75, 18, .7, 8.9, 2,0

' Company maintenance policy
DATA .85,.85,.85,.85,.85

'Initial distribution of ships
DATA 1,20,2,7,2,8,3,15,2,1,2,50,3,4,4,77,2,3,3,37
DATA 2,82,1,9,4,40,1,8,3,7,4,33,3,12,1,25,4,56,4,11
DATA 3,27,1,15,2,50,2,34,2,42,2,44,3,80,3,20,1,42,2,28
DATA 3,21,4,21,3,35,1,34,1,27,3,11,2,11,3,9,1,5,1,57
DATA 2,4,3,28,2,15,4,3,2,27,2,7,2,8,4,16,3,29,3,20

'Distance and climate data

'DISTANCES
DATA 0,1200,4500,6500
DATA 1200,0,4000,6000
DATA 4500,4000,0,4000
DATA 6500,6000,4000,0

'CLIMATE
'December to February
DATA 0,3,5,7
DATA 2,0,5,7
DATA 5,5,0,8
```

```
DATA 6,6,8,0

'March to May
DATA 0,3,5,6
DATA 2,0,5,6
DATA 5,4,0,8
DATA 6,6,7,0

'June to August
DATA 0,4,5,5
DATA 3,0,5,5
DATA 5,5,0,6
DATA 5,5,6,0

'September to November
DATA 0,4,5,5
DATA 4,0,4,5
DATA 5,5,0,6
DATA 5,5,6,0

'Freight matrix
DATA 0,7.74,16.25,27.12
DATA 7.74,0,14.77,20
DATA 16.25,14.77,0,14.77
DATA 22.12,20,14.77,0

'Traffic density
DATA 3,2,1,2
DATA 12,2,1,1,1,1,1,2,2,3,3,4,5
DATA 18,2,1,1,1,1,1,1,1,1,1,2,2,2,3,3,3,4,4
DATA 11,2,2,1,1,1,1,3,3,4,4,5
DATA 16,2,2,1,1,1,1,1,1,2,2,2,3,3,3,4,4
DATA 11,5,4,4,3,2,1,1,2,3,3,4

'Probable distribution of ships
DATA .83,.97,.54,.82,.96,.34,.62,.86,.98,.23,.51,.72,.87
DATA .96,.14,.33,.56,.73,.87,.96

'Visibility factors
DATA 9,8,4,5
DATA 8,7,4,4
DATA 7,7,5,3
DATA 7,6,6,6

'Port characteristics - risk of running aground during passage
DATA .5,.4,.9,.7


FUNCTION COLLISION (RK, PASS)
SLOPE = .5
        ND = 0
LOOKOUT:
        ND = ND + 1
        TRAFFIC = RND
        K = HAZCOL(RK, ND)

        K0 = 0: K1 = 0
COUNTSHIP:
        K0 = K0 + 1
        K1 = K1 + K0
```

```
        IF K0 + .5 < K THEN GOTO COUNTSHIP

        NS = -1
NUMBSHIP:
        NS = NS + 1
        IF NS > K THEN GOTO MXSHIP
        IF PTRAFFIC(K1 + NS) < TRAFFIC THEN GOTO NUMBSHIP
MXSHIP:
        'NS = Number of ships encountered
        QK = 1 + 9 * EXP(-SLOPE * NS)
        PROBCOL = 1 / (QCREW * QK)
        IF NS = 0 THEN PROBCOL = 0
        RISKCOL = 500 * RND
        IF PROBCOL > RISKCOL THEN GOTO BADDAY
        IF ND + .5 < PASS THEN GOTO LOOKOUT
        COLLISION = 0
        GOTO GOODDAY
BADDAY:
        COLLISION = PROBCOL * .4 / (QCREW * STR)
GOODDAY:

END FUNCTION

FUNCTION DDYNAMIC (PASS, ALPHA)
DRAN = RND
DDYNAMIC = .0002 * PASS * SQR(ABS(LOG(DRAN)) * 2 * ALPHA * ALPHA)

END FUNCTION

FUNCTION DSTATIC (PASS)
DRAN1 = RND: DRAN2 = RND
DSTATIC = ABS(.0012 + .002 * (-LOG(DRAN1) * COS(6.28318 * DRAN2)) * PASS / 91)

END FUNCTION
```

Year: 1 Quarter: 4

444	-13	-18	125	502	138	376	-139	-29	-409
14 .56	14 .59	15 .55	14 .64	15 .59	14 .70	15 .65	11 .70	16 .74	14 .75
-390	992	650	617	849	196	312	365	-437	341
10 .56	16 .60	14 .55	16 .65	16 .60	14 .70	15 .64	14 .70	14 .75	14 .74
-2701	419	321	-992	756	-1843	39	737	-229	-1448
10 .57	15 .60	14 .55	12 .64	15 .60	11 .70	12 .65	15 .70	14 .74	13 .75
426	64	154	93	-178	600	-132	-462	489	-389
16 .56	14 .60	14 .55	13 .65	15 .60	15 .70	15 .64	16 .70	15 .75	12 .75
869	502	-1205	279	62	-874	599	478	-1598	433
16 .56	15 .60	14 .55	15 .65	14 .59	13 .70	14 .65	14 .70	13 .75	14 .75

	TOTAL		THIS QUARTER	
	LOST	DAMAGED	LOST	DAMAGED
WEATHER	0	0	0	0
COLLISION	0	2	0	0
GROUNDING	0	0	0	0
FIRE	0	4	0	0

Cargo distribution at end of year 1 quarter 4:

0	300000	485000	0
125000	0	440000	0
429000	765000	0	429000
320000	345000	0	0

Year: 2 Quarter: 4

1124	-40	782	1231	961	901	785	71	475	102
30 .51	29 .53	30 .49	31 .60	30 .54	29 .64	29 .59	26 .64	32 .68	28 .70
-41	1644	1223	812	781	768	878	929	431	-40
25 .50	31 .55	28 .50	30 .60	29 .53	29 .65	29 .59	29 .65	29 .69	25 .68
-2048	975	1148	-472	692	-2367	209	905	303	-599
25 .51	29 .54	28 .51	27 .59	27 .54	28 .64	25 .60	28 .64	29 .68	27 .69
1360	977	117	754	-1402	-1917	-1024	-2332	628	468
31 .51	29 .54	28 .49	28 .60	30 .55	28 .65	29 .58	28 .64	29 .70	26 .69
1401	528	-836	573	65	-291	416	765	-1167	925
30 .50	28 .54	29 .50	29 .59	28 .54	28 .64	27 .60	27 .63	28 .69	28 .69

	TOTAL		THIS QUARTER	
	LOST	DAMAGED	LOST	DAMAGED
WEATHER	0	0	0	0
COLLISION	0	4	0	0
GROUNDING	0	3	0	0
FIRE	0	5	0	0

Cargo distribution at end of year 2 quarter 4:

0	562000	800000	0
240000	0	880000	0
672000	1355000	0	725000
430000	455000	0	0

Year: 3 Quarter: 4

189	535	-186	1708	1482	-2852	1797	1157	1016	246
44 .46	45 .48	45 .58	45 .55	44 .48	38 .00	44 .53	41 .58	48 .63	43 .64
492	2147	1345	1132	1129	263	991	1494	1357	449
39 .45	45 .49	42 .57	44 .55	42 .48	45 .60	42 .53	43 .59	43 .64	42 .63
-1723	2133	2046	242	1591	-1907	727	795	1158	-431
39 .45	45 .49	43 .57	42 .53	42 .48	43 .57	39 .54	44 .57	44 .63	43 .64
1934	1706	346	1610	-1309	-2448	-1690	-1892	1288	1140
47 .45	44 .49	43 .57	44 .55	43 .49	42 .58	45 .53	42 .59	44 .65	39 .63
1886	1051	-462	1574	-85	599	989	966	-496	1333
43 .44	44 .49	44 .57	43 .53	45 .48	42 .58	43 .55	40 .58	43 .64	43 .63

	TOTAL		THIS QUARTER	
	LOST	DAMAGED	LOST	DAMAGED
WEATHER	0	2	0	0
COLLISION	0	6	0	1
GROUNDING	1	6	0	1
FIRE	0	7	0	0

Cargo distribution at end of year 3 quarter 4:

0	567000	1150000	0
240000	0	896000	0
753000	2817000	0	791000
430000	455000	0	0

Year: 4 Quarter: 4

714	13	507	1751	1481	-2852	1756	1689	1012	982
58 .40	60 .41	61 .52	59 .59	61 .41	38 .00	58 .47	57 .53	63 .57	57 .59
-95	2856	1943	1445	1622	1221	1862	2176	1648	1364
54 .40	60 .44	57 .52	59 .59	55 .42	60 .55	59 .48	59 .53	56 .57	57 .58
-813	2486	2750	918	2408	-882	1399	1245	1266	485
54 .40	60 .44	59 .51	56 .59	57 .42	58 .52	53 .48	58 .51	58 .58	58 .58
3000	2209	-194	1803	-690	-1740	-859	-1403	2181	1849
62 .40	58 .44	59 .51	56 .59	59 .43	56 .54	60 .48	58 .54	60 .60	54 .58
2135	1590	263	1840	687	1275	1138	1305	52	2047
58 .39	60 .44	60 .52	57 .59	60 .43	56 .53	56 .49	54 .52	58 .59	58 .58

	TOTAL		THIS QUARTER	
	LOST	DAMAGED	LOST	DAMAGED
WEATHER	0	4	0	0
COLLISION	0	8	0	0
GROUNDING	1	6	0	0
FIRE	0	9	0	0

Cargo distribution at end of year 4 quarter 4:

0	560000	1525000	0
240000	0	937000	0
959000	4229000	0	856000
455000	455000	0	0

Year: 5 Quarter: 4

1383	1109	994	2521	1851	-2852	2248	2743	-319	1733
73 .34	77 .34	75 .47	74 .54	75 .35	38 .00	73 .42	72 .59	78 .52	72 .54
-199	1196	2752	2682	2375	2115	334	2733	2300	1922
68 .34	75 .38	73 .47	75 .53	70 .36	76 .49	72 .42	76 .59	70 .52	71 .52
-934	2229	1465	-1288	2989	174	1755	2117	2107	708
71 .35	76 .38	73 .46	67 .54	72 .37	75 .46	65 .42	74 .59	75 .52	72 .53
3672	3095	372	2303	46	-945	-974	-1180	3327	2205
77 .34	74 .38	73 .45	72 .53	75 .38	71 .48	73 .42	71 .59	76 .54	70 .52
2802	1988	836	2875	1241	1874	1810	1928	-2500	2285
72 .33	74 .38	74 .46	71 .53	74 .37	70 .46	71 .44	68 .59	70 .55	72 .52

	TOTAL		THIS QUARTER	
	LOST	DAMAGED	LOST	DAMAGED
WEATHER	0	10	0	0
COLLISION	0	13	0	0
GROUNDING	1	7	0	0
FIRE	0	11	0	2

Cargo distribution at end of year 5 quarter 4:

0	565000	1775000	0
240000	0	978000	0
1215000	5766000	0	996000
430000	455000	0	0

COMP	SHIP	VOY	REVENUE	STR	QCREW	L/D	(W)	(C)	(G)	(F)	(W)	(C)	(G)	(F)
1	9	707	11.411	.458	.600		0	0	1	0	2	2	1	2
2	10	726	18.210	.463	.600		0	0	0	0	2	3	2	1
3	10	720	11.322	.463	.600		0	0	0	0	4	4	0	4
4	10	732	11.921	.463	.600		0	0	0	0	1	3	3	2
5	10	716	15.139	.463	.600		0	0	0	0	1	1	1	2

TOTAL REVENUE = 68.00320

NC	WEATHER	COLLISION	GROUNDING	FIRE	TOTAL
1	1.003	1.740	6.117	3.032	11.893
2	1.325	3.370	1.120	1.184	6.999
3	2.420	4.072	0.000	6.644	13.136
4	0.498	3.683	4.766	2.533	11.479
5	1.069	1.349	2.385	2.412	7.214