HUMAN PERFORMANCE DURING THE EVACUATION OF PASSENGER SHIPS

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B. Sc., B.E.(Hons.)

THESIS SUBMITTED FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY (Ph.D)

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CLAYTON, MELBOURNE, AUSTRALIA

SEPTEMBER 2001

SYNOPSIS

The 1995 SOLAS (Safety of Life at Sea) conference adopted a new regulation on the evacuation analysis of ships constructed on or after 1 July 1999 (II-2/28-1). The regulation stipulates that an evacuation analysis is required at the early stages of design to identify and eliminate congestion that may occur during an evacuation in realistic circumstances.

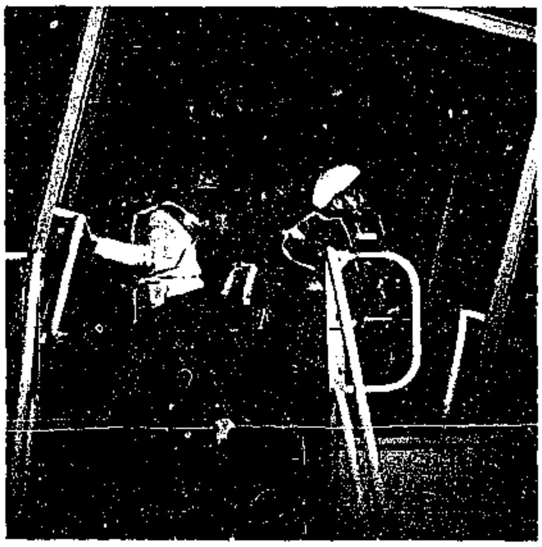
Current on-land building evacuation theory has been adopted by the maritime sector in the evacuation analysis of ships. However, there remain many deficiencies in this modern approach. In general terms the deficiencies are due to the fundamental differences between the psychological and physical states of the individuals involved for the 'at sea' and 'on land' cases as well as the relative means of logistical management and evacuation policies of the two environs.

In particular the following areas of concern are not adequately modelled in evacuation analysis of maritime vessels:

- Influence of safety media and travel experience on the evacuation knowledge of passengers;
- Dynamic and quasi-static motions of the vessel on the evacuation walking speed of passengers.

This thesis presents the findings of research specifically undertaken to assess the implications of quantifiable human factors the evacuation analysis of passenger ships including: the affect of safety knowledge on evacuation way finding behaviour and the influence of dynamic and quasi-static vessel motions on motor ability performance of evacuees. The data is assessed on both a micro-scale (the influence on the individual) and a macro-scale (the influence on the overall evacuation success).

Empirical models and data gathering techniques have been developed to assist in the development of a rational basis for the evacuation analysis of passenger vessels in the early stage of design.



Motor Ability Trials on the 1st MATE Facility at Luna Park, Melbourne

STATEMENT OF ORIGINALITY

I certify that this thesis contains no material, which has been accepted for the award of any other degree or diploma in any university of college. To the best of my knowledge and belief, this thesis contains no material previously published or written by any other person, except where due reference is given in the text of this thesis.

Signed:.[redacted]...

(Mr. Adam Timothy Brumley)

Date:..........27/09/02..........

ACKNOWLEDGEMENTS

The author is grateful to Associate Professor Leonard L. Koss for his guidance, enthusiasm and encouragement throughout the candidature.

For financial and technical support, the author is grateful to Monash University, Australian Maritime Engineering Cooperative Research Centre (AME CRC), Australian Maritime Safety Authority (AMSA) and AMOG Consulting. In particular I would like to thank the following from these organizations: Sean O'Neill, David Harrod, Mike Julian, Roger Timms and Ian Williams (AMSA), Dr Andrew Potts (AMOG Consulting); Ron Laemle, Prof. Jon Hinwood (Monash); and Narelle Haworth (Accident Research Centre).

A number of other organizations have contributed through in kind support including: TTLines, Queenscliff-Sorrento Ferries, P&O, Sydney Ferries, Ansett Australia, Luna Park, Melbourne, Australian Maritime College and Safety Marine Australia.

Most importantly, I would like to express my sincerest gratitude to my loving wife, Lynne, spirited daughter, Grace, and my new born son, Wills, for providing the self-belief to commence, the determination to continue, the peace to remain focussed and the motivation to finish.

This thesis is dedicated to all that have experienced tragedy at sea.

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1. INTRODUCTION

1.1 GENERAL INTRODUCTION

In the wake of major maritime disasters such as the sinking of the Estonia in 1994[1] and in the light of the growth in the numbers of high speed ferries and large capacity cruise ships[2], there is increased attention being paid to escape and evacuation at sea. In particular IMO (2001a) SOLAS regulation II-2/28-1.3 required that, for ro-ro ships constructed on or after 1 July 1999, escape routes shall be evaluated by an evacuation analysis early in the design process. IMO (2001a) stated that the aim of such analysis is to identify and eliminate as far as practicable, congestion that may develop during abandonment due to the normal movement of passengers and crew along escape routes.

At the 44th session of the IMO Subcommittee on Fire Protection it was recognised by IMO (2000a) that signs that meet prescriptive requirements might not meet the evacuation performance based requirements. While IMO (2001b) and IMO (1997) required some form of risk analysis to support the proposed design arrangements, the procedures for doing this are ill defined. Hence the regulations are open to subjective interpretation and inconsistent application. The effectiveness of design approaches to meet regulatory requirements based on existing methods is yet to be assessed through any rational means.

AMECRC (1998a & 1998b) minutes on workshops in Sydney and Perth identified that, prior to recent introduction of SOLAS regulation II-2/28-1.3 by IMO, evacuation trials were typically completed in the latter stages of construction of new build high-speed ferries in accordance with IMO (1995b) requirements of the HSC Code.

The former IMO (1995b) requirements of the HSC Code allowed for evacuation trials to be completed on only one side of the ship and in cases where this is impracticable, the administration may consider a partial evacuation trial using a route which the critical path analysis shows to be most critical. AMECRC (1998a and 1998b) minutes identified that these trials can be expensive, disruptive and may force designers to err on the side of conservatism to ensure that the trial after construction meets regulatory requirements. The IMO (1995b) requirements of the HSC Code also state that evacuation trials should be conducted whilst the vessel is docked (i.e. in relatively calm conditions) and consequently there is no consideration of the violent wave action and gradually listing environment of a capsizing vessel. AMECRC (1998a and 1998b) minutes confirmed this practice. It should be noted that evacuation trials by MSA (1996), Wood (1996), BC Ferries (1999) and Ostergaard et al (2001) have been conducted for vessels in open seas. However these are typically for research purposes and/or

[1] JAIC EFS (1997)

[2] IMO (2000a)

are generally focussed on crew and emergency services response and co-ordination rather than passenger activities. In addition IMO (1998e) have recognised that the evacuation analysis provides a rational basis for design optimisation and certification approval.

The performance of evacuation analysis software tools is critically dependant on the input data as well as the methodology for handling such data. Due to the unique characteristics of the maritime scenario the validity of both these factors requires assessment. This thesis provides the basis for comparison of conventional means of evacuation analysis against the requirements of the maritime specific scenario.

1.2 NOMENCLATURE

The variables relating to this study are defined where they are used first in the text. In addition, they are given here for quick reference. The variables are expressed in terms of the representative symbol, the units of application, and a definition of the variable.

Symbol	Units	Definition
α	-	Significance level
δ	m	non-encounter length
ϕ	rad	Mean list angle
η_i	m or rad	Displacement for i = 1,2..6 degrees of freedom
ρ	P/m^2	Crowd density
ρ_g	P/m^2	Group density
ρ_c	P/m^2	Counter flow density
σ	Rad	Roll amplitude
ω	Hz	Roll frequency
ξ_{age}	-	Age performance factor
$\xi_{congestion}$	-	Congestion performance factor
ξ_{gender}	-	Gender performance factor
ξ_{infant}	-	Infant carrying performance factor
$\xi_{kinetosis}$	-	Sea sickness performance factor
ξ_{SCi}	-	Subcondition performance factor (i=1,2..4)
ζ	m	Encounter length
Θ	rad	Phase shift
a	m/s^2	
A	m/s^2	Lateral acceleration acting at VCG
A'_t	N	Measured lateral acceleration required to tip a passenger over (applied at the passenger CoG)
A_d	-	Percentage of passengers that listen to announcement/drill
A,B,C,D	-	Vessel classifications
Age	yr	Mean age of the sample population
VCG	m	Vertical centre of gravity of the passenger as measured from the centre of gravity of the vessel.
$C_{Tipping}$	-	Coefficient of tipping
D_{MII}	s	Failure duration - Time taken to overcome an MII
e_x	-	Experience factor
Er	-	Environmental Force Factor
E_{TASK}	-	Task effectiveness

Symbol	Units	Definition
F_{or}	N	Overturning resistance
$F_{Tipping}$	N	Predicted lateral force required to tip a passenger over (applied at the passenger CoG)
F'_t	N	Measured lateral force required to tip a passenger over (applied at the passenger CoG)
F()	-	Undefined function
g	m/s^2	Gravitational acceleration
G	-	Percentage of the sample population that is male
h	m	Average height of passenger CoG
I_s	-	Information system parameter
k	N/m	Passenger effective stiffness
l	m	Average ½ stance width of passenger
L_a	-	Percentage of passengers to look at layout of the ship
m	kg	Mass of the passenger
m_s	-	Media system factor
M	Nm	Moment acting on a rigid body in dynamic/capsizing environment about the fixed stabilising foot.
MII_{rate}	Failures/min	Frequency of occurrence of motion induced interruptions (MII)
N, N	-	Sample size
n_g	-	Number of people walking in the same direction as the person under investigation
n_c		Number of people walking the opposing direction as the individual under examination
N_{female}	-	Number of passengers in the sample that are female
N_{male}	-	Number of passengers in the sample that are male
N_p	-	Percentage of passengers that look at notices/pamphlets
P_e	-	Percentage of passengers with previous experience
Q	P/ms	Passenger Flow
R_t	-	Symptom Severity Ranking
s	m	Rigid Body displacement of a vessel
S	-	Standard deviation
SC_i	-	Subcondition (where i=1,2..4)
S_x	-	Percentage of the population that select area x as the first destination in an evacuation. Where x = m destination = muster/assembly station = e =external area =el =lifeboat/embarkation area

Symbol	Units	Definition	
		=e2	=outside deck/exit/doors
		=e3	=upper decks
		=e4	=overboard
		= i	=internal area
		=i1	=foyer/reception
		=i2	=lower deck/car deck
		=i3	=cabin/seat
		=i4	=crew/wait
		=i5	=don't know
T	-	T statistic	
$T_{1/2}$	s	½ lateral natural period of the passenger	
$T_{\alpha/2}$	-	Critical T value from Student T distribution	
T_{CALM}	s	Time taken to perform a task in calm conditions	
T_{WAVES}	s	Time taken to perform a task in dynamic conditions	
V	m/s	Walking speed	
$\overline{V\delta_{i,j}}$		Predicted normalised dynamic velocity (for environmental condition i, person j)	
$\overline{V\delta'_{i,j}}$		Measured normalised dynamic velocity (for environmental condition i, person j)	
V_d	m/s	Dynamic walking speed – on dynamic/capsizing deck	
V_n	m/s	Normal walking speed - on stationary horizontal deck	
V_r	-	Velocity ratio	
$\overline{Vr_i}$		Predicted mean velocity ratio (for condition i)	
$\overline{Vr'_i}$		Measured mean velocity ratio (for condition i)	
w	m	Width of Corridor	
$(\bar{x}, \bar{y}, \bar{z})$	m	Position of a considered point relative to the centre of gravity of the vessel.	

1.3 OUTLINE OF THESIS

The organization of this thesis involves a series of literature reviews on evacuation analyses techniques, the availability maritime specific data and the application of such data and techniques to determine the required performance measures. As a result of the review, various issues are identified as requiring further investigation. To address the issues, empirical models to support the hypothesis are proposed based on the supporting data gathered and analysed.

The topics addressed in this thesis are presented in the following order:

- Following this introductory chapter, Chapter 2 provides a review of the characteristics of evacuations, evacuation analysis approaches and empirical models that have been developed to support evacuation analysis. Relevant codes and regulations relating to evacuation analysis of passenger ships are included in the review. Finally a general statement of the applicability of existing evacuation analysis models on the evacuation of passenger ships is developed.
- Chapter 3 identifies the scope required to support the thesis developed from the literature review in chapter 2.
- Chapter 4 provides a more detailed review of the motor ability performance of evacuees in a dynamic, capsizing environment. The experimental methodology used for developing supporting data is described and empirical models describing the motor ability performance of ship evacuees are developed and discussed.
- Chapter 5 provides a more detailed review of the way finding behaviour of evacuees on a passenger vessel. Again, the experimental methodology used for developing supporting data is described and empirical models describing the destination selection performance of ship evacuees are developed and discussed.
- Chapter 6 provides a discussion on a maritime specific computational evacuation model developed to assess the significance of the maritime specific factors such as motor ability and destination selection performance on the time required to evacuate a ship. Results of a parametric study using the model are presented and discussed.
- Chapter 7 presents conclusions drawn from the research into human behaviour during the evacuation of passenger vessels.
- Chapter 8 presents the main recommendations arising from this thesis.

2. LITERATURE REVIEW

2.1 OVERVIEW

IMO (2001a) has identified the need to develop an evacuation analysis design approach to model the emergency evacuation of maritime vessels that considers the available safety equipment, evacuation arrangement, and personnel complement and evacuation conditions.

Attempts have been made to develop software simulator programs that will permit evaluation of evacuation scenarios from a variety of maritime vessel types under a range of conditions. However the IMO or maritime community has accepted none of these in general due to concern of the applicability of such tools for the maritime market. This lack of faith in the existing software tools, whether deserved or not, is evidenced by the introduction of the interim evacuation guidelines by IMO (1999b). The guideline was introduced in June 1999 under the premise that 'computerised simulation systems are still under development.' The interim guidelines make provision for a 'simplified evacuation analysis' that can be readily implemented and assessed.

The following literature review is focussed on the existing means of conducting evacuation analysis and relative shortcomings of such means in meeting the requirements of the maritime evacuation scenario. The review covers the following elements:

- The evacuation process;
- Evacuation scenarios;
- Research into the evacuation of passenger vessels;
- Evacuation models; and
- Evacuation analysis design tools.

2.2 BACKGROUND

A comparison by Spouge (1996) of passenger fatality rates in different modes of transport identified that sea transportation is more dangerous than car, bus, rail and air transportation (in terms of fatalities per passenger km). BTCE (1996) identified the cost of maritime accidents in Australia alone as AUS$316 million per year. This is four times the cost of aviation and rail accidents. Spouge (1996) identified that over the fifteen years preceding 1996 over 750 passenger ships have been involved in a major crisis situation that has resulted in a full-scale evacuation. At least fifteen of these incidents have lead to the death of over 50 passengers, the worst case recording a death toll of over 4000 lives. In this period over 11500 people have lost their lives and even in our safety conscious era this figure is still increasing.[3] In some of these events the crisis was so severe that adequate time to perform an effective evacuation was not available. However, in many cases, improved layout design, crew training, management organization and passenger education could have lead to a decrease in the loss of life.

The influence of human behaviour on evacuation has been the focus of research for quite some time in the case of on-land structures. SFPE (1989) cited reference documents on the design of exits back to 1935. However the majority of relevant data to modern day evacuation analysis techniques is cited from the late seventies to mid eighties. SFPE (1989) identified human interaction during evacuation as an important consideration in effectively assessing the degree of safety of a facility. Along with many others, Galea and Owen (1994) claimed that, with the advent of powerful personal computers, mathematical simulations offers the potential to address the complex interaction, decision making and knowledge gathering capabilities of an evacuating crowd.

Beck and Yung (1994) discussed probabilistic risk assessment models developed for on land building fire evacuations to assess evacuation systems. An important link in the chain for the risk assessment is to characterise the expected number of fatalities. Beck and Yung (1994) recognise that this can only be handled through an appropriate egress model and remark a requirement for a suitable understanding of human behaviour during an evacuation to obtain more accurate results. Egress models are considered a valuable tool for designing safe and cost effective building layouts and readily tie into the formal safety assessment approach.

SPFE (1989) and more recent publications such as Saunders (1995) provided evidence of the increasingly more sophisticated database on human behaviour during the evacuation of on-land structures. However, Harbst and Madsen (1993) identified that the database on human behaviour for

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[3] The number of lives lost is based on a list of the most significant maritime disasters. Unfortunately, however the reporting of maritime incidents of 3rd world countries is not comprehensive so that the figure provided is an optimistic estimate.

floating structures, particularly passenger vessels, is void of valid, formally collated data. Boltwood (1995) identified that the majority of current research is based on qualitative inquiry reports and interviews. It is evident from the limited empirical data available that research focus to date has been on the development of software tools rather than collating valid quantitative data for the evacuation analysis of passenger ships. Brumley and Koss (1997) identified that evacuation analyses for ro-ro passenger ferries and cruise ships have adopted statistics on the basic modes of behaviour of occupants evacuating from on-land structures. Harbst and Madsen (1993), Boltwood (1995) and Reisser-Weston (1996), have all recommended either implicitly or explicitly that statistical information for on-land structures should be adopted for the case of the evacuation of passenger ships. It is noted that there has been no formal assessment on the validity of the assumption that the levels of human interaction, decision-making and knowledge gathering are the same for these quite different conditions.

In particular the on-land building statistical information has been gathered for the particular scenario of evacuation in the event of a fire and in fact evacuation analysis is still handled by the Fire Protection Subcommittee IMO even for maritime structures. Furthermore the IMO (1999b) recommended the use of mobility data from the on land database specified by SFPE (1995). In the absence of better statistical data Harbst and Madsen (1993) have recommended that the on-land human behaviour statistics be used for the case of a fire on board a passenger ship. Despite the widespread application of on land data for maritime cases Brumley and Koss (1997) have identified sufficient differences in the organisational structure between ship and building evacuations to warrant further detailed investigation.

One of the major differences between on land and ship evacuations is the evacuation destination on a ship relative to buildings. Building evacuation destination is typically located external to the building at some safe distance. Based in the evacuation procedure requirements as identified by IMO (1995b) for high speed craft the evacuation destination can be divided into three locations which passengers must report to sequentially; muster or assembly station (typically inside the ship), embarkation station (on external deck) and finally the launched life craft (safe distance from stricken vessel). In the event of major scenario differences, such as ship capsize rather than on board fire, the human behavioural characteristics may differ even further from the statistical information already gathered.

Another parameter that is a key difference between building and ship evacuation is ship motion. Rolnick and Gordon (1991) categorised ship motion according to its effects on humans as impact, vibration and tilt effects. Newman (1976) discussed the effect of motion of a ship on the sailor leading to the common dictum "One hand for the ship and the other for myself." Arwas and Rolnick (1984) claim that with respect to pitch and roll the phrase demonstrates the effort needed for simple act in rough seas and the requirement for adequate handles throughout the vessel. Newman (1976) claimed that the sailor is required to add a mechanical forcing function to learned sensorimotor responses already in existence. Newman (1976) claimed for more severe conditions it may be beyond the ability of most people to develop good modified response patterns, which leads to people anchoring the body as much as possible and limiting movement to the fewest possible body segments. Newman (1976) discussed the complex feedback systems of the nervous systems utilising both vestibular signals and other related system signals to counteract the effects of motion and discusses of the rapid breakdown of task performance when the limits to the compensatory capability are exceeded.

Furthermore, Smith (1997) provided a comprehensive summary on research into the influence of marine vessel motions on seasickness. Rolnick and Gordon (1981) gave a concise summary of laboratory and field studies which provide evidence of the widely acknowledged view that, while seasickness does not have a direct effect on task performance, it can give rise to cognitive, emotional and motivational deficits which result in performance deficits and fatigue.

To define the appropriate evacuation analysis technique for the maritime scenario a comprehensive understanding of the evacuation process is required. This is discussed in the Section 2.3

2.3 EVACUATION PROCESS

2.3.1 Overview

Harbst and Madsen (1993) have identified that the evacuation of passenger ships takes place in five broad stages, each placing different physical and psychological demands on the occupants of the ship. They describe the 'pentaphase division' of the timed progression of critical situations as:

- Pre - risk assessment and preparation by individuals prior to the incident;
- Awareness - period between actual starting time of an accident and the point at which the accident is accepted as being a crisis situation;
- During - period where the accident is accepted and passengers evacuate;
- Stop - period between the actual end of the incident and the perceived end of the incident;
- Post - no longer any perceived danger or accident has developed to such an extent that it cannot cause further damage.

Former IMO (1995b) requirements on modelling maritime evacuation analysis only considered the 'during and stop' stages and neglect the explicit modelling of the 'awareness' stage as described by Harbst and Madsen (1993). Furthermore, IMO (1995b) did not require consideration of the 'pre' stage on the evacuation process. Accordingly evacuation analyses did not consider the psychological behaviour of individuals 'during' the evacuation based on their predisposition. Nor was their any requirement in IMO (1995b) for explicit consideration of the impact of vessel motions on walking speed 'during' the evacuation.

Experience of the Jersey Harbour Department (1995) has shown that the predicted time to evacuate the entire vessel in accordance to IMO (1995b) requirements can be severely optimistic and provides little insight into the true mechanism of the evacuation process. In recent times software packages, such as that described by Poon (1994) designed for the evacuation of occupants in buildings, consider the different stages of the evacuation and attempts have been made to incorporate these stages based on the varying human behavioural characteristics for each stage.

2.3.2 Generic Evacuation Scenario

The success of an evacuation was recognised by Saunders (1995) as being dependant on the human behaviour of the occupants. Human behaviour during evacuations may be simply described as the thoughts, decisions and resultant actions of occupants of premises that require an evacuation. The behaviour also includes the interaction between evacuees and rescuers. Harbst and Madsen (1993) reported on Retterstfl & Weisæth's observations that our basic behaviour during an accident is independent of the accident's character. After comparing incidents aboard ships with knowledge gained from fires in restaurants and similar buildings Harbst and Madsen (1993) qualitatively confirmed the Retterstfl & Weisæth observation stating, "Basic human behaviour in crisis is independent of the crisis and location."

To better understand the implications of this statement a more rigorous definition of, 'basic human behaviour,' for the specific case of evacuation is required. Kuo et al (1994) have echoed work done by Harbst and Madsen (1993) and Canter et al (1990) in providing a set of basic stages of behaviour that can be readily recognised in the majority of evacuation scenarios. These stages are quoted verbatim as follows:

'*The interpretation stage* - People try to understand the nature of the incident and decide what to do.

The preparation stage - Once the danger is recognised people will begin to prepare for giving or following instructions.

The action stage - This is when people start to be actively involved in either overcoming the cause of the emergency or evacuating from the danger zone.'

2.3.2.1 The Interpretation Stage: Cue Perceptions

The ability of people to understand the nature of the incident is dependant on the number and type of warning cues accurately perceived by the occupant. Reisser-Western (1996) suggested that it is the goal of the evacuee to assess 'whether to treat the warning cue as being a genuine emergency or not'. He also states that 'People are very poor at defining the severity of an emergency situation.' Harbst and Madsen (1993) confirmed this observation stating 'Most people need several signs that something is wrong, or they need to be seriously affected by a threat, before they will do anything.' Evidence provided by Harbst and Madsen (1993) of people ignoring initial cues include but is not limited to the 'Salem Express' grounding, the 'Skagerak' grounding, the Kings Cross Station fire, 'Bradford football stadium fire, and the 'Discotheque Stardust' fire.

Reisser-Western (1996) identifies that warning cues can come from a number of sources including primarily alarm signals and messages as well as visual, auditory and olfactory cues from the emergency stimulus itself. Harbst and Madsen (1993) identified the following warning cues that may assist in the decision making process:

- Alarms;
- Instructions from the crew;
- Physical effects;
- Actions of other passengers;
- Actions of the crew;
- Changes in vessel manoeuvrability.

Where physical effects may include flames, heat and smoke in the event of a fire; and, water ingress, noise and abnormal vessel motions in the event of a ship grounding or collision.

Boltwood (1995) discussed the impact of cues when combined with alarm signals. Cues are identified as important when combined with alarm systems due to the poor human perception characteristics. While a single cue such as a gradual list to a vessel or the flow of smoke through as nearby passageway can often be explained away by a myriad of alternative insignificant scenarios, Boltwood (1995) claimed that the inclusion of a simultaneous alarm signal increases the probability of correct crisis identification. Similarly, while an alarm system can be inaudible, unintelligible or ignored as a false alarm, the inclusion of an additional cue helps convey a message that something is wrong and, at a minimum, instigate some further investigation by the occupants.

2.3.2.2 *The Preparation Stage*

The preparation stage defines the time when occupants will prepare to respond to the threat of the crisis incident. Bryan (1982) listed typical types of preparation as follows:

- Get dressed;
- Gather belongings;
- Secure valuables;
- Finish normal activities (i.e. save work document);
- Read evacuation instructions;
- Wet towels for face (in event of fire);
- Gather companions.

2.3.2.3 *The Action Stage*

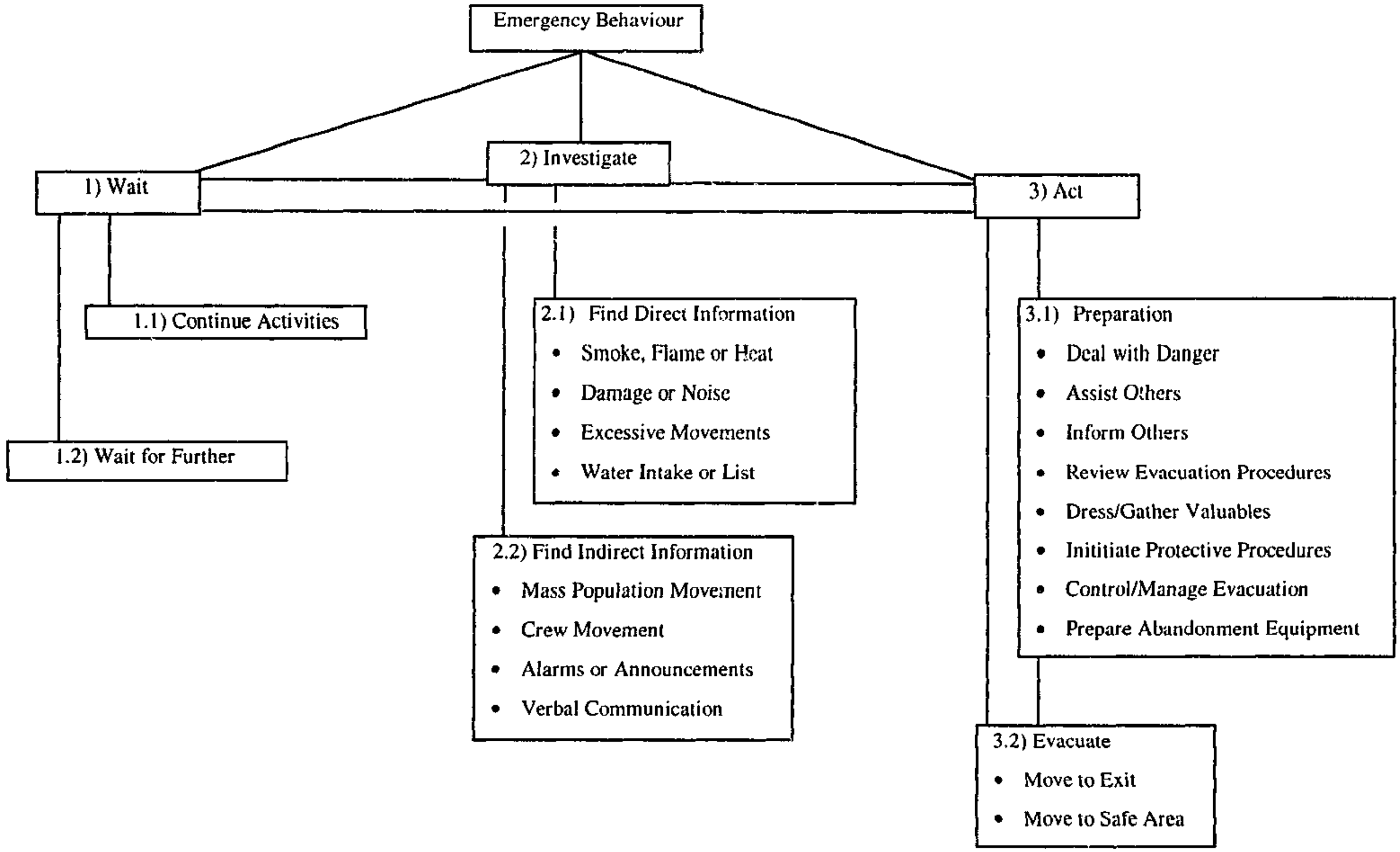
Saunders (1995) refined the action stage into seven sub-stages as follows:

- Continue normal activities;
- Investigate further;
- Alert others;
- Initiate protective procedures;
- Wait for assistance;
- Evacuate;
- Overcoming cause of emergency.

Saunders (1995) definition included some factors that may be considered as the preparation stage and in general the definition of the various stages of evacuation may be inconsistently categorised.

To avoid such inconsistencies an alternative definition of the process, based on a definition by Reisser-Weston (1996), is offered in Figure 2.1.

Figure 2.1 Generic Evacuation Process



SFPE (1995), Canter (1990), Levin (1987), Saunders (1995), Brennan (1996) and Reisser Weston (1996), Ozel (1993), Purser and Raggio (1995) and Muir (1996) provided further details on research of evacuation of buildings and aircraft. The main areas of research that provide quantitative data for on land structures include:

- Acceptance Time;
- Preparation Time;
- Response Actions/Times;
- Way Finding or Route Choice;
- Motor Ability - impact of smoke/visibility, congestion, counter flow, blockage, assistance, handrails on walking speed through stairwells, corridors and open areas.

2.3.3 Performance Shaping Factors

The factors which influence an "individual's capacity to respond adequately to emergencies' are described by Reisser-Weston (1996) as Performance Shaping Factors (PSF). Boltwood (1995) provided examples of factors that influence the ability of occupants to carry out the tasks set before them. The factors described by Reisser-Weston (1996) and Boltwood (1995) are shown in Table 2.1.

Table 2.1 Performance Shaping Factors

Performance Shaping Factors	Description	Examples	Factor Influenced
Structural	Physical characteristics, rules and hierarchies of the working/living environment including the structure purpose and layout	Organization Authority figures Assistance Distribution	Goal Selection Way finding Walking speed Congestion
Effective	Emotional, cultural and social factors influencing stress, perceived risk, trust and cultural norms	Obedience/Co-operation Comprehension/Understanding Group behaviour Risk perception Queuing	Way finding Acceptance Acceptance Acceptance Walking speed
Informational	Media, communication, training, education, familiarity and experience	Alarms and Informational Systems Knowledge of procedures Familiarity with layout Training/Experience	Acceptance Way finding Way finding Way finding
Task/Resources	Responsibilities and requirements of occupants	Role Gender Age	Goal Selection Acceptance Acceptance
Environmental	Local time varying factors which describe the changing environment	Threats Cues Visibility Toxicity Pressure Congestion	Acceptance Acceptance Way Finding Walking speed Walking speed Walking Speed
Physical	Individual traits physical traits	Fitness Exertion Urgency	Walking speed Walking speed Walking speed

2.3.4 Performance Measures

Performance measures provide a mechanism for assessing the level of success of an evacuation. Typical performance measures for evacuation identified by Lovas, Wikland and Drager (1993) are provided in Table 2.2.

Table 2.2 Performance Measures, after Lovas, Wikland and Drager (1992)

Evacuation Time	Travel Time	Average Evacuation Time
		Total Evacuation Time
	Queuing Time	Average Queue Length
		Maximum Queue Length
Route Complexity	Route Lengths	Maximum Route Length
		Total Route Length
	Path Complexity	Number of Turns
		Up/Down Moves
Accident Impact	Injuries	# Dead Persons
		# Injured Persons
	Damages	# Hazardous Paths
		# Unavailable Exits
		Path Reliability
Note: # is defined as 'number of'		

2.3.5 Maritime Scenario

For the maritime scenario there are a number of sub-stages that may be defined for the evacuation analysis of a passenger vessel. Brumley and Koss (1996b) outlined the stages of an evacuation of a ship based on IMO (1995b) requirements as follows:

- Safety management;
- Crisis discovery;
- Crisis reporting;
- Crisis assessment;
- Muster warning signal;
- Acceptance of crisis;
- Reaction to acceptance;
- Muster and receive instruction;
- Abandonment assessment by crew and captain;
- Embarkation warning signal;
- Evacuation to embarkation point;
- Evacuation to survival craft and clear of mother vessel;

These stages are discussed further in the Sections 2.3.5.1 to 2.3.5.11

2.3.5.1 Safety Management

IMO (1998e) identified some of the issues relating to safety management as follows:

- Safety Culture/Motivation;
- Contingency Planning/Emergency Response;
- Manuals/Procedures/Checklists.

These issues impact on crew training, equipment maintenance, passenger layout, safety plan familiarisation and risk acceptance. IMO (2001a) Chapter III, Part b Reg 37 required that passenger vessels carry muster lists that identify the action to be taken by crew and passengers when the alarm is sounded. In addition to identifying crew responsibilities the muster list also identifies substitutes for key personnel, should they become disabled. IMO (2001a) Chapter III, Part b Reg 35 identified training manual requirements and Reg 30 identifies weekly abandon ship and fire drill requirements.

IMO (1997) also required that the owner and/or those responsible for the operation of the ship comply with the requirements of the International Safety Management Code. The ISM code is expressed in broad terms and is based on general principles and objectives. IMO (1997) required that the organization that has assumed responsibility for operation of the ship, 'should establish procedures for the preparation of plans and instructions for key shipboard operations concerning the safety of the ship.' IMO (1997) required emergency preparedness that involves the following:

- 'Procedures to identify, describe and respond to potential emergency shipboard operations;'
- 'Programmes for drills and exercises to prepare for emergency actions;'
- Measures for ensuring the responsible organization for ship operations 'can respond at any time to hazards, accidents and emergency situation involving its ships.'

NATO (1988) showed that training and experience increase the ability to handle a critical situation. The IMO (2001a) safety management system provided information on the likely performance of the evacuation process such as the following:

- Training level and capabilities of the crew;
- Number of crew available and responsibility of each crew member;
- Number, type and location of craft available;
- Equipment maintenance and performance standards;
- Training/education/experience of passengers;
- Number of passengers.

When designing a ship, the designer assumes that the management structure, level of training of the crew and maintenance of equipment is in accordance with IMO (2001a) requirements. The contingency requirements of IMO (2001a) did allow for the loss of the available human resources due to the crisis itself where crewmembers may be incapacitated or isolated due to the event. Similarly IMO (1998c) has recognised that certain escape routes, assembly stations, embarkation station and equipment such as survival craft, though not necessarily damaged, may be inoperable due to isolation or listing. Despite these contingencies there is no critical assessment and legislative recommendations on the means of modelling the impact of inadequate management of personnel and equipment that may cause inadequate evacuation performance.

On larger vessels, the number of crew available to assist in internal search and rescue can critically affect the successfulness of an evacuation. NOR (1991) identified that on the Scandinavian Star, for example, only 50% of the passengers in their cabins actually tried to evacuate. Had more crew been available to search these cabins and guide passengers to safety, the number of deaths may have been significantly reduced.

Harbst and Madsen (1993) described the management stage as the 'Pre' stage and relate it to the risk evaluation by passengers and crew. Background knowledge of the safety management system provides the crew and safety management staff with a basis with which to evaluate risks or dangers to the vessel. Passengers do not have direct access to this information. Accordingly, passengers can only evaluate the risks based on their initial perceptions combined with information transfer through announcements, placards, visual presentations and evacuation drills provided by the vessel crew. Harbst and Madsen (1993) identified that information to passengers has the following effects:

- Counteracts panic and furthers the cause of the type of behaviour which is sought;
- Reduces the number of passengers that would otherwise remain passive;
- Assists in making passengers react.

However, Harbst and Madsen (1993) provided no quantitative data to support the above claims.

2.3.5.2 Crisis Discovery

The discovery of a crisis can be a very critical stage of the evacuation. For example if a fire is discovered early enough, the lower levels of smoke in the evacuation routes can enhance the way-finding capabilities. Using standard on-land evacuation analysis tools, NOR (1991) found that the estimated time taken to evacuate the ship was approximately 30 minutes for the 'no smoke' condition. This was increased to up to 13 hrs for the levels of smoke considered in the actual event.

Reisser-Weston (1996) found that quite often, as is the case for many on-land structures, people would assume that someone else knows more about the situation than they do. Occupants of on-land structures have justified the visualisation and smell of smoke as the result by a number of non-critical causes.

Canter (1980) found that those in a position of responsibility would generally accept and investigate a potential critical event. However due to the many different roles and responsibilities of the crew it perceivable that confidence in the importance of crisis indicating cues may be reduced. Harbst and Madsen (1993) cited two examples where the dangers have been under-evaluated: Scandinavian Star and the Scandinavian Sun. In both cases it took approximately 10 minutes before action on the bridge resulted after the initial discovery by crew of the incident. Although the use of monitoring equipment has significant potential benefits, Reisser-Weston (1996) pointed out that the reliability and hence the faith in the system can critically affect its performance. Economic ramifications of initiating an evacuation to muster stations provide an incentive for the ships master to delay the order while crew investigate the validity, and seriousness of the event. Boltwood (1995) identified that in such events the Master would typically keep passengers informed by frequent PA reports. Alarm signals were only used where there was an imminent life-threatening situation.

2.3.5.3 Crisis Reporting

Once the passenger, crew or monitoring system has discovered the crisis the reporting system becomes the critical factor. Reisser-Weston (1996) identified that the physical and organisational structure is often vital in deciding the individual's reaction to warning cues. Brennan (1996) identified that people may feel the need to investigate the crisis first hand before passing the message up the organisational structure. Reisser-Weston (1996) pointed out that for a system without a rigid hierarchy, such as multiple occupancy buildings, there is the potential for this stage to be repeated over and over for isolated individuals, particularly in ambiguous situations. Canter (1980) found that in a structure, such as a hospital, where there is a rigid hierarchy of positions and the work is spread throughout the building, fire is detected quickly and informational cues are acted on effectively. Reisser-Weston (1996) also discussed the issue of assigned and perceived responsibility and the impact of training and drills on performance. Given IMO requirements on ship safety it may be expected that ships crews would be equally efficient as hospitals. However, Boltwood (1995) identified that the ability of crew to carry out emergency duties could be less than expected.

2.3.5.4 Crisis Assessment

A well-organised reporting system can reduce the time taken to pass important information on to the 'real' decision makers. In doing this, the risk of initiating an unnecessary evacuation may increase. Aside from the economic and health factors associated with the completion of an unnecessary evacuation, false alarms risk reducing the performance of the crew as discussed by Reisser-Weston (1996). If the administration of the vessel adopts a 'fast-track' reporting system, Reisser-Weston (1996) implied that they may expect degradation in crew response time and will be required to adopt a more intensive training schedule.

The decision making process of the safety management team was required by IMO (2001a) to be well defined for a number of possible scenarios. It is the responsibility of the person in charge, the master, to know precisely what is to be done at each stage of each type of emergency. IMO (2001a) Chapter 3 Part B Reg 29 identified that a decision support system to cover all foreseeable emergency situations for emergency management be provided on the navigation bridge for the ships master. Boltwood (1995) identified that Masters generally agree that the best approach when an emergency occurs is to opt for early informational public announcements using tannoy systems, which may introduce a precautionary muster. Balls (1996) identified that, where only part of the vessel is affected by the emergency, especially in large vessels with numerous fire zones and watertight sections, only those directly affected should be made aware of the problem initially if the emergency is unlikely to spread throughout the vessel.

2.3.5.5 Muster Warning Signal

When issuing the muster-warning signal it is important to appreciate that many people may not respond or may delay response to a single warning system.

Reisser Western (1996) presented statistics that show that perception of the seriousness of a situation is partly dependent on the level of audibility of the alarm system. JAIC EFS (1997) confirmed that people may be drunk, seasick, or asleep in which case they may hear the announcement or alarm but not listen to it. Boltwood (1995) similarly identified that passengers may not speak the language of the announcement or may have a hearing impairment. Jersey Harbour Department (1995) found that, during the grounding of the Saint-Malo ferry off Point Corbiere, many of the passengers were not aware of the safety procedures due to seasickness and distracting noises at the time of the safety announcement. Even during the evacuation it was found that many of those having difficulty donning lifejackets did not refer to their safety cards.

One way of ensuring complete evacuation is to send a searching team to wake, and/or inform the passengers of the situation. NOR (1991) identified that this process is time and resource consuming in a situation where there is little of either. IMO (2001a) Ch 3, Pt b Reg 37 only required that the passenger ship have procedures in place for locating and rescuing passengers trapped in their staterooms rather than a systematic check of all staterooms.

2.3.5.6 Acceptance of Crisis

Once the passengers have become aware of the warning cues, it has been found that many of them will ignore the cues and continue with whatever they were doing prior to the cue realisation. Multiple cues are often required when the crisis is not locally obvious. Canter (1980) and Purser (1995) identified that for on-land office buildings surveys showed that up to 60-85% of occupants ignored the first cue. Brennan (1996) identified that the acceptance of the first cue depends on the following factors:

- Responsibility to others;
- Involvement in safety oriented fields;
- Size of travelling group (people who are alone, seek answers quicker);
- Severity of cue;
- Task involvement.

2.3.5.7 Reaction to Acceptance

The reaction stage is the most widely examined stage in modern evacuation research. Most simulation packages begin the evacuation analysis at the time when the occupant reacts to the crisis cues (refer Section 2.6). Typical reactions used in modern evacuation analysis techniques are as identified by Saunders (1995) and documented in Section 2.3.2.

A statistical spread of the above reactions has been obtained from studies of on land structures (hotels, restaurants, etc). However, Harbst and Madsen (1993) and Boltwood (1995) identified that in the case of the ship reactions have not been quantitatively examined. Thus it has become common practice in modern day evacuation analysis techniques to utilise on-land data for the offshore case. Galea (1996) and Reisser-Weston (1996) both described models that are offered for the evacuation of passenger ships on this basis.

2.3.5.8 Muster, Receive Instruction and Don Lifejackets

IMO (2001a) required that Muster stations must have ample room for marshalling and instruction of passengers. It is noted that the term 'muster station' is a traditional term used in the maritime industry. Due to passenger confusion it has more recently been replaced with the term 'assembly station.' In this thesis the words are used interchangeably. In addition to giving instruction on the crisis situation and the evacuation requirements, the crew may be required to instruct/assist passenger in the donning of lifejackets. IMO (2001a) regulation III/7.2 required that lifejackets shall be provided for every passenger on board. However this regulation does not restrict where lifejackets are located. The operator has a choice whether to locate lifejackets in cabins, on deck or at the muster station. IMO (2001a) regulation III/22.2 stated, as a minimum, the ship shall carry lifejackets for that not less than 5% of the total number of persons on board in conspicuous places on deck or at muster stations. Furthermore IMO (2001a) regulation III/26.5 stated that, not withstanding regulations III/7.2 and III/22.2, a sufficient number of lifejackets shall be stowed in the vicinity if the muster station so that passengers do not have to return to cabins to collect lifejackets. Regardless of whether the passenger dons a lifejacket at the assigned cabin or at the muster/assembly station IMO (1998c) required that a muster shall include the following:

- Assembly of passengers at the muster station;
- Check the passengers according to the passenger list;
- Make passengers aware of orders specified in the muster list;
- Check that lifejackets are correctly donned.

The muster list and emergency requirements were documented in IMO (2001a) regulation III/37.3 which identified crew requirements in the event of an emergency. The duties identified in the muster list included ensuring that passengers were suitably clad and had donned their lifejackets correctly.

The stage of lifejacket distribution and checking can be a very difficult and confused process without adequate design of the muster area. In muster stations where the roof is low and crowds are dense, the instructions from the crewmember may become inaudible. Boltwood (1995) and Jersey Harbour Department (1995) both provided qualitative evidence of such audibility issues.

Wood (1996) identified two initiatives that reduced confusion during the muster phase of the evacuation validated through a large-scale ferry evacuation trial, Exercise Invicta conducted by the UK Marine Safety Agency (MSA). The first initiative was the decision for the crew to wear distinctive hats (yellow baseball caps). The second was the use of hand held megaphones in the muster stations to ensure that instructions could be heard over background noise.

Wood (1996) also identified an effective means of distributing lifejackets through directing passengers in an anti-clockwise direction past two lifejacket storage points. The arrangement allowed for an accurate check on passenger numbers.

Ostergaard and Jorgensen (2001) found that the crew were difficult to distinguish after the passengers had donned their lifejackets. Ostergaard and Jorgensen (2001) reported that the handing out of lifejackets at the muster/assembly area created a clear bottleneck due to the narrow nature of the storage area and passengers remained near the doors of the storage lockers after donning lifejackets which prevented those that did not have jackets from accessing the locker. Furthermore Ostergaard and Jorgensen (2001) identified that passengers had difficulties unbuckling lifejackets, which further delayed evacuation times.

2.3.5.9 ***Abandonment Assessment***

Balls (1996) claimed that the saying, 'the ship is your best lifeboat,' 'still holds good.' He also identified that, where stability is guaranteed, mustering all persons in a safe haven on board may be preferable to embarking survival craft. Ostergaard and Jorgensen (2001) also claimed that, 'generally the ferry is considered the safest place for the passengers to stay and most captains want them to be waiting there as long as possible.'

Paterson et al (1996) identified through model test that life rafts are, "vulnerable to capsize or damage when directly impacted by breaking waves". Wood (1996) also identified in the Exercise Invicta that a, "number of life rafts failed to inflate properly". JAIC EFS ([illegible]) also found a number of overturned lifeboats and damaged life rafts. Jardine-Smith (1996) stated, "How life saving equipment can or will be used in any particular incident will depend on the circumstances at the time - including the judgement and skill of the masters and crews of rescuing craft." He also states that, "'launching and particularly the recovery of rescue boats can be fraught with difficulties." Jardine-Smith (1996) claimed that the use of standard survival craft will be a,' difficult decision to take as they may not be recoverable in the prevailing conditions". Golden (1996) identified the, "vast majority of ship wreck victims will die from cold," or, more specifically, hypothermia. Golden (1996) quoted survival times of fully clothed men at 5°C, 10°C and 15°C as 1 hour, 2 hours and 6 hours respectively.

The decision making process to assist the Master in an emergency may include consideration of the above perceptions and consequently, the ultimate decision to abandon ship may not be obvious. The decision making process will be dependant on the Master having a realistic appreciation of the time it will take to completely evacuate crew and passengers relative to how long the ship can last before becoming uninhabitable.

2.3.5.10 Evacuation to Embarkation Point

Wood (1996) identified that, in moderate evacuation scenarios, the passengers will be under the guidance and control of the crew and the passengers will be handled in groups during the process of evacuating from the muster station to the embarkation point. In such circumstances decisions on evacuation routes will be made by the crewmember in accordance to safety management procedures. Accordingly, the process of evacuation will be controlled and predictable during this stage. Where the crewmember in charge is advised or determines that the original Embarkation Point is no longer available, the crewmember is required to follow the contingency arrangements in the Muster List and Emergency Procedures.

It is arguable, in such a 'controlled' environment whether human factors due to interaction between passengers need be modelled during the stage of evacuation from muster stations to embarkation points. However, even modern evacuation analysis design tools can differ in the interpretation of this relatively easy stage to model. Goldberg and Koss (1996) identified that, based on a number of simple crowd density evacuation models there is some variation in the resultant evacuation times can be as much as 70% for narrow stair widths and 20% for wider stair widths.

Wood (1996) did point out, "in an emergency situation, where it is immediately obvious that an abandon ship situation exists, the mustering and evacuation of passengers/crew will proceed simultaneously." In such circumstances, the evacuation process will be far less controlled and accordingly far more complex.

2.3.5.11 Evacuation to Survival Craft

The evacuation to survival craft includes the time taken to board the life craft, enter the water and move to a safe distance from the ship in distress. Evacuation times during this phase are dependant on the particular abandonment system in place and the performance of the crew. Since vessels are required to complete regular trial runs of the safety equipment on board (especially davit launched systems) in accordance with IMO (2001a) requirements, data of the effectiveness of these systems is readily accessible.

Brumley (1996a) witnessed an evacuation trial using davit-launched life raft that indicated that the life raft could take of the order of 10 minutes to deploy. Manufacturers claim that Marine Evacuation Systems (MES), that rely on inflatable rafts and slides, can be deployed in as little as four minutes and can hold over 100 people. Wood (1996) reported that during Exercise Invicta lifeboats were bowsed and ready for boarding within 5 minutes, 30 seconds from the emergency alarm (2 boats, 55 person capacity). These boats were deployed and clear of the boat within 4 minutes, 20 seconds (with less than 21 people on board). The total time for deployment for these lifeboats was 9 minutes and 50 seconds. This time is consistent with the davit-launched life rafts witnessed by Brumley (1996a). Wood (1996) also reported on life rafts associated with the MES systems. Of the 21 life rafts used, 3 failed (nearly 15%). The average time between launching the life raft and marshalling them clear was just over 21 minutes. However, Woods (1996) found there was significant variation in times between different life rafts. A summary of Woods (1996) findings, taken from detailed run times, is provided in Table 2.3.

Table 2.3	Inflatable Life Raft (ILR) Performance of the Exercise Invicta MES			
Milestone	Minimum (Minutes)	Average (Minutes)	Maximum (Minutes)	Standard Deviation (Minutes)
1. ILR Container Bowsed In	0.7	7.4	18.8	7.1
2. ILR Boardable	0.5	2.3	14.8	3.5
3. 1st Person Descends	0	2.7	7.82	2.7
4. 45th Person Descends	5.0	6.7	12.9	2.0
5. Life raft Marshalled Clear	0	2.1	5.2	1.4
Total	8.6	21.1	39.7	9.0

Note: 1. Summary of the performance of 16 of 21 life rafts. Only rafts with complete results have been included

2. Times are recorded as time taken complete each milestone starting from the previous milestone.

3. Life rafts had a capacity of 45 people. MES platforms are designed to accommodate 2 ILR at each point in time

Galea (1996a) identified the risk of significant injury during evacuation trials using similar inflatable slides in the aircraft industry. Galea (1996a) reported that 'between 1972 and 1991, a total of 378 volunteers (or 6% of participants) sustained injuries ranging from cuts and bruises to broken bones'. This includes a female volunteer sustained injuries leading to permanent paralysis.

Rutgersson and Tsychkova (1999) conducted an experimental investigation of the launching process for lifeboat/davit evacuation systems to obtain data about the risks connected with launching under realistic ship motion behavioural conditions. The study focussed on a partially enclosed lifeboat with a capacity of 150 persons and a typical underdeck davit whereby the lifeboat was lowered vertically from the winches by two cables. The study investigated the influence of the severity of environment (based on heeling angle of the ship) on the risks of impact with the ship, slamming against waves and possibility of capsizing of the lifeboat. The assessment was based on video recordings of 300 tests as well as physical measurements. Incident risk categories during the launching of lifeboats were developed by Rutgersson and Tsychkova (1999) and are presented in Table 2.4.

Table 2.4	Incident Risk Categories - Lifeboat Systems		
	Low Risk	**Moderate Risk**	**High Risk**
Injury due to Impact Loads on Lifeboat			
Probability of Injury	< 0.5%	0.5%-50%	>50%
Accelerations (m/s^2)	< 6	6-9	> 9
Capsize of Lifeboat			
Probability of Capsize	< 0.5%	0.5%-50%	>50%
Roll Angle (°)	< 30	30-70	> 70

Rutgersson and Tsychkova (1999) estimated the time for turning out from stowed to embarkation position as 2-5 minutes based on discussion with crew on the M/S Mariella "Viking Line." Boarding time of lifeboats is stated as 10 minutes for the Greben PEL-150 based on an evaluation and test report for davit-launched lifeboats. Further discussion with the crew on the M/S Mariella "Viking" indicate an ordinary disconnect time of 1-3 minutes in calm conditions. Rutgersson and Tsychkova (1999) referred to Cox and Lloyd (1977) and Hosoda and Kunitake (1985) to provide an estimate of the degradation of human performance in dynamic conditions.

Rutgersson and Tsychkova (1999) provided a comparison of evacuation times for two environmental scenarios as follows:

- Condition 1. - The ship is in an upright state, under calm conditions. The launching height is 16m, and lowering Speed is 0.7 m/s.
- Condition 2 - Condition 2 has the same parameters as condition 1 except that condition 2 has a wave height of 3m and roll period of 8 seconds (leading to a roll amplitude of 7 degrees).

The difference in evacuation times calculated as 14 minutes for condition 1 compared with 22-24 minutes for condition 2.

A general description of the results is presented in Table 2.5. Rutgersson and Tsychkova (1999) also presented the specific risks relating to the launch heights and davit arm lengths.

Table 2.5 General Description of Risk to Injury and/or Capsize during Life Boat Launch			
Wave Height	Average Roll Angle	Leeward	Windward
Intact Mother Ship			
1m	1	Low	Low
	1.5	Low	Low
	2.1	Low	Low
2m	2.3	Low	Moderate
	3.0	Low	Low-Moderate
	4.0	Low-Moderate	Moderate-High
3m	2.9	Low	High
	4.4	Low-Moderate	High
	6.8	Moderate-High	Moderate-High
Damaged Mother Ship (20° List into Windward Side)			
1m	2.1	-	Low
2m	2.3	Moderate	-
	3.0	High	Low
	4.0	High	-
3m	2.9	Moderate-High	High
	4.4	Moderate-High	Moderate
	6.8	Moderate-High	Moderate
Damaged Mother Ship (20° List into Leeward Side)			
2m	2.3	-	Moderate
	3.0	-	Moderate
	4.0	-	Moderate-High
3m	2.9	Low	High
	4.4	Low	Moderate-High
	6.8	Low	Moderate-High

In addition to lifeboats, Rutgersson and Tsychkova (2000) also investigated the performance of "slide" and "fall" evacuation systems. They identify the advantages of slide systems as follows:

- More space onboard when it is not in use;
- One Launching device for many life rafts;
- Demand on number of skilled seamen for operation is limited;
- The risk of serious accidents during training and calm conditions is low.

The main disadvantages are described as follows:

- Large exposure to wind, waves and cold;
- Difficult for children, elderly and disabled;
- The slide exposed to the interaction between the waves and the vessel motions for a relatively long time.

The "slide" systems come in two forms including slides and chutes. Rutgersson and Tsychkova (2000) identified that chutes have the following disadvantages:

- Platform and life rafts are in dangerous vicinity of the mother ship during the whole evacuation phase;
- Where there is reflection of waves platform motions will effectively double;
- People may hesitate to use chutes in severe environments.

Functional test of all "slide" systems are required at the 20 degree heeled ship. For the tests conducted by Rutgersson and Tsychkova (2000) on slide systems the incident risk categories are defined in Table 2.6.

Table 2.6 Incident Risk Categories -Slide Systems

	Low Risk	**Moderate Risk**	**High Risk**
Probability of Injury	< 0.5%	0.5%-50%	>50%
Deformation of Slide (temporary buckling)	< 1m or 1-2m occasionally	1-2m or > 2m occasionally	> 2m
Steepness of Slide – max. Min.	<45° >5°	45-60° -15-5°	>60° <-15°
Platform Condition (under water or out of water)	none	<25% of platform	>25% of platform
Maximum roll angle of platform	<20°	20-40°	>40°

Table 2.7 provides an overview of the risk associated with the evacuation using slide systems.

Table 2.7 General Description of Risk to Injury during Slide Launch

Wave Height	Wave Period (s)	Leeward	Windward
Intact Mother Ship			
1m	5	Low	Low
	6	Low	Low
	8	Low	Low
2m	5	Low	High
	6	Low	High
	8	Low-Moderate	Low-Moderate
3m	5	Low-Moderate	High
	6	Low-Moderate	High
	8	Moderate-High	Moderate-High
Damaged Mother Ship (20° List into Windward Side)			
1m	5	Low	Low
	6	Low	Low
	8	Moderate-Low	Low
2m	5	Low-Moderate	Moderate-High
	6	Moderate	Moderate-High
	8	Moderate-High	Hugh
3m	5	Low	High
	6	Low	High
	8	Moderate	Moderate-High
Damaged Mother Ship (20° List into Leeward Side)			
1m	5	-	Moderate
	6	-	Moderate
	8	Low	Low-Moderate
2m	5	Low	High
	6	Low	High
	8	Low-Moderate	Moderate-High
3m	5	Low	-
	6	Low	High
	8	Low-Moderate	High

Rutgersson and Tsychkova (2000) also provided risk categories with injury due to "fall" systems, however the effectiveness of the "fall" system is equated with the effectiveness of a lifeboat system.

It is noted that the results of both the slide and lifeboat tests indicated that there can be a high risk of injury to passengers during lifeboat launches even for relatively low roll amplitudes (3-4°) or wave heights (2m) on an intact vessel. Furthermore Rutgersson and Tsychkova (2000) developed an approach for determining evacuation time based on the risks of injury/system failure. Rutgersson and Tsychkova (2000) provided an estimate of the effectiveness of the evacuation system for a typical example as only 41% in dynamic conditions when compared with still conditions. It is noted that Rutgersson and Tsychkova (2000) provided no quantitative evidence of the connection between the risk categories developed and evacuation times.

Rutgersson and Tsychkova (2000) noted that the work conducted does not include consideration of installation and maintenance of life-saving appliances and the human aspects connected with operation of evacuation systems.

2.4 EVACUATION SCENARIOS

2.4.1 Overview

Harbst and Madsen (1993) categorised evacuation scenarios on board ships into the following groups:

- Fire and Explosions;
- Running aground, collision, leakage;
- Other - hostage taking, bomb threats, boarding, engine damage and loss of manoeuvrability, loose cargo, food poisoning, hitting mines, accidents with dangerous materials, loss of ship stability.

DNV Technica (1996) identified fire and flooding as the principal hazard scenarios, each requiring explicit hazard reviews within the ship hazard assessment. In particular DNV Technica (1996) identified generic accident scenarios as collision, grounding, impact, flooding and fire/explosion. DNV Technica (1996) explained the Hazard categorisation in Figure 2.2.

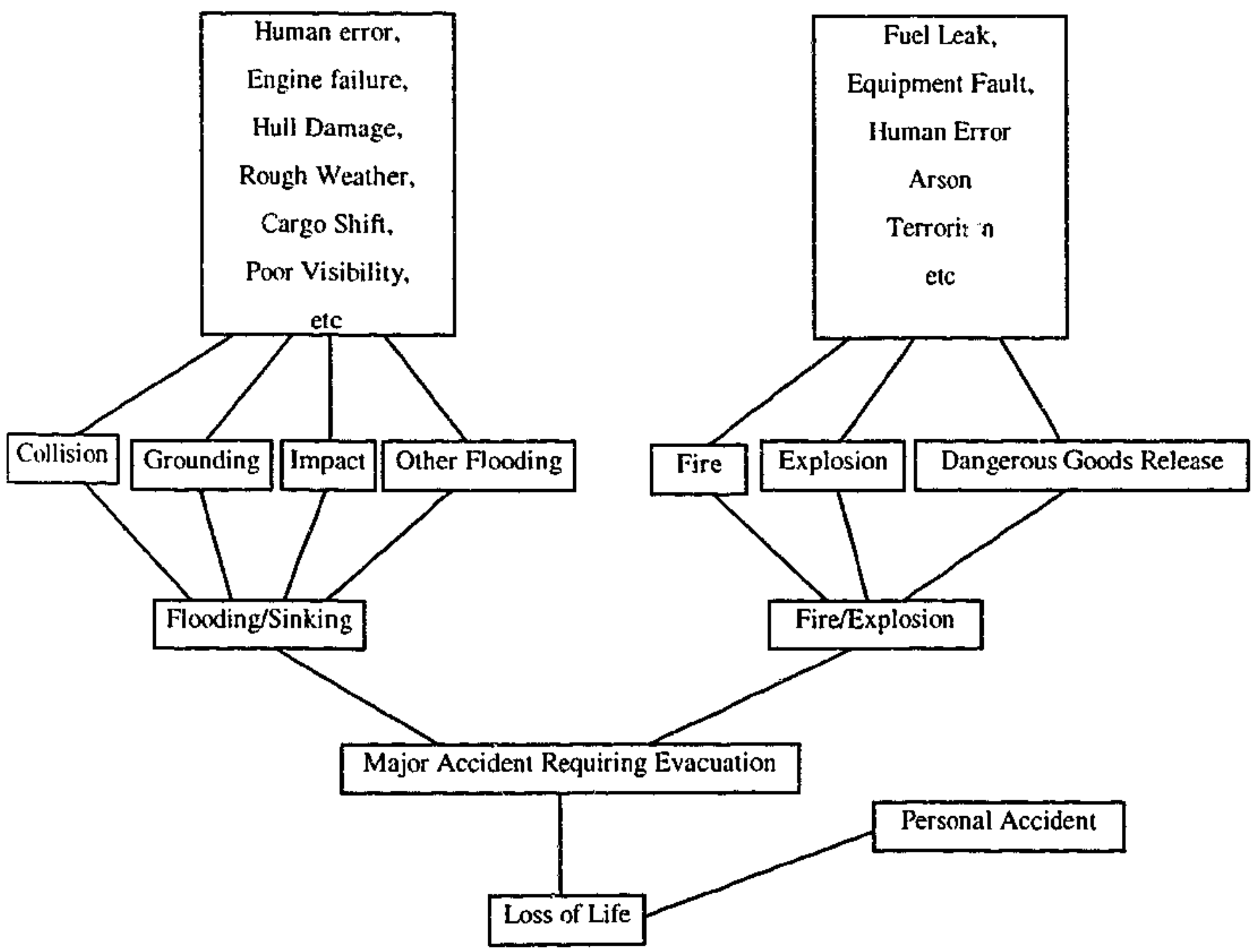


Figure 2.2 Hazard Categorisation Onboard Ships, after DNV Technica (1996)

Casualty categories based from other sources on ship casualty data are as follows:

- *'Lloyds Casualty Database,'* Lloyds Maritime Information Services (LAIS), since 1975
  - Foundered - sank in heavy weather or due to leaks;
  - Wrecked/Stranded - on shore, sea bed, underwater wrecks;
  - Collision - with another ship;
  - Contact - with dock walls, piers, bridges, offshore structures etc;
  - Fire/Explosion - excluding those initiated by collision;
  - Missing - lost at sea with no news received;
  - War loss - due to hostile acts;
  - Hull/machinery damage - not attributable to any other category;
  - Miscellaneous - unclassifiable for lack of information.
- 'DoT Casualties to Vessels and Accidents to Men', Marine Accident Investigation Branch (MAIB) since 1989
  - Foundering/Flooding;
  - Stranding/Grounding;
  - Collision/Contact;
  - Fire/Explosion;
  - Missing;
  - Capsizing;
  - Machinery Damage;
  - Heavy Weather Damage;
  - Other.
- 'Analysis of World Merchant Ship Losses' Lloyd's Register, 1891-1975
  - Foundered;
  - Wrecked;
  - Collision;
  - Burnt (i.e. fire/explosion).
- 'DNV Collision and Grounding Analysis' Det Norske Veritas (DNV), 1970-78
  - Collision;
  - Contact;
  - Grounding- onto an underwater rock, wreck, reef etc.;
  - Stranding - onto the shore where it is visible above the water.
- *'COST-301 Casualty Analysis'* Netherlands Maritime Research Institute (MARIN), 1978-83
  - Collision (meeting);
  - Collision (crossing);
  - Collision (overtaking);
  - Stranding/Grounding;
  - Contact/Ramming;

  - Foundering.
- 'Analysis of Marine Incidents in Ports and Harbours' National Maritime Institute (NMI), 1976
  - Sinking (i.e. foundering);
  - Grounding;
  - Collision-with another ship underway;
  - Striking-with a moored anchored vessel;
  - Impact (i.e. contact);
  - Fire/Explosion;
  - Drifting - a drifting vessel which is a hazard but causes no damage;
  - Anchor Loss;
  - Fouling - becoming entangled with port installations or another vessel's moorings;
  - Ranging - severe movement relative to the berth due to wind, tide, currents or a passing vessel.
- DNV Technica (1996) identified other major sources of shipping data as follows:
  - ILU Casualty Return, Institute of London Underwriters;
  - IMO Damage Cards, International Maritime Organization;
  - SRD Major Hazard Incident Data Services, Safety and Reliability Directorate;
  - HCB Incident Log, Hazardous Cargo Bulletin;
  - MAIB Investigation Reports, Marine Accident Investigation Branch (MAIB), UK DoT;
  - Modern Shipping Disasters, Hooke (1989);
  - CADA Database, DNV Classification;
  - DAMA Database, DNV Classification;
  - World Insurance Report, Financial Times Business Information Ltd;
  - Marine Accident Reporting Scheme (MARS), Nautical Institute;
  - Lloyd's Casualty Return, Lloyds Register;
  - ILU Hull Casualty Statistics, Institute of London Underwriters;
  - MAIB Annual Report, Marine Accident Investigation Branch (MAIB), UK DoT;
  - Salvage and Fire Analysis, Harvey (1986);
  - Department of Safety: Ship Safety, National Audit Office (1992);
  - NMI Dover Strait Casualty Analysis, National Maritime Institute;
  - NMI Coastal Casualty Analysis, National Maritime Institute;
  - Lloyd's Register Ro-Ro Analysis, Lloyds Register;
  - DNV Ro-Ro Analysis, Jansson 1981.

The major source of statistical analysis adopted by DNV Technica (1996) is based on data from Lloyd's Register. A comparison between the categories described by DNV Technica and Lloyd's Register indicates a significant overlap in categorisation as shown in the following table.

Table 2.8 Hazard Categorization		
DNV Technica (1996) Broad Categories	**DNV Technica (1996) Fine Categories**	**Lloyd's Register**
Fire/Explosion	Fire	Fire/Explosion
	Explosion	
	Dangerous Goods Release	
Flooding/Sinking	Collision	Collision
	Impact	Contact
	Grounding	Wrecked
	Other Flooding	Foundered
		Hull/Machinery
Personal Accident	Personal Accident	Not Considered
Not Considered	Other	Miscellaneous
Not Considered	Not Considered	Missing

For the purpose of the evacuation of passenger ships the broad categories identified in Table 2.8 by DNV Technica (1996) can be related to the statistical information provided by Lloyd's register.

2.4.2 Flooding/Sinking versus Fire/Explosion

Hart et al (1996) reported on a review of the worldwide casualty statistics of passenger ships completed by Lloyd's Register of Shipping over a 15-year period from 1980 to 1995. Of the 797 recorded serious casualties 76 involved fatalities. Of the casualties involving fatalities, the majority (58%) involved flooding/sinking environments (wrecked/stranded, collision or foundering). The remaining 42% may also have involved some degree of flooding/sinking as a secondary result of the event (fire/explosion, hull/machinery failure). Of the total casualties, the majority (62%) involved flooding/sinking environments (wrecked/stranded, collision, foundering or contact) while the remaining 38% may also have involved some degree of a secondary result of the event (fire/explosion, hull/machinery failure).

2.4.3 Listing and Heeling

Listing and heeling are defined herein as the gradual inclination of the vessel deck relative to the horizontal due to the gradual change in the mass distribution within the ship. DNV Technica (1996) provided accident descriptions of forty ro-ro passenger vessel, twenty-one ro-ro cargo vessels and seven other passenger vessels including the cause of the incident, the number of survivors, the number of dead and the on-board scenario at the time of the incident. The mechanism of capsize is summarised for each of the passenger vessel incidents in Table 2.9.

Table 2.9 Accident Description				
Vessel	**Accident**	**Time to Sink**	**Capsize Description**	**Fatalities/ People on Board**
Ro Ro Passenger Vessels				
Princess Victoria (1951)	Foundering	5 hrs	45° at 4 hrs	134/172
Skagerak (1966)	Foundering	8 hrs	Sudden 40°	1/145
Heraklion (1966)	Foundering	10 min	-	217/264
Wahine (1968)	Foundering	> 7 hrs	25° at 6.5 hrs 45° at 7 hrs	51/735
Nissos Rodos (1978)	Fire	NS	Developed list	0/158
Saitobaru (1978)	Collision	NS	Developed list	0/238
Santa Ana (1989)	Fire	NS	Was beached	0/115
Zenobia (1979)	Foundering	18 hrs	Abandoned 10° Sudden 40°	0/151
Tampomas II (1981)	Fire	30 hrs	45° at 30 hrs	666/1136
Arion (1981)	Explosion	NS	Developed list	1/400
Jan Heweliusz (1987)	Foundering	NS	Rested at 45°	NS
Aldonza Manrique (1982)	Explosion	NS	NS	NS
European Gateway (1982)	Collision	<20 min	40° at 3 min Rested at 90°	6/70
Chrissi Avgi (1970)	Explosion	2 hrs	Developed list	28/42
Sweet Name (1983)	Collision	NS	NS	>27/400
Hua Lien (1983)	Wrecked	OK	NS	0/104
Presidente Diaz Ordaz (1984)	Contact	NS	Rested at 80°	1/508
A Regina (1985)	Wrecked	NS	NS	0/213
Norland (1985)	Wrecked	OK	Listed slightly	0/731
Farah II (1986)	Fire	NS	Developed list	NS
Dona Josephina (1986)	NS	15 min	Developed heel	199/414
Herald of Free Enterprise (1987)	Miscellaneous	4.5 min	30° at 3 min 90° at 4.5min	193/593
Santa Margarita Dos (1987)	Miscellaneous	NS	Capsized rapidly	5/250
Earl Granville (1989)	Wrecked	OK	No list	0/707
Mazatlan (1989)	Fire	NS	Sank	0/355
Hamburg (1989)	Collision	OK	No list	0/381
Scandinavian Star (1990)	Fire	NS	NS	0/482
Princess Mika (1991)	Fire	NS	Sank	No fatalities
Dronning Margrethe II (1991)	Collision (Fire)	7.5 hrs	Large heel	0/46
Moby Prince (1991)	Collision	OK	NS	141/142
Sol Phryne (1991)	Fire	NS	Sank	NS
Salem Express (1991)	Wrecked	20 min	Sank	464/544
Jan Heweliusz (1993)	Flooding	> 7 hrs	30° at 03:38 70° at 03:53 Capsize at 11:00	52/61
New Orient Princess (1993)	Fire	OK	NS	0/533
Al-Qamar Al-Saudi Al-Misri (1994)	Fire	>24 hrs	Ship sank	21/590
Saray Star (1994)	Fire	NS	Ship sank	0/79
Al Loloa (1994)	Fire	>24 hrs	Ship sank	0/62
Sally Star (1994)	Fire	OK	NS	0/111
Estonia (1994)	Hull/Machinery	33 min	30° at 3 min 90° at 20 min	852/989
Tallink (1995)	Wrecked	OK	10° at < 20 min	0/1101

Table 2.9 Accident Description				
Vessel	**Accident**	**Time to Sink**	**Capsize Description**	**Fatalities/ People on Board**
Stena Challenger (1995)	Wrecked	OK	No list	0/145
Passenger Vessels				
Priamurye (1988)	Fire	OK	No list	11/388
Jupiter (1988)	Collision	40 min	Ship sank	4/585
Maksim Gorkiy (1989)	Impact (with ice)	OK	Trimmed	0/952
Oceanos (1991)	Hull failure	OK	NS	0/565
Royal Pacific (1992)	Collision	< 15min	Heeled rapidly	9/534
Sally Albatross (1994)	Grounded	OK	25° at 2 hrs	0/1259
Achille Lauro	Fire	48 hrs	40° at 48hrs	2/979
Note: NS Not Stated; OK Ship remained afloat				

It is noted from the summary in Table 2.9 that the vessel has developed a list and/or sunk in a large proportion of the reported incidents. Listing appears to be caused by grounding, collision, failure of watertight fixings, failure or fatigue of hull panels or overtopping of waves on to the deck in extreme conditions. It is also noted that listing may also be caused from explosions and as a result of fire fighting. The categorisation of contributory factors to ship evacuation scenarios is offered by Kristiansen (1996) as described in Table 2.10.

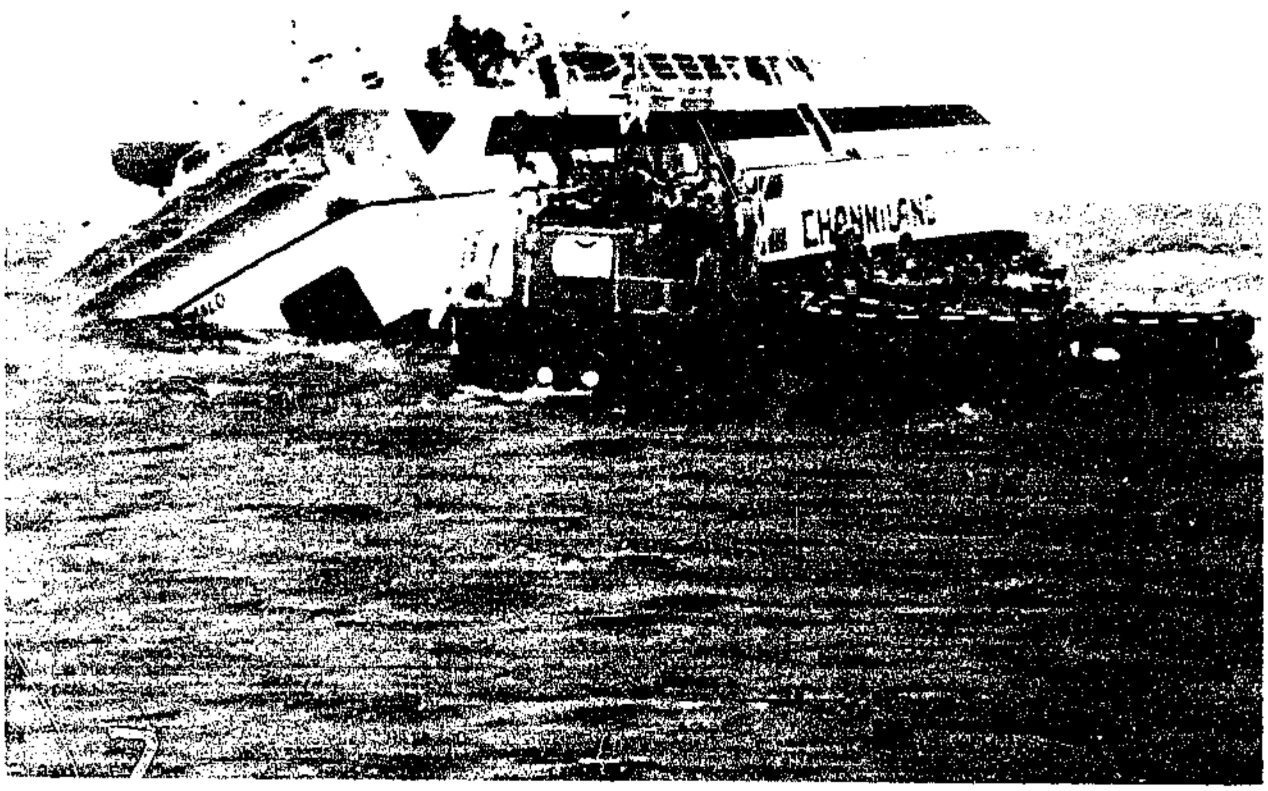


Figure 2.3 St Malo Ferry Sinking of Point Corbiere

<table>
<tr><th colspan="3">Table 2.10 Categorisation of Contributory Factors, after Kristiansen (1996)</th></tr>
<tr><th>HAZARD CATEGORY</th><th>CAUSE CONTRIBUTORS</th><th>CONSEQUENCE CONTRIBUTORS</th></tr>
<tr><td>Collision</td><td>Poor visibility
Rough weather
Navigational confusion</td><td rowspan="4">Flooding
Heeling
Grounding
Cargo shift
Flammable cargo
Fire
Engine failure
Power failure
Low stability
Open watertight doors
Lifeboat failure
Inaccurate mayday
Delayed mayday
Rough weather
Poor visibility
Low temperature</td></tr>
<tr><td>Grounding</td><td>Unauthorised route
Failure to use radar
Excessive speed</td></tr>
<tr><td>Impact</td><td>Steering failure
Engineer failure
Power failure</td></tr>
<tr><td>Flooding</td><td>Rough weather
Cargo shift
Bow door damage
Stern door damage
Side door damage
Open bow door
Open side door
Loading/unloading
Low Stability
Trim
Squat
Bow wave
Autopilot failure
Stabilising tank control failure
Inaccurate weather forecast
Inadequate structural design</td></tr>
<tr><td>Fire Explosion</td><td>Rough weather
Flammable cargo
Electrical failure
Oil leak
Heeling
Cargo shift
Bomb
Arson</td><td>Explosion
Fire
Flooding
Heeling
Grounding
Fire alarm failure
Fire door failure
Engine failure
Power failure
Steering failure</td></tr>
</table>

Spouge (1996) claimed a 'clear conclusion' from his findings that, 'at an angle around 45°, escape from inside the ship presents much less difficulty than the subsequent evacuation of the ship.' Spouge (1996) recounted the recommendations from the European Gateway accident that, 'consideration should be given to catering for the possibility that a vessel may have to be abandoned when listing more than 15°.'

Boer (1993) identified that the rate of change of the list angle can occur rapidly or increase slowly depending of the cause of the event, the design of the vessel, and the sub-surface terrain. A general analysis of ships listing by Boer (1993) indicated a rapid initial development followed by a temporary stability (15 minutes in the case of the European Gateway). This is supported by the summary of the DNV Technica (1996) incident descriptions in Table 2.9.

2.5 RESEARCH INTO EVACUATION OF PASSENGER VESSELS

2.5.1 Overview

There are a number of different areas of research that are relevant to validating ship evacuation analysis approaches. The areas of research requiring increased effort for evacuation analysis as gleaned from IMO FP/43/4/4 (1998) are as follows:

- *Hazard Identification and Accident Statistics* - Quantification of the Risk/Probability of various scenarios occurring;
- *Acceptance Time* - Time to accept that an action is required. (Time between cue and action commencement);
- *Preparation Time* - Time to gather belongings, group friends, dress warmly, don lifejackets, read/listen to instructions;
- *Response Actions/Times* - choose whether to evacuate, wait, search for information;
- *Data on Way Finding or Route Choice* - selection of best route based on signage, blockage, visibility, information, experience, assistance, group movement, shortest distance and action;
- *Motor Ability* - walking speed and ability to remain stable based on inclination, motions, smoke/visibility, congestion, counter flow, blockage, assistance, hand rails and generic passenger/crew characteristics;
- *Data on Survival Craft* - preparation time, loading time, launching time, risk of failure;
- *Design limitations* - safety management and vessel layout are limited by IMO policy, regulations and guidelines such that much of the data required can be bounded.

The following methods have been used in research of Ship Evacuation Analysis:

- Evacuation trials;
- Field survey;
- Accident investigations;
- Laboratory experiments on maritime specific issues.

A review of the status of the research in each of the above fields is discussed in Sections 2.5.2 to Sections 2.5.5

2.5.2 Evacuation Trials

Evacuation trials in accordance with IMO (2001a) are typically focussed on providing an internal assessment of crew performance using survival craft including preparation time, loading time, launching time and risk of failure as discussed in Section 2.3.5.11.

However, three major, large-scale evacuation trials, which have been conducted in recent times with the specific aim of increasing the database of knowledge for evacuation of ships, are as follows:

- Exercise Invicta - January 1996 as described by Wood (1996)
- CANAM SAREX 2000 - February 1999 as described by BC Ferries (1999)
- M/F Kronprins Frederik - 2001 as described by Ostergaard and Jorgensen (2001)

These trials had differing objectives. However, in there entirety, they provide information on a substantial range of the factors relating to evacuation analysis. The trials are summarised as follows:

- Major Objectives:
    - Practice emergency response management,
    - Exercise crew response including mass evacuation,
    - Exercise traffic control and casualty evacuation,
    - Practice tracking and reconciliation of passenger/casualty/crew lists;
- Performance Measures:
    - Chute evacuation times,
    - Heli-hoist evacuation times,
    - Muster time,
    - Abandon times,
    - Total evacuation times,
    - Lifeboat preparation time,
    - Survival craft success rate,
    - Life jacket donning times,
    - Detailed run times for the evacuation;
- Factors Assessed:
    - Muster lists,
    - Evacuation plan,
    - Family/friend dispersion,
    - Impedance of evacuation flow due to casualties,
    - Influence of open/enclosed decks on effectiveness of muster.

While these evacuation trials do provide valuable information that should be considered in the development of an evacuation analysis approach, there are limitations including the impact of environmental conditions such as list and roll and the influence of safety media on the selection of evacuation routes and destinations.

Wood (1996) noted that Marine Safety Agency (MSA) came under, 'criticism from a number of quarters, claiming that such exercises (as the Exercise Invicta) should be carried out in the Channel at night and that the volunteer passengers should be more representative of the travelling public.' Wood (1996) also noted that, 'even those taking part suggested greater realism.'

However, Purser and Raggio (1995) considered that, 'even in real evacuations, many occupants may never come into contact with the (threat) will not have known at the time whether the incident was real or a drill.' Brennan (1996) provided evidence that evacuees misinterpret the required urgency of an evacuation unless they are directly confronted with the source of the emergency. Brennan (1996) claimed that despite our intuitive feelings in this area, people do not panic as much as we might think during evacuations because they tend not to believe that the threat is real. Accordingly, the belief that evacuation trials are not useful is rejected by many researchers in the field of evacuation of on land buildings in the event of fires. In particular SFPE (1989) identified that a key conclusion about fire related human behaviour is that the, 'movement of people in normal buildings and in many simulated emergency evacuation (drills) is a good basis for predicting their movement in a fire emergency.' SFPE (1989) states that, 'people should not be expected to react faster or move more efficiently in a fire emergency than they do normally.'

Rapid capsize events, such as the Estonia as described by JAIC EFS (1997) resulted in rapid acceptance by passengers that the threat is real and risk of casualties is high. However, even when directly confronted with a threat evacuees have been observed as having an optimistic view of events. Boltwood (1995) identified an example of the general optimism by evacuees where a couple notice water flowing into their cabin, yet did not perceive that the threat would go beyond the capabilities of the crew to control it. Brennan (1996) noted a similar incorrect perception in buildings where smoke may be progressing through corridors.

2.5.3 Field Survey

Field surveys of passengers of vessels during operation provide a means of assessing the effectiveness of experience, layout complexity, and safety information media in providing assistance in way finding and/or route choice. To date there has been little data formally collated and compiled based on field surveys with regard to evacuation analysis of passenger vessels. Field surveys of passenger are historically focussed on seasickness such as the work conducted by Smith (1997). Brumley and Koss (1998) investigated the influence of passenger safety knowledge and experience on destination selection. Brumley and Koss (1998) developed an empirical model for determining destination selection in the evacuation of maritime structures based on field data surveys of a number of different types of vessels. Section 5 provides a review of way-finding and/or route choices in the evacuation of passenger vessels in more detail along with a detailed description of the work by Brumley and Koss (1998).

2.5.4 Accident Investigations

Accident investigations provide the only available means of validating laboratory research and field surveys as well as evacuation trials. However Boltwood (1995) identified that much of the information from maritime accident investigations is in a qualitative rather than quantitative format. Recent investigations, such as those described by JAIC EFS (1997) and Jersey Harbour Department (1995), provide more relevant quantitative data such as estimated muster and embarkation times as well as destination choices and delay factors. Despite recent improvements in the investigation of maritime evacuations, there are still no accident investigation reports that provide quantitative validation of human behaviour models.

Saunders (1995) stated that the use of case studies or questionnaires administered to survivors of an emergency to provide information has higher validity but a lower reliability than controlled laboratory simulations. Saunders (1995) also identified that human behaviour models for building fire emergencies have in the main been derived from post hoc interviews, surveys and fire incident reports of building fires from which a large number of fatalities have occurred. Harbst and Madsen (1993) have reviewed maritime accident investigation reports and compared the qualitative findings to the human behaviour models for building fire emergencies.

The Australian Transport Safety Bureau (ATSB) is currently investigating a minor incident on a large passenger ferry that has already been involved in a series of field surveys by Brumley and Koss (1998). ATSB were advised of the research conducted in this thesis along with other requirements for validation of human behaviour models for the evacuation of passenger vessels. Accordingly a validated model is anticipated in the near future. Accident investigations have the potential to provide information on and validation of the following:

- Hazard Identification and Accident Statistics as discussed by DNV Technica (1996) and reported in Section 2.4.
- Acceptance Time - Time to accept that an action is required as identified by Harbst and Madsen (1993);
- Preparation Time - Time to gather belongings, group friends, dress warmly, don lifejackets, read/listen to instructions as identified by Saunders (1996);
- Response Actions/Times - choose whether to evacuate, wait, search for information as identified by Reisser Weston (1996);
- Way Finding or Route Choice - selection of best route based on signage, blockage, visibility, information, experience, assistance, group movement, shortest distance and action as identified by Brumley and Koss (1998) and Boer (2000);

DNV Technica (1996) provides a detailed account of the maritime casualties trends over recent times. This also include detailed summary of Hazard Assessments (HA) which identify the effect of hazards on the vessel passengers and crew; whether safeguards exist to minimise risk; and whether further risk reduction risks are required. Fire and flooding hazard reviews address the accident prevention and mitigation measures in each compartment of the ship. DNV Technica (1996) claimed that while HA's are considered to be an essential element of a modern approach to safety they are entirely judgmental, poor at anticipating highly unlikely but potentially catastrophic events and are, in general, not suitable for inclusion in an evacuation analysis simulation in a comprehensive form.

DNV Technica (1996) explained that Quantitative Risk Assessments (QRA) provide a fully numerical approach to safety assessment which is more conducive to a uniform analytical assessment that can be included in a ship evacuation analysis approach. QRA builds on the hazards identified in the HA and quantifies their frequency and consequences. QRA is dependant on statistical analysis of historical data that gives generic values. Historical data is generally only available for more catastrophic events and does not cover in great detail minor incidents. The disadvantage of QRA is that is necessarily more generic by nature.

Accident investigations provide the input information on sinking rates, flooding and fire development and the fatality rates which may be used to assist in validation of simulation tools but do no necessarily provide clear guidance on algorithm requirements. JAIC EFS (1997) detailed the evacuation process to such an extent as to identify various factors which are perceived as essential components of an evacuation including.

- Mobilisation of the command group on the bridge;
- Alarms and activities by the bridge;
- Activities by crew members;
- Obstructions to evacuation;
- Passenger and crew member reactions;
- Limits for evacuation;
- Rescue equipment.

2.5.5 Laboratory Experiments

Laboratory experiments focus on both mechanical and physical parameters relating to the evacuation of passenger ships as well as human factors research. The work by Rutgersson and Tsychkova (1999 2000) discussed in Section 2.3.5.11 identify the most focussed appraisal of survival craft performance and the risks associated with operation in dynamic conditions. Boer and Vrandelvelt (1999) have conducted a series of trials in a mock-up floor plan of a capsizing vessel to investigate the effectiveness of alternative media systems as discussed in Section 5.1.

Finally the influence of deck motion on performance has been assessed in detail for a range of naval operational task. Despite this, HSE (1999a) indicated that, in the frequency range associated with ships, only motion sickness is considered in the existing standards covering performance degradation. HSE (1999a) stated that other low frequency effects such as postural stability and motion-induced fatigue are not covered at all by ISO2631/1 (1997) or any other standard.

The system describing motor ability performance in dynamic conditions has many similarities to the conceptual model of factors in the causation of motion sickness developed by Griffin (1990) and shown in Figure 2.4.

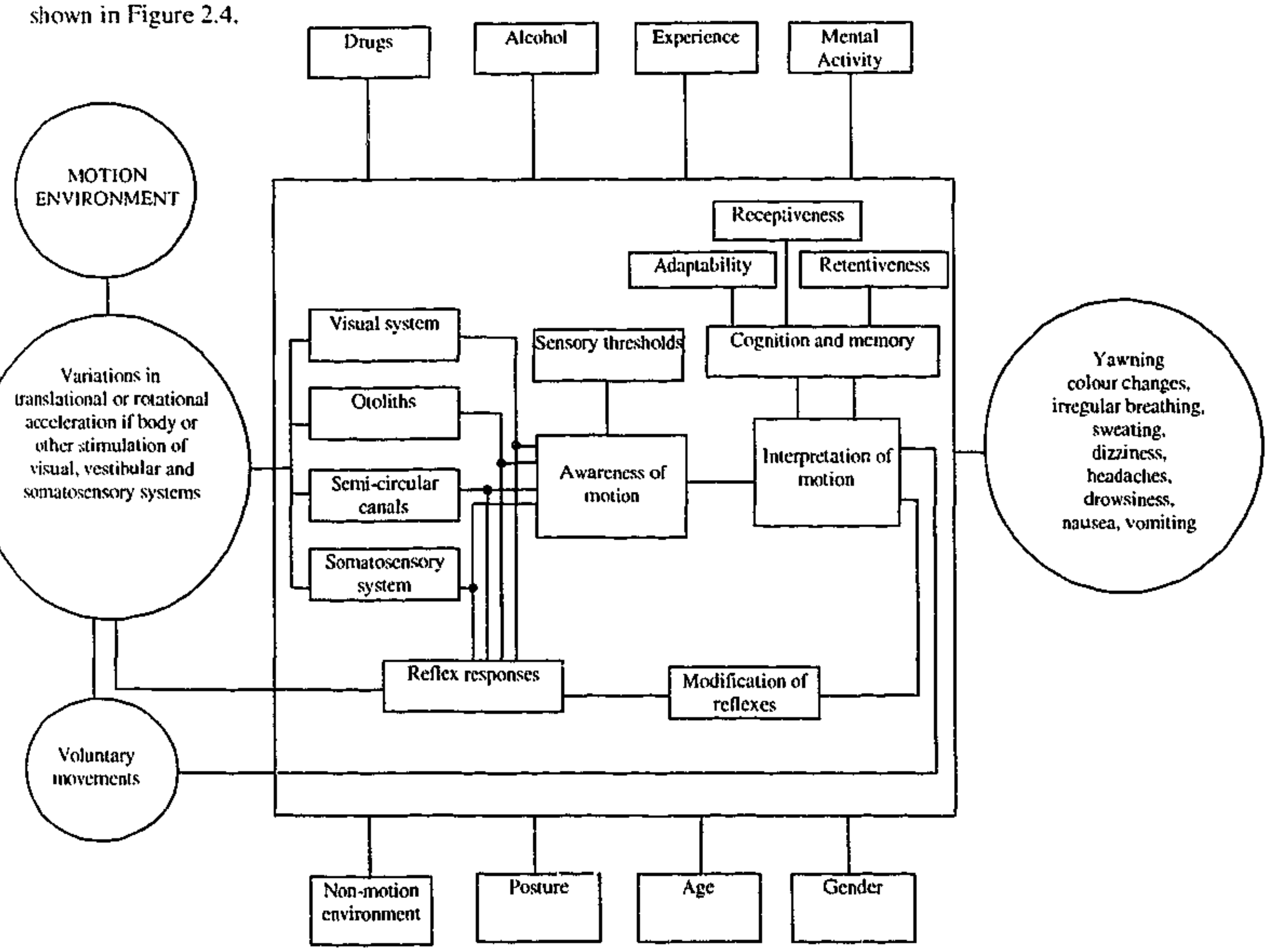


Figure 2.4 Factors in the causation of motion sickness, after Griffin (1990)

Birren (1949) believed that most people who experience a transient bout of motion sickness could exert themselves sufficiently to perform adequately when necessary. He developed the phrase, "Peak Efficiency," to describe this phenomenon. Birren (1949) claimed that this is not the case for normal daily activities where people will operate at, "Maintenance Efficiency." In the event an evacuation it may be presumed that people will operate at, "Peak Efficiency," to get off the vessel. Accordingly motion sickness is of secondary importance to evacuation analysis only.

While it is not the intent here to examine detailed theories of the causation of motion sickness it is noted that in a literature review by Smith (1997) there is a correlation between individual susceptibility and factors such as vehicle control, age and gender. Smith (1997) also noted that there is little or no conclusive evidence of a correlation with individual susceptibility to hereditary factors, personality traits, vestibular impairment or alcohol use. Based on tentative assessments of adaptability, retentivity, receptivity on motion sickness susceptibility, Reason and Brand (1975) claimed, "Adaptability is clearly the most potent factor." However, it should be noted that Wertheim et al (1995) speculated that adaptation to seasickness might be dependant on the specific pattern of ship motions. Based on a survey of 3618 participants, Lentz and Collins (1977) found that 'psychological characteristics may be associated with motion sickness susceptibility'. Brumley and Koss (2000c) examined some of the parallels between motion sickness and motor ability. A fuller appraisal is provided in Section 4.6.6.

Dobie (2000) reviewed the area of Motion Induced Fatigue and identified that existing research indicates that measured levels of energy expenditure were relatively small compared to the subject's capacity to do work. Indeed Dobie (2000) presented the findings of research in 1997 that found that peak oxygen consumption, as a measure of physical workload, might indeed be lower in a moving rather than stationary environment. Dobie (2000) suggested that this may be a question of motivation rather than cardiorespiratory response. HSE (1999b) reported conflicting information that suggests that experiments have shown energy expenditure in the region of 15-20% higher in pitch and roll motions. HSE (1999b) suggested that MIF models require more sophistication. For the purposes of evacuation of passenger ships MIF is, like motion sickness, considered as a secondary factor.

The decision making of passengers and crew is an important aspect of an evacuation. Research reviewed by Dobie (2000) on the influence of motions on cognitive performance noted that there is little evidence that motion has any influence at all. Four independent bodies of research all conclude that vessel motions do not influence cognitive performance.

Postural stability in a dynamic environment has been a topic of research since the concept of motion-induced interruptions was introduced by Applebee, McNamara mad Baitis (1980). While there has been research on performance degradation due to postural stability, the issue of reduced walking speed of passengers during evacuation has not yet been addressed in detailed, nor validated, other than for the work by introduced by Boer and Bles (1998) and the work detailed in this thesis. The background of research into Postural Stability is discussed in detail in Section 4.

2.6 EVACUATION MODELS

2.6.1 Overview

Due to the complexity involved in assessing the evacuation of multi-story buildings, software tools are commonly adopted to handle the evacuation analysis. The evacuation models used as the basis for these software tools may vary depending on the complexity of the solution and the desired focus of the tool. The evacuation models currently adopted are described herein to identify the current shortcomings of the conventional means of assessing evacuation as it applies to the maritime scenario.

Bypass (2001a) described the division of evacuation models as microscopic and macroscopic models where the former relates to explicit modelling of the activities as each individual person while the latter refers to consideration of the performance of as a group without distinguishing between individuals. MacGregor Smith and Towsley (1981) and Lovas (1994) provided a further breakdown of these models as described in Table 2.11

Table 2.11 Evacuation Analysis Models

Bypass (2001)	MacGregor Smith and Towsley (1981)	Lovas (1994)
Macroscopic Models	Basic Empirical Models	Basic Empirical Models
	Hydraulic Flow Models	Hydraulic Flow Models
	Analytical Models: Deterministic Network Flow Stochastic Network Flow	Global View Point Models: Deterministic Network Flow Stochastic Network Flow
Microscopic Models	Simulation Models.	Single View Point Models.

Bypass (2001a) identified that macroscopic models neglect interaction between people and the variation of human behaviour. Human factors associated with the evacuation process are discussed in Section 2.3, which identifies the need for consideration of human factors in the evacuation analysis of passenger ships. Microscopic models provide the only mechanism of inclusion of human factors in the evacuation process. It is noted that while many models include provision of human factors, many only assess the impact of these factors during the action stage of the evacuation. Accordingly the acceptance and reaction times are often not considered. For completeness all the models identified in

Table 2.9 are described in Sections 2.6.2 to 2.6.5. However, for the purposes of this thesis only microscopic models will be considered for detailed review.

2.6.2 Basic Empirical Models

Based on experience with fire drills Pauls (1985) developed a single empirical formula to determine the evacuation time from buildings. This model provides mechanism for estimating evacuation times but neglects many of the parameters that may significantly influence these times. This model requires no internal layout information except for stair width.

2.6.3 Hydraulic Flow Models

Lovas (1994) stated that developed Hydraulic Flow Models using analogy to fluid flow through pipelines. While this model allows for resistance to flow (i.e. congestion) it does not consider the impact of reverse flow. Lovas (1994) claimed that these models are useful for unidirectional flow through congested regions where queuing and bottle necks form.

2.6.4 Global Viewpoint Models or Analytical Models

Lovas (1994) described Global Viewpoint Models as considering evacuations as seen from the outside observer. These models consider the overall population migration rather than behaviour of individuals. This model does not consider many of the behavioural aspects of the individual based on local environment observations. Lovas (1994) explained that this approach is used to provide a lower bound estimate or optimisation of evacuation time.

This approach is based on a set of prescribed critical paths that identify major evacuation routes. Chalmet et al (1982) claimed that, 'many of the behavioural concerns do not seem to be representable with (these) models.'

Lovas (1994) identified two subcategories of the Global Viewpoint model as follows:

a) *Deterministic Network Flow* -The Deterministic Network Flow model allows for the consideration of groups through a network of alternative routes. However the user predetermines these routes. Chalmet (1982) identified that in such models the objective is to develop the optimal evacuation plan with regard to organized group movement of passengers down a prescribed path.

b) *Stochastic Network Flow* - Lovas (1994) claimed that the objective for Global Viewpoint Stochastic Network Flow models is similar to that of Deterministic Network flow models in that the objective is to optimise routing and estimate measures related to evacuation times. In these models a change in environment or accumulation of knowledge for an individual during the evacuation will not lead to a change in behaviour of the individual. The random assignment of walking speeds and/or evacuation routes is conducted prior to the evacuation run.

2.6.5 Individual View Point Models or Simulation Models

Lovas (1994) described Individual View Point Models as considering each evacuee individually with defined behavioural and physical attributes that can be modified as the evacuation progresses. In addition factors that may influence decisions and actions may also vary with time.

Individual viewpoint models require the discretisation of space and time to allow time domain modelling. Conventional modelling techniques have two alternative approaches for consideration of space, or the modelling of the deck layout, as follows:

- Grid Based Systems;
- Node-Arc Systems.

Bypass (2001a) described that grid-based systems are based on the consideration of the deck as a system of square sided cells (typically $0.15m^2$) which are either accessible or not accessible. Cells that are not accessible represent walls or furnishings while accessible cells represent pathways available for evacuation. During each time step of the simulation an individual can move a number of cells depending on the designated walking speed of the passenger, which is explicit to each passenger and modified on each time step depending on the environment and interaction with other people. Bypass (2001a) described the process of movement through such a grid-based system as 'cellular automation'. The advantages of grid-based systems are as follows:

- Discrete modelling of the location of individuals through highly congested open areas;

Watts (1987), described network models as a graphical representation of paths or routes by which objects or energy may move from one point to another. The connected points in a network are referred to as nodes (or junctions) where starting points are referred to as source nodes and ending points are referred to as sink nodes. The connections between the nodes are called arcs (or branches or links). The digraph (directed graph) is one in which the arcs have an associated direction usually indicated by an arrowhead to signify the local co-ordinate system (up-stream and down-stream). A path is defined as a sequence of arcs connecting more than two nodes. A tree is referred to as the group of paths with a common intercept. The advantages of network systems are as follows:

- Simple to construct and audit;
- Simple to modify and/or optimise;
- Simple to impose obstructions;
- Research data is the form that can be readily applied to network models.

- Reduced processing time, which allows for improved consideration of human factors and multiple runs to obtain statistical value of performance measures.

A comparison of the two layout systems for the purposes of evacuation of maritime vessels indicates the following:

- Small interval grid wise models are, by their very nature, based on arbitrary input data in a manner that is inconsistent with the method to which the relevant empirical mobility data is gathered for large complex structures. For example, walking speed measurements are based on time taken to traverse a given distance with consideration of obstacles, crowd density and crowd flow patterns. To infer from such data that walking speeds is known for discrete grid based intervals on the scale of a characteristic body width is not scientifically supported for the evacuation of passenger vessels. Likewise information on flow through doorways is determined based on a set flow rates of groups whereas other information such as aggression/urgency has not been recorded in any of the literature reviewed in this thesis.
- Queuing models for network systems, such as that described by Lovas (1994a), evaluate which individuals emerge through constriction first, based on a first in first out basis. While queue jumping may have been observed in aircraft evacuation trials, as described by Galea, Owen and Lawrence (1996), the application of human factors such as aggression/urgency to identify queue jumping in grid based models is currently arbitrarily assigned.
- Grid based models were originally developed for application in the aircraft industry which has an evacuation time limit of 90 seconds as described by Galea, Owen and Lawrence (1996). However, IMO (1999b) has an evacuation limit of 30 minutes for Embarkation and Launching of life rafts and 60 minutes overall. The implication of this disparity between requirements is that the influence of minor time differences for the aircraft industry is key to approval, whereas this is not necessarily the case in the maritime industry. In the aircraft industry the small time scales dictate a requirement to model the layout using a fine scale discrete x-y grid system. Furthermore the aircraft industry has conducted experiments in congested environments and Galea, Owen and Lawrence (1996) has validated the x-y grid system for such evacuations. This is not the case in the maritime industry and given the large size and complex nature of the vessel layouts, an x-y grid systems unnecessarily increases user and process time and increases the requirement for high power computer hardware.
- In particular the discrete movements of individuals in a dynamic/environment environment indicate that passengers will change their body form to resist falling. However, no quantitative data has been obtained to identify the small-scale impact of these movements on surrounding people. Therefore grid wise modelling can only arbitrarily assign the discrete location without consideration of these factors.

2.7 EVACUATION ANALYSIS DESIGN TOOLS

2.7.1 Types

There exist a number of software tools that may be classified on the basis of applicability to the evacuation analysis of maritime vessels in the early stages of design as follows:

- *Research Tools:* Research Tools are developed to prove a particular thesis rather than to a design requirement. Biomechanical simulators have been developed to address specific issues relating to gait and stability of individuals. Zhao et al (1998) identified that, 'most widely used postural biomechanical models are confined to either the sagittal or frontal plane,' and joints, 'are modelled as simple hinges (with) muscles replaced by joint actuators.' Zhao et al (1998) indicated that recent three-dimensional models are limited either to single limbs or stationary individuals. Zhao et al (1998) explained that, because the human body is a highly sophisticated, non-linear and dynamic system several assumptions and simplifications are made when developing biomechanical simulators. Zhao et al (1998) claimed that even if replicating control systems of intact individuals were possible it would not be an optimal approach for duplicating human performance. Computation processing requirements of biomechanical simulators make it impractical for use on thousands of full-bodied individuals.
- *Land Based Evacuation Tools:* SFPE (1989) provided a comprehensive literature review of land-based models that consider the evacuation of buildings including small residential dwellings, multi-storey buildings, factories and industrial sites, public areas, shopping precincts and hospitals. The evacuation process is described in Section 2.3 and the models used include all those mentioned in Section 2.6.
- *Mass Transport Based Evacuation Models:* Transportation models are used for both logistical and emergency purposes. Galea (1994a) claimed that the basic geometries of air, sea and rail passenger enclosures, 'possess sufficient common features to allow a similar treatment.' Furthermore Galea (1994a) stated that existing software structures allow the application of specific sub-components, such as behavioural sub-models, to be easily interchanged with more appropriate models design for the specific application. Based on work by Galea (1994a) and the literature review herein the categories of transport models may be summarised as follows:
    - Air: The aircraft evacuation models consider the influence of confined space evacuation with consideration of the specific apparatus that are involved in aircraft accidents. These models assume a level stationary body. However the influence of smoke can be included.
    - Rail: Train evacuation models are similar to aircraft models in the level of complexity required and the confined space, congested evacuation scenario. Exits are readily defined and route choices are readily evaluated.

- Sea: Ship evacuation models to date are typically based on existing transport or land-based models. As such the specific nature of the maritime scenario is rarely addressed. In particular the issue of vessel motions and list are rarely considered and the specific nature of the multi-phase evacuation philosophy is often not modelled. Abandonment can be modelled explicitly or approximated as a flow rate with intermittent availability. Maritime models may be required to assess expansive areas and hence network models rather than grid-based models may be more suitable. In addition the impact of incorrect route choice on the overall evacuation time may be significant due to the long evacuation paths under consideration. Hence way finding models based on behavioural parameters are essential.

- *Hazard Development Models:* Hazard Development Models are typically used in conjunction with egress models to determine the rate of progression of a hazard to enable the potential for fatalities to be modelled based on toxicity levels from the development of smoke.

2.7.2 Existing Models

Table 2.10 provides a brief commentary on over 30 evacuation simulators. The comments made are based on reviews from alternative sources and published literature by the developers as referenced herein.

Table 2.12 Evacuation Analysis Software Tools Summary		
Package	**Description**	**Reference**
AEA Egress	Graphics, grid based queuing model that implements shortest-path routine; user friendly; blockage and fire modelled.	Uni-Duisburg (2000b)
ASERI	Microscopic model that includes human behaviour and assesses each individual. Only limited information available in reference. ASERI has been validated as fit for purpose ESECX (Evaluation of Simulation Models of Evacuation from Complex Spaces) study by SINTEF.	Soma et al (1996)
ASET-B	Available Safe Egress Time – Basic	Harrington (1999)
BFIRES	Applicable for single-family houses; grid base; way finding behaviour is modelled.	Watts (1987) Lovas et al (1993)
BFSM	Includes fire growth and spread (based on regression analysis of fire tests); uses deterministic model.	Watts (1987)
BGRAF	Stochastic human behaviour model; CAD input; animation of process; multi-phase route choice capability; considers signage, alarms and smoke; and shortest path.	Ozel (1992) Ozel (1988) Lovas et al (1993)
BYPASS	A grid based stochastic model; includes life rafts and boats, queuing, congestion and way finding.	Uni-Duisburg (2000a)
EMBER	Comprehensive fire development and evacuation simulation model for on-land buildings	Watts (1987)
ERM	Small buildings analysing rescue, network based	Watts (1987)
EVACNET+	Network based optimal route model; local effects are ignored for route choice; queues are considered; no behavioural modelling,	Watts (1987) Donegan et al (1994) Kisko et al (1985) Drager et al (1993) Thompson et al (1996) Owen et al (1996)
EGRESS	Hexagonal grid system, congestion modelled, for multi-storey buildings, has behaviour model, smoke	Thompson et al (1996) Thompson et al (1993) Ketchell et al (1993) Owen et al (1996) Boltwood (1995)
EGRESS TIME	Queuing model with congestion appearing at doorways and stairs; Congestion is not modelled in corridors and aisles; no human behaviour modelling.	Uni-Duisburg (2000b)
ELVAC	Calculation of Elevator times.	Klote (1993) Klote et al (1992)
ESCAPE	Delay times based on the number of people in vicinity, movement of others, influence of smoke on visibility (not toxicity and fatalities), training, exit choice, shortest route, exit familiarity, exit markings, congestion.	ReisserWeston (1996a) ReisserWeston (1996a) Boltwood (1995)
EVACSIMa	Stochastic network based; human behaviour and threat development; queuing; way finding based on signage; couple with LBL provides muster, embarkation and escape; does not consider impact of vessel motions.	Kisko et al (1985) Drager et al (1992) Drager et al (1993) Soma et al (1995) Soma et al (1996) Lovas (1994a) Lovas (1994b) Lovas (1993)
EVACSIMb	Node-Arc stochastic model including human behaviour; route choices are deterministic; limited user interface; multi-storey buildings	Poon (1995) Poon (1994)

Table 2.12 Evacuation Analysis Software Tools Summary		
Package	**Description**	**Reference**
EVACSIMc	Node-Arc model including human behaviour; route choices are deterministic; limited user interface; designed for evacuation of a small room.	Kopp (1999)
EVACUSHIP	Node-Arc model including human behaviour and vessel motions	Section 6.
Evacuation Behaviour Model	Represent possible outcomes based on known probability distributions and represents groups of movement (10 people), includes signage, wardens.	Weinroth J (1989)
EVADE	Network elements (corridors and stairs), queuing, blockage, list (coefficients are uncertain), panic/apathy	Soma et al (1986)
EXIT89	Large populations from high rise buildings (move in crowds, i.e. no individual movement), shortest route, smoke, no explicit behavioural considerations	Thompson et al (1996) Thompson et al (1993) Fahy (1989) Owen et al (1996)
EXITT/ TENAB/ FAST	Network description and time dependant calculations (aimed at residential buildings), does consider fire, does not consider congestion, limited capacity, movement deterministic	Shestopal et al (1996) Thompson et al (1996) Fahy (1989) Owen et al (1996) Uni-Duisburg (2000b)
EXODUS	Primarily air, sea and rail of confined space geometries; Spatial fine two dimensional grid including obstacles; Influence of crew, queuing and hazard, shortest route, familiarity, overtaking, jump obstacle, exiting (hesitation); Simulated evacuation times were not consistently similar to real scenarios. In building EXODUS no attempt has been made to create algorithms to assess human specific behaviour	Thompson et al (1996) Galea et al (1998) Galea et al (1996) Galea (1996) Galea et al (1994a) Galea et al (1994b) Uni-Duisburg (2000b)
FEES/MB	Egress from multi family buildings, grid based system.	Watts (1987)
LBL-C/ LBL-F	Models lifeboat performance including availability, collision, unsuccessful release, collision, capsizing, damage, flooding, sea rescue operation,	Soma et al (1995) Soma et al (1989)
MOBILIZE	Simple model demonstrating adaptability for complex structures, queuing, influence of crew and alarms, blockage	Weinroth (1989) Lovas et al (1993)
Okazaki et al	Grid based potential model, includes queuing, calibrated against ship evacuation trials.	Okazaki et al (1993)
PEER	Evacuation and rescue, only concentrates on abandonment phase.	Forland
SIMULEX	Potential map over grids, (populations 2000-3000), CAD based input, overtaking, queuing and jostling, real time play back	Thompson et al (1996) Thompson et al (1993) Owen et al (1996) IES (2000)
SURVIVAL	An update of the EXITT/TENAB module to integrate the smoke density during the evacuation	Uni-Duisburg (2000b)
SURVIVE	Evacuation from mines and evaluates evacuation equipment, training and routes	Lovas et al (1993)
VEGAS	Virtual reality tool (models physical appearance and location of individuals in detail), group behaviour, alarm awareness, and smoke. Must define evacuation routes via target points. Attempts to convert this package to the maritime scenario failed.	Thompson et al (1996) Still (1993) Thompson et al (1993) Owen et al (1996) Boltwood (1995)
WAYOUT/ FIRECALC/F IREWIND	Multi-room, multi-storey, only considers merging flows, congestion, deterministic node arc model, Congestion, fire modelling, no human behaviour.	CSIRO (1995a) Shestopal et al (1996) Uni-Duisburg (2000b)

2.7.3 Suitability of Design Tools for Maritime Environment

While many packages are intended to provide a multi-purpose tool for evaluation of the full array of hazard scenarios only the following explicitly address the hazards, behaviour and performance that is specific to the maritime scenario. These are as follows:

- EVACUSHIP[4] - EVACUSHIP was developed to meet the explicit requirements of IMO and meet the shortfall of existing tools on the market. EVACUSHIP incorporates the findings of this thesis and has been used to verify the hypothesis presented in Section 3. A description of EVACUSHIP is provided in Section 6.
- EVACSIMa[5] - EVACSIM is specifically focused for the maritime market. EVACSIM will incorporate the findings of the upcoming BRITEURAM project on way finding in 2001. While EVACSIM focuses on local way finding routines there is no inclusion of the maritime specific destination selection based on passenger experience and media systems. These factors are distinctly different to familiarity and influence of signage and can significantly influence overall evacuation times.
- Okazaki/Matsushita[6] - This package is based on research by the Japan Ministry of Transport and is represented as a research-based tool that is still under development. This tool does consider some elements of way finding assessment. However there is no consideration of list/motions or destination selection. Literature available on this product does not discuss the detail of modelling of the more generic behavioural aspects considered.
- LBL[7] - LBL is designed to assess the abandonment phase of the evacuation. This tool can be used in conjunction with muster evacuation packages to assess the entire evacuation phase. IMO (2001a) recommend that the abandonment phase be validated through field trials and based on manufacturer data.
- BYPASS[8] - BYPASS includes consideration of human factors using a grid based stochastic model. The model has been developed to meet IMO requirements and the developers have some knowledge of the maritime scenario. However the model includes performance degradation due to list and roll from operational tasks that have not been validated as applicable to walking tasks. In addition smoke influences on physical performance and way finding patterns are also not included. In addition the package focuses on local way congestion based algorithms rather than maritime specific behavioural algorithms.

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[4] Section 6

[5] Kisko et al (1985), Drager et al (1992), Drager et al (1993), Soma et al (1995), Soma et al (1996), Lovas (1994a), Lovas (1994b) and Lovas (1993).

[6] Okazaki et al (1993)

[7] Soma et al (1995), Soma et al (1989)

[8] Uni-Duisburg (2000a)

2.8 SUMMARY OF LITERATURE REVIEW FINDINGS

2.8.1 Overview

A number of evacuation analysis approaches that assess the evacuation of passenger ships have been developed over the past years and are based on significant background research. These tools are currently being improved in attempt to meet IMO requirements. To date no accepted model has been explicitly recognised as suitable such that preliminary simplified evacuation processes are still being applied.

The technical grounds for the lack of acceptance of the proposed approaches is the inappropriate consideration of the influence of the following on the evacuation process:

- Wave induced dynamic vessel motions;
- Capsizing induced quasi-static vessel motions;
- Safety media systems;
- Improved life safety systems;
- Maritime specific route choices and local way finding;
- Training and experience.

Importantly the evacuation analysis approach should focus on the behavioural factors that influence significantly the evacuation process including local and global destination and route choice procedures. There is no evidence in the literature that a grid-based system is more accurate than the node arc model. In addition the node arc model more is more representative of the way that the empirical data on walking speeds has been developed/gathered.

2.8.2 Evacuation Analysis Approach

A review of the available literature indicates that the evacuation analysis approach should consider the following:

- Stochastic generation of passenger characteristics;
- Import deterministic crew characteristics;
- Generate (node/arc) layout using visual based tools;
- Refine layout using exact specification;
- Import signage, hand and kick rails;
- Check design parameters against prescriptive guidelines;
- Import media and vessel usage data;
- Determine approximate vessel motions;
- Import variable list scenario;
- Import variable smoke scenario;
- Model human behaviour to determine:
    - Preparation time,
    - Waiting and delay times,
    - Goal selection,
    - Destination selection,
    - Global route selection,
    - Local route selection;
- Model mustering phase including impact on physical performance due to congestion and hazard development (smoke/list/motions);
- Model abandonment phase using manufacturer specified and historical transfer rate and availability statistics;
- Present basic statistical performance data and raw data in a form suitable for manipulation by sophisticated statistical tools and inclusion in the overall safety case assessment.

2.8.3 Way Forward

2.8.3.1 Research, Empirical Data and its Application

The empirical data required for an evacuation analysis of maritime scenario is incomplete and rarely applied in its entirety. In particular, prior to the commencement of this thesis, no information on destination and route selection based on information media and passenger experience or the influence of vessel motions on the motor ability of passengers was available in the form required for evacuation analysis. Validation of the laboratory data gathered in this thesis is only available through accident investigations which to date have been restrictive with regard to the inclusion of the required investigation techniques.

2.8.3.2 Maritime Specific Algorithms

Although fine grid-based models may be considered more sophisticated than node arc models, local behavioural algorithms of fine grid-based models are inconsistent with the application of the founding empirical data. As such developers of fine grid models are forced to provide arbitrary parameters without valid scientific basis.

Node-Arc models have sufficient capacity to model the known and quantifiable behavioural attributes of maritime specific algorithms. These models also free processing power for the specific modelling of more important behavioural attributes.

2.8.3.3 Maritime Specific Evacuation Simulators

All maritime specific software tools are currently under development to include some form of maritime specific data and the full capability of a single evacuation tool that is comprehensive in the evacuation of maritime vessels is yet to be realized. Behavioural models tend to focus on handling of global and local route selection as well as developing delay times.

2.8.4 Summary of Required Topics of Research

Based on the findings of the literature review, this thesis is focussed on obtaining experimental data and the empirical models on the following:

- The influence motor ability of passengers in a listing/rolling environment;
- The influence of maritime specific safety media and passenger experience on route choice selection.

3. SCOPE OF THESIS

3.1 HYPOTHESIS

The literature survey has shown that the present maritime evacuation analysis is predominantly based existing on-land techniques employed for high-rise buildings.

In particular the maritime evacuation procedure makes little allowance for maritime specific features of the evacuation process which include both psychological and physical factors such as:

- Motor ability in dynamic conditions;
- Way finding behaviour based on vessel safety media systems.

Consequently, prior to the commencement of this thesis, the requirement for the inclusion of maritime specific features in an evacuation analysis has never been formally demonstrated.

Thus, the hypothesis of this thesis is:

'Maritime specific features have a significant influence on the evacuation analysis outcomes of passenger vessels: These features should be considered in the early stage of design.'

To prove this hypothesis, the completion of the following tasks is required:

- Obtain representative data of the maritime scenario;
- Develop empirical models to describe the influence of maritime specific variables;
- Develop an evacuation analysis tool to incorporate the maritime specific data;
- Develop a rational basis for evaluating the magnitude of influence that the maritime features have on the evacuation analysis;
- Assess the performance of the evacuation models with and without maritime specific factors.

- An experimental program is required to provide maritime specific data in a form that may be readily quantified and applied to the evacuation analysis.

Information sufficient to validate human behaviour, such as action selection and cue acceptance, is of interest. However these variables are dependant on the availability of records from real incidents, which are both rare and difficult to obtain. Australian Transport Safety Bureau (ATSB) has been requested to provide validation, based on a minor incident leading to the successful evacuation of a large passenger ferry. Although the findings had been collated at the time of submission of this thesis they were unavailable for distribution to the public. Accordingly action selection and cue acceptance have not been incorporated in this thesis.

The motor ability of passengers in dynamic and/or capsizing conditions is a physical parameter that may be examined directly through measurement in a laboratory environment. However the performance may be subject to some psychological and physical parameters that are difficult to measure. Validation through field trials is not ethical given the operational risks associated with disabling a vessel. Post accident investigations can provide little more than qualitative assurance of the results due to the difficulties associated with measurement and reporting of environmental conditions and passenger performance.

The way finding behaviour based on vessel safety media systems and experience is a more subjective measure that requires assessment through interviews and questionnaires. The way finding behaviour is best assessed through site visits and post accident investigations. As previously stated, opportunities to influence post accident investigations in the maritime industry is difficult under the existing system. Given the legal sensitivity of the findings, comprehensive validation of site survey findings is not currently available. The ATSB have been advised of the work of this thesis and input into the evacuation investigation surveys has also been provided for the current accident investigation underway by the ATSB. Accordingly for the first time the results will be presented in a format that is sufficient to validate the way finding behaviour on vessels during an evacuation.

The motor ability and way finding performance of evacuees from a passenger vessel are assessed using entirely different means (i.e. Laboratory experiments versus site surveys). Accordingly, the analysis of these factors is presented separately in the following Sections:

- Section 4: Motor Ability in the Maritime Environment;
- Section 5: Way Finding Behaviour on Passenger Ships.

4. MOTOR ABILITY IN THE MARITIME ENVIRONMENT

4.1 MOTOR ABILITY BACKGROUND

Knudson and Morrison (1999) defined kinesiology as the academic discipline interested in the study of human movement and identify the key features as:

- Risk of injury/safety (i.e. is the technique safe? Is there a low probability of chronic or acute injury?)
- Effectiveness in accomplishing goal (i.e. how does shifting the weight influence stability and hence improve outcome?);
- Efficiency of attaining goal (i.e. economical use of energy; excessive movements);
- Rationales in action (i.e. shorten stride in icy conditions to maintain stability);
- Range of correctness (i.e. difference in stance and weight shift).

Knudson and Morrison (1999) described qualitative analysis in kinesiology as the systematic observation and introspective judgement of the quality of human movement for the purpose of providing the most appropriate intervention to improve performance. Analysis approaches include:

- Pedagogy;
- Biomechanics;
- Motor Development.

As opposed to human movement in sports and disability rehabilitation there is only limited opportunity to intervene to improve performance during evacuations. Furthermore evacuation of passengers may involve the interaction of thousands of individuals such that the mainstream techniques developed for human movement analysis may be impractical for application to evacuation analysis.

Cunningham and Cullen (1993) likened human movement of pedestrian flows to vehicular flow. They describe the principle parameters of the movement of pedestrians as passenger flow, speed and crowd density. Cunningham and Cullen (1993) defined these as:

- Passenger Flow (Q) - Number of moving objects (passengers) crossing a unit channel width in a unit time;
- Walking Speed (V) - How many units of distance passed per unit time;
- Crowd Density (ρ) - Number per unit of channel area.

Cunningham and Cullen (1993) described the principles of pedestrian flow as distinct from vehicular flow as, 'the ability to cross a pedestrian traffic stream, to walk in the direction opposing a major pedestrian flow and generally to manoeuvre without conflicts and changes in walking speed and gait.'

They describe additional factors that contribute to the walking experience as comfort, convenience, safety, security and economy of the pedestrian system. Some of the factors described by Cunningham and Cullen (1993) that are relevant to evacuation of passenger ships are as follows:

- Comfort - temperature control and weather protection;
- Convenience - short walking distances, direct routes, grades, surface treatment and condition, ramps, mechanical transportation devices, directional signing, directory maps, other features design to simplify travel;
- Safety - separation of pedestrians, traffic control devices, fire safety;
- Security - lighting, open lines of sight, closed circuit television, controls on activity;
- Economy: costs associated with delays, costs associated with the provision of services on route.

The views of Cunningham and Cullen (1993) were typical, if not advanced, in the area of research of general pedestrian flow as well as evacuation analysis. As noted from the work by Cunningham and Cullen (1993) the external environment is more controllable from a design perspective than the biomechanical and cognitive behaviour of the evacuees.

Brumley and Sincock (2000) conducted a review existing standards applicable to the safe access of pontoons in Australian waters and identified the following:

- AS1428.1 (1998) provided an indication of safe access for stationary ramps and walkways based on the research by the Australian Uniform Building Regulations Coordinating Council to address the needs of people with vision impairment, other ambulant people with disabilities as well as manual and electric wheelchair users. The guidelines are based on the 80% rule which allows 80% of the most able bodied people in a disability group and at least 80% if the combined groups to be able to achieve independent access with reasonable ease and safety. The guidance provided in AS1428.1 is based on the physical access capabilities and needs of adult people with disabilities as determined by empirical testing of people with disabilities aged 18 to 60 years. The guidelines indicate that access ramps longer than 9m and steeper than 1:14 cause serious steering and control problems for many electric wheelchair users and ambulant people with disabilities. Some wheelchairs have been found to tip over backwards on step ramps of 1:6 and now a 1:8 gradient for kerb and step ramps are required.
- In contrast AS3962 (1991) required that the maximum slope on a gangway should be less than 1:4 unless this results in gangways longer than 15m whereby the maximum slope can be increased to 1:2.7. The basis for these figures is not directly apparent from the description within AS2962 (1991). However Brumley and Sincock (2000) indicated that it is likely that the criteria is a

compromise between safety requirements and practical limitations of pontoon arrangements, locations and local environment.

As noted in Section 2.5.5 Applebee, McNamara and Baitis (1980) introduced the concept of motion-induced interruptions on postural stability in a dynamic environment with the view of identifying performance degradation. Graham (1990) extended the theory for application to the frequency domain. Boer (1993) defined postural stability and locomotion as important factors requiring investigation in a dynamic and/or capsizing environment. Boer (1993) identified through experiments that the listing environment causes problems with walking and maintaining balance, even more so in cyclic motion patterns, such as dynamic roll. Boer (1993) defined motion-induced interruptions (MIIs) as unwanted deviations of an easy task. The research by Boer (1993) focussed on tasks such as standing, normal walking, heal/toe walking, and balancing on one leg. In particular he found the following:

- Leather soles on wooden floor will slip easily at 19°;
- Postural adjustments are required at 20°;
- Most problems occur while trying to walk.

Boer (1993) did not quantify the impact of listing on the walking speed of evacuees. However it is noted by Boer (1993) that Quasar evacuation analysis design tool EVACSIM accommodates for list of 15° by dividing walking speed by 1.3. This factor is applied independent on the magnitude of roll. Boer (1993) did not provide any scientific data to support the use of this factor.

Boer (1993) identified the following inadequacies on human stability data gathered prior to 1993:

- There is an insufficient number of subjects to obtain confidence in results;
- Different age groups need to be assessed;
- The motions and list assessed are too small (should assess up to 30°);
- Group behaviour is not assessed;
- Walking speeds are not assessed/recorded.

Crossland and Rich (2000) provided validation of the use of the lateral force estimator for assessing human stability performance in dynamic conditions for a number of simple naval operational tasks. The approach is used to assess 'Task Effectiveness' based on the number of predicted MIIs. Where Crossland and Rich (2000) defined MIIs as the incident where ship motions become sufficiently large to cause a person to slide or loose balance unless they temporarily abandon their allotted task to pay attention to keeping upright. The definition includes non-seated tasks including standing, walking, lifting and moving objects.

The technique presented by Crossland and Rich (2000) is based on the work by Graham (1990) and is aimed at linking 'dynamic motions to human performance for a range of tasks that allow predictions of the frequency at which a crew member will slide, stumble or lose their balance.' The technique for linking vessel motions to MIIs is based on the combinations of lateral and vertical accelerations that cause postural control problems.

Crossland and Rich (2000) provided evidence of the validity of their techniques through experiments carried out with Naval personnel on a moving simulator using motions profiles of typical Naval craft. The motion profiles included multiple degrees of freedom. Although Crossland and Rich (2000) provided evidence of the validity of this approach for simple 'stationary' tasks, they admit that they have limited confidence in the application of their experimental vidence for validation of this approach to determining walking speeds.

The main concern by Crossland and Rich is based on the experimental apparatus that, due to dimensional restraints, required them to make use of a treadmill rather than using long passageways. It was verbally confirmed by Crossland and Rich that there were clear signs that treadmill contaminated the data and that walking characteristics were modified due to the presence of a treadmill.

Boer (1993) investigated the physical restraints on walking in the listing environment and found the following:

- In a corridor width of 1m only one person can walk at a time;
- In a corridor width of 0.76m, the largest 5% of the population will be unable to remain in the upright position at a list of greater than 7°;
- In a corridor width of 2m, the largest 5% of the population will be unable to remain in the upright position at a list of greater than 30° where there are two people side by side;
- In a corridor width of 2m with 2 people side by side, the largest will be unable to remain in the upright position at a list of greater than 30°;
- An evacuee's posture may change to face direction of list;
- A coefficient of friction of 0.8 is recommended.

Graham (1990) referred to a dry deck coefficient of 0.7. However English (1998) indicated that most people can walk safely on horizontal surfaces with a coefficient of friction of 0.4. English (1998) also states that the general premise of a coefficient of friction of the surface of 0.5 is sound. However he does note that the unexpected wet or greasy spot may bring the coefficient of friction down to 0.2, which causes most slip or fall accidents.

Boer and Bles (1998) presented an experimental program for investigating the effects of dynamic ships motions and the effects of list/heel on passenger walking speeds in corridors. The findings of this research were presented Bles, Nooy and Boer (2001). This research included 60 people aged 18-83 years of age for trim angles up to 20° and list angles of 15°. The walkway length was 1.6m and width was 1.1m. The research also included consideration of stairwells (6 steps) and tilted laterally and longitudinal and entry/exit through doors. The results of the work by Bles, Nooy and Boer (2001) were presented in Section 4.4.4 to provide comparison with the work of this thesis.

Zhao (1998) reported on experimental tests currently in progress to provide reliable insights into the biomechanics and control mechanisms for maintaining stable standing. Zhao (1998) identified experimental tests to collect three-dimensional kinematic data, muscle activation and ground reaction forces. Zhao's (1998) research is focussed on developing a Functional Neuromuscular Stimulation (FNS) model to enable paralysed individuals to perform activities previously impossible. Zhao (1998) indicated that the major difficulty in designing FNS standing systems is to 'produce timely postural corrections as necessary for maintaining dynamic balance in the presence of destabilising disturbances such as intrinsic sway and unanticipated extrinsic perturbations.'

Brumley and Koss (1998) addressed the issue of the impact of dynamic and capsizing conditions on the walking speed and stability of evacuees based on the preliminary findings of research specifically undertaken to assess the implications of quantifiable human factors on the evacuation of passenger ferries and cruise ships.

The impact of a reduction in walking speeds in a sinking ship environment as observed by Brumley and Koss (2000a) relates directly to the feature of kinesiology defined by Knudson and Morrison (1999) as the, 'effectiveness in accomplishing goal.' where the goal is to evacuate as quickly as possible.

However, the impact of reduced stability relates to all the key features identified by Knudson and Morrison (1999). The features of most importance to evacuation analysis are the, 'risk of chronic or acute injury,' 'effectiveness in accomplishing goal' and the, 'efficiency of attaining a goal.' All three will relate directly to the performance measures identified in Section 2.3.4

The work by Brumley and Koss (1998) did not include consideration of the, 'efficiency of attaining a goal' which may impact in the reduced performance of evacuees in the latter stages of evacuation where fatigue may play an important role.

Brumley and Koss (1998) did not quantify the consequences of stability failure (i.e. the magnitude of injury) as explicit intervention measures were employed to reduce the likely outcome of a failure event. Brumley and Koss (1998) define the instability measure as the frequency of use of handrails and kick rails for assistance when explicitly instructed against using such support devices 'unless they are required to prevent falling over.' The preliminary report by Brumley and Koss (1998) was based on three alternative environmental conditions and tested 211 people. The database has since been extended to 985 people and includes over 20 conditions. An overview on the findings of the research is reported in Brumley and Koss (2000a) and Brumley and Koss (2000b). A full description of the research is discussed in Sections 4.2 and 4.3.

Fleet Technology (2001) also developed a test facility to look at the influence of vessel motions on evacuation of passengers and tests are currently underway. The results of this research had not been released into the public domain at the time of submission of this thesis.

4.1.1 Dimensional Analysis

Based on the previous work in the area of motor ability and motion sickness in the marine environment the independent variables that may influence the walking speed and stability of passengers include:

- Individual Specific
  - Physical (i.e. gender, age, injury/disablement, size, weight, strength, co-ordination, reflexes, skill, fatigue, experience, footwear, adaptability);
  - Psychological (i.e. fear, caution, anxiety, apathy, confusion);
  - Physiological –i.e. nausea, dizziness, disorientation, sickness, pain).
- Scenario Specific
  - Inclination;
  - Motions;
  - Assistance available (i.e. handrails, kick rails, walls, other people etc);
  - Congestion;
  - Floor type;
  - Blockages (i.e. reverse flow, furniture etc);

Of these, the principal factors that can be readily assessed based on standard demographic information available to vessel operators are the physical factors such as:

- Individual Specific,
  - Physical - gender, age, disablement;
- Scenario Specific,
  - Deck inclination (quasi-static list/trim angle due to capsize),
  - Vessel dynamic motions (i.e. motions due to impact and wave induced motions),
  - Assistance available,
  - Congestion (i.e. population density),
  - Floor friction,
  - Blockages (i.e. counter flow).

For the purpose of this study the focus is placed on the readily quantifiable factors as identified above. It should be noted that Smith (1997) developed measures of estimating physiological and psychological factors through the sea sickness incidence measures. However these are not commonly measured and would not provide an adequate basis for generic vessel evacuation analysis. It is also noted that the factors such as age and gender may not necessarily directly influence motor ability rather these may act as descriptors for parameters such as strength, size, weight, disablement and even footwear.

The biomechanical approach to assessing motor ability performance of passengers in the environment of a capsizing ship is predominantly dependant on the system of forces acting on the body (due to the vessel motions and inclination) relative to the available forces to resist overturning and sliding (including inertia forces, friction forces as well as internal muscular forces.) Conceptually the system describing motor ability performance is simple. However the process to validate the system is complex due to the following:

- There are three linear degrees of freedom for vessel motion (surge, sway, heave);
- There are three angular degrees of freedom for vessel motion (roll, pitch, yaw);
- There are two degrees of freedom for vessel capsize (longitudinal/lateral);
- The local human motions may be different depending on where the passenger is located on the vessel due to the coupling of motions from various degrees of freedom;
- There may be significant physical variation in characteristic dimensions of passengers which influence the application of environmental forces on the body;
- There is potential for significant variation in the ability of people to resist forces including the ability of humans to dynamically shift the centre of gravity and stability base (i.e. foot location) to compensate for motions which is driven by cognitive behaviour and dependant on strength, reflexes, co-ordination, skill and experience;
- The body form is not symmetric in the sagittal and frontal planes and accordingly compensation to motions depends on the direction from which motions are encountered relative to the body direction.

4.1.2 Co-ordinate System

The co-ordinate system discussed herein is based on the standard system used for assessment of vessel motions in the area of naval architecture. The co-ordinate system is divided into two systems as follows:

- Global Co-ordinate System (Ship Co-ordinate System);
- Local Co-ordinate System (Evacuee Co-ordinate System);

These co-ordinate systems are defined in Appendix 1.

4.1.3 Simplification of System

As previously stated the system is dependant on multiple degrees of freedom for capsizing and dynamic motions. For the purpose of demonstrating the significance of maritime specific environment on the evacuation analysis of maritime vessels, only one degree of freedom of motions (roll) and one degree of freedom of capsizing (list about the longitudinal axis) has been assessed in detail in this thesis. This approach allows for the data gathered within this research to be the basis for further work on other degrees of freedom while also being valid for interim applications.

The selection of the roll/list degree of freedom is based on the following assumptions:

- DNV Technica (1996) and Brumley and Potts (1996e) provided evidence that large vessels will weather vane to be beam on to the waves when forward control and power is lost which will lead to roll motions;
- Pinkster (1988) indicates that the response of vessels to beam seas is typically larger than head seas due to the large exposed area and relatively small amount of damping and stiffness for roll motions;
- DNV Technica (1996) provided historical evidence that the major sinking motion of vessels in the early stages of evacuation is to gradually list about the longitudinal axis;
- IMO (2001a) identified that the ability to launch life raft is only required to be limited to 20°. Accordingly the early stages of evacuation are critical for the purposes of a successful evacuation.
- Large vessels have greater evacuation paths along the longitudinal axis that will result in the local axis system of the passenger being in line with the vessel. This is demonstrated in Figure 4.1;
- Graham (1990) identified that for monohulls it is known from experience that lateral motions are the primary cause of instabilities. This is due to the body being optimised for forward, not sideways movement. Accordingly local sway and roll motions on the body (resulting in transverse forces) have a more destabilising influence on forward egress than heave, surge and pitch (resulting in inline forces). However it should be noted that vertical component of heave and pitch motions has the potential to be more physically demanding as it results in the evacuee having to climb up or down to make forward progress;
- Data already exists and criteria have been established within standards AS1428.1 (1998) and AS3962 (1991) for walking up stationary ramps (inclination about the lateral axis) but very little was known about listing and rolling environments.

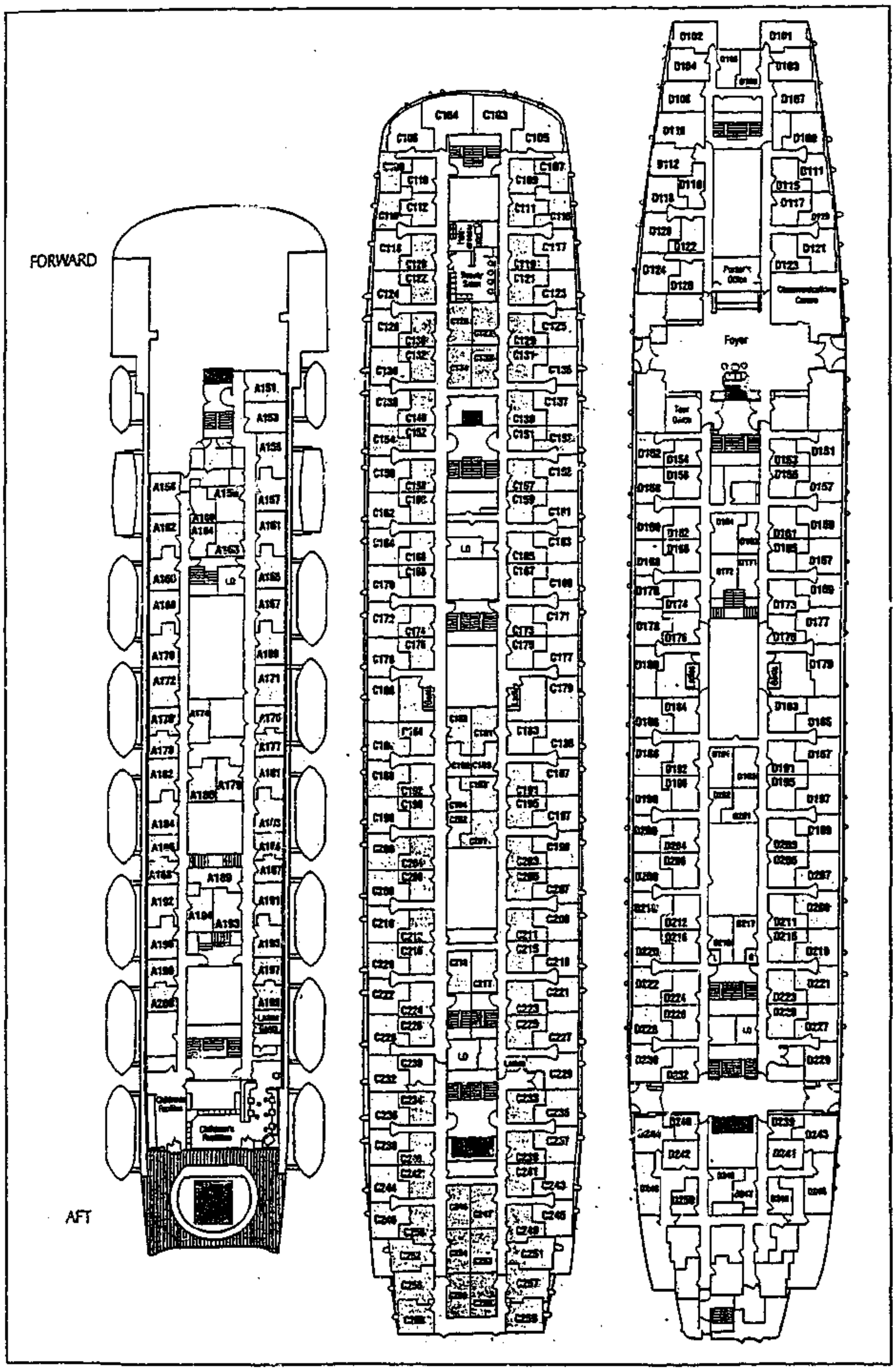


Figure 4.1 Typical Deck Layout

4.1.4 Dimensional Analysis

To correlate experimental data more easily it is convenient, in a physical system with two or more quantities that are interrelated, to set up dimensionless quantities that are in turn interrelated. Using the Force/Length/Time (FLT) system of dimensions, the independent variables, for the single degree of system, are described as follows:

Independent Variable	Symbol	Unit	Dimension
1. Mean list angle	(ϕ)	rad	(none)
2. Roll amplitude	(σ)	rad	(none)
3. Roll frequency	(ω)	Hz	(1/T)
4. Congestion (density)	(ρ_c)	people/m^2	(1/L^2)
5. Reverse flow (density)	(ρ_r)	people/m^2	(1/L^2)
6. Passenger vertical centre of gravity	(VCG)	m	(L)
7. Passenger mass	(m)	kg	(FT^2/L)
8. Overturning resistance	(F_{or})	N	(F)
9. Normal walking speed	(V_n)	m/s	(L/T)
10. Dynamic walking speed	(V_d)	m/s	(L/T)
11. Gravity	(g)	m/s^2	(L/T^2)

The normal walking speed is the walking speed of the evacuee on an open horizontal surface. This is used as a calibration factor to eliminate bias of the population sample tested (such as disabilities, co-ordination and general walking capabilities). It is recognised that in a dynamic/capsizing environment the impact of lateral forces on the body may trigger deficiencies in walking capabilities that would not normally influence walking speed on a flat horizontal surface. The full development of various non-dimensional parameters is included in Appendix 3. It is noted that, based on simple force balance system, the peak acceleration, A, acting on a static body is a function of many of the independent variables listed. That is:

$$A = f(g, \phi, h, \omega, \sigma) \qquad (4.01)$$

Where A = peak acceleration acting on a static body CoG.

Ignoring congestion and counter flow the dimensional analysis of Appendix 3 indicates that:

$$V_d/V_n = f\,(F_{or}/m.A) \quad (4.02)$$

For the purposes of simplicity the non-dimensional parameters identified are referred to as follows

$$Vr = V_d/V_n = \text{Velocity Ratio} \quad (4.03)$$

$$Er = F_{or}/m.A = \text{Environmental Force Factor} \quad (4.04)$$

4.1.5 Related Predictive Motor Ability Models

As previously stated Crossland and Rich (2000) developed an approach refined by Graham (1990) that relies on evaluation of the relative forces on the body due to vessel motions to determine the task effectiveness of an individual. The approach is based on the assumption that the individual behaves as a passive rigid body and is based on the following concept:

When the combination of lateral and vertical accelerations due to vessel motions, becomes greater than the stabilising gravitational acceleration, then the body will tip or leave the supporting surface.

This concept provides an estimate of the likelihood of a person falling or momentarily pausing to maintain stability by either changing posture or using a fixture to provide support (such as hand rails, kick rails or walls).

The momentary pausing of the body leads to an increase in time to complete a set task. Hence, in the instance of evacuating a vessel, the average walking speed of an individual will decrease. To appreciate the implications of this, the model is developed from first principles.

A person overturning/tipping is dependent on the sum of the moments around the tipping pivot point, the person's foot. In the vessel environment it is assumed that six degrees of freedom that may have force contributions. Appendix 1 provides an approach for determining the accelerations acting on a body offset from the vessel centre of gravity. This approach is modified herein to define the sum of the moments acting on a body in the y-z plane causing the body to overturn laterally. The sum of the moments are shown in Figure 4.2 and described by equation 4.05

That is, instability occurs when $\Sigma M > 0$ (4.05)

Where, $\Sigma M = M_2+M_3$

$M_2 = m.h(g.\sin(\phi+\eta_4)+\ddot{\eta}_2-\ddot{\eta}_4\bar{z}+\ddot{\eta}_6\bar{x})$

$M_3 = m.l(-g.\cos(\phi+\eta_4)+\ddot{\eta}_3+\ddot{\eta}_4\bar{y}-\ddot{\eta}_5\bar{x})$

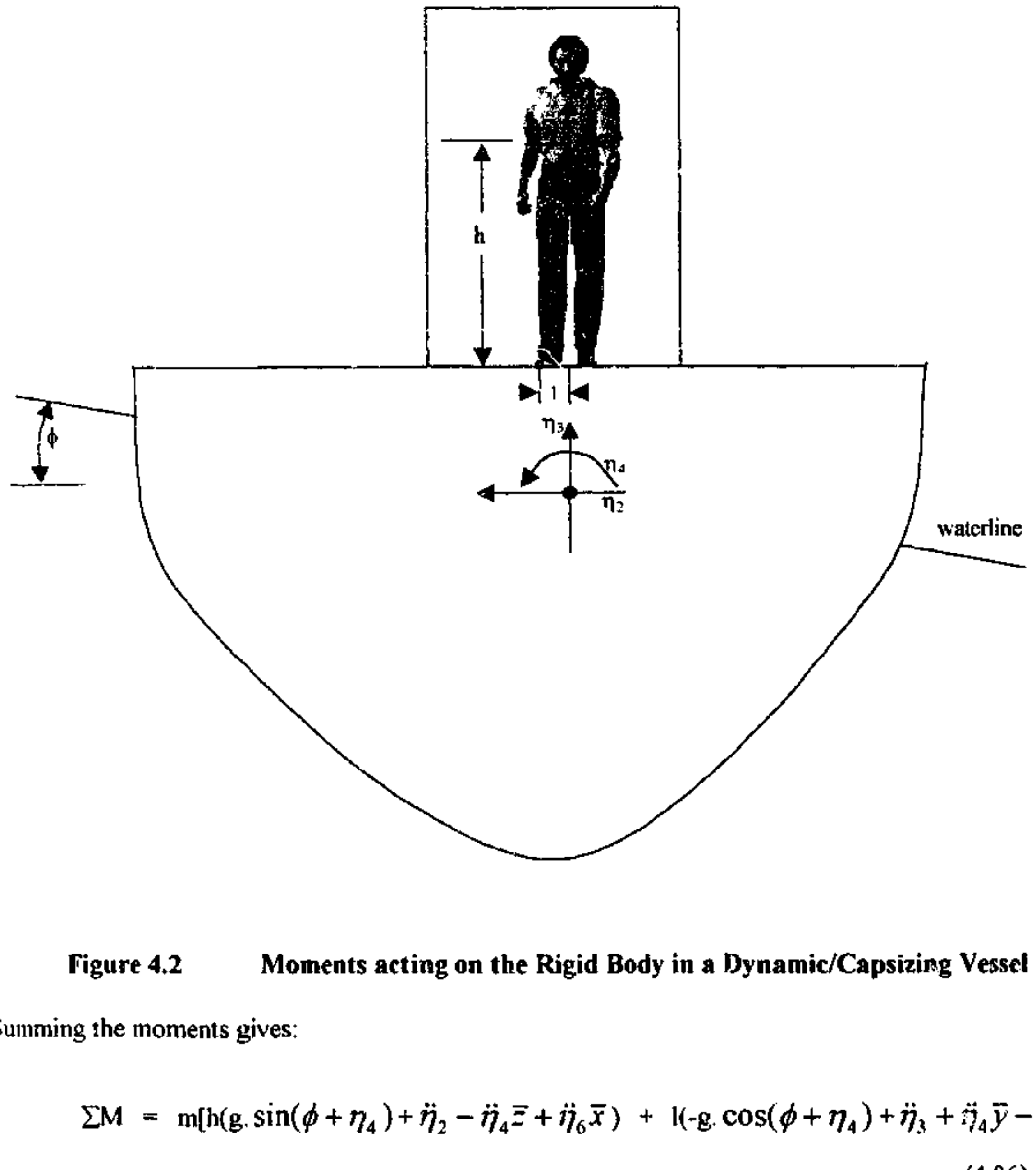


Figure 4.2 Moments acting on the Rigid Body in a Dynamic/Capsizing Vessel

Summing the moments gives:

$$\Sigma M = m[h(g.\sin(\phi+\eta_4)+\ddot{\eta}_2-\ddot{\eta}_4\bar{z}+\ddot{\eta}_6\bar{x}) + l(-g.\cos(\phi+\eta_4)+\ddot{\eta}_3+\ddot{\eta}_4\bar{y}-\ddot{\eta}_5\bar{x})] \quad (4.06)$$

Hence instability occurs when:

$$h(g.\sin(\phi+\eta_4)+\ddot{\eta}_2-\ddot{\eta}_4\bar{z}+\ddot{\eta}_6\bar{x})+l(-g.\cos(\phi+\eta_4)+\ddot{\eta}_3+\ddot{\eta}_4\bar{y}-\ddot{\eta}_5\bar{x})>0 \quad (4.07)$$

For the scenario assessed by Crossland and Rich (2000), the body centre of gravity is located at co-ordinates (0,0,h) and the capsize angle is small. Accordingly the equation may be simplified further to:

For the scenario assessed by Crossland and Rich (2000), the body centre of gravity is located at co-ordinates (0,0,h) and the capsize angle is small. Accordingly the equation may be simplified further to:

$$g.\eta_4 + \ddot{\eta}_2 - h.\ddot{\eta}_4 + l/h.\ddot{\eta}_3 > l/h.g \qquad (4.08)$$

This equation is the same as that identified by Crossland and Rich (2000).

For the simplified scenario under investigation in this thesis the body centre of gravity is also located at co-ordinates (0,0,h) and there are no sway or heave components. However, the capsize angle is large. Hence the equation may be simplified to:

$$g.\sin(\phi+\eta_4) - h.\ddot{\eta}_4 > l/h.g.\cos(\phi+\eta_4) \qquad (4.09)$$

Other than the environmental characteristics the independent variable of importance for both scenarios is the ratio of the half stance width over the height of the person's centre of gravity which Crossland and Rich (2000) identified as the tipping coefficient.

4.1.6 Preliminary Analysis: Tipping Coefficient

The theoretical tipping coefficient for the sample population tested in this thesis is of the order of 0.185 based on an average height of 1.73m and body width of 0.43. Graham (1990) assumed a body width of 0.46 and centre of gravity height of 0.91, which leads to a theoretical tipping coefficient of 0.25. NHFA (1990) identified the 95% percentile of population height in Australia as 1.85m for men and 1.73m for women. Averaging across men and women this gives a height of 1.79m. Still (2001) identified the average 95% percentile width over 12 nationalities as 0.454m. The combination of these parameters gives a theoretical tipping coefficient of 0.188. Crossland and Rich (2000) found that the empirical tipping coefficients for all tasks completed in a dynamic environment were on average 0.222 and ranged from 0.133 to 0.273.

This broad agreement between theoretical estimates and actual results is sufficient to warrant further consideration and refinement of the approach adopted to better suit the motor ability requirements for vessel evacuation. In particular, it should be noted that the tipping coefficient that Crossland and Rich (2000) observed for the case that best represents the theoretical model developed (standing aft) was 0.243 which is much larger than the 0.185 estimate. This may be explained by the potential of those tested increasing their stance width, reducing their centre of gravity, or moving their torso to cope with vessel motions.

It should be noted that the above variables may be defined in the same format as that identified in the non-dimensional analysis and using the convention specified in the global co-ordinate system.

$$A = h.\ddot{\eta}_4 + g.\sin(\phi+\eta_4) \qquad (4.10)$$

Where, $\eta_4 = \sigma \cos(\omega t + \Theta)$

$\ddot{\eta}_4 = -\sigma.\omega^2 \cos(\omega t + \Theta)$

And $F_{or} = m\,(l/h.g.\cos(\phi+\eta_4)) \qquad (4.11)$

Such that the velocity ratio is:

$$V_d/V_n = f\,(m\,(l/h.g.\cos(\phi+\eta_4))/m(h.\ddot{\eta}_4 + g.\sin(\phi+\eta_4))) \qquad (4.12)$$

This may be simplified to:

$$V_d/V_n = f\,((l/h.g.\cos(\phi+\eta_4))/(h.\ddot{\eta}_4 + g.\sin(\phi+\eta_4))) \qquad (4.13)$$

Or $Vr = f(Er) \qquad (4.14)$

Where Er $= (l/h.g.\cos(\phi+\eta_4))/(h.\ddot{\eta}_4 + g.\sin(\phi+\eta_4))$

It is also noted that the task effectiveness defined by Crossland and Rich (2000) is equivalent to the velocity ratio defined by Brumley and Koss (2000) such that:

$$E_{TASK} = T_{CALM}/T_{WAVES} = V_d/V_n = Vr \quad (4.15)$$

Crossland and Rich (2000) related the measured MII to the task effectiveness using the following formula:

$$E_{TASK} = 1 - MII_{RATE}\, D_{MII}/60 \quad (4.16)$$

Brumley and Koss (2000) directly measured the velocity ratio (or Task effectiveness) and the environmental accelerations in accordance with the dimensional analysis. The stability failures also were recorded but are not essential for developing a walking speed model.

While the approach adopted by Crossland and Rich (2000) is consistent with that derived by Brumley and Koss (2000) the data currently gathered by Crossland and Rich (2000) is limited in the following areas:

- No measurement reported on the MII duration for walking tasks;
- No consideration of changing of body form or position;
- No consideration of the influence of fear and/or caution;
- Only a small sample group selected (15 people);
- Large capsize angles are not addressed;
- Correlation for predicted versus measured MIIs appears poor in the region of interest.

4.2 MOTOR ABILITY EXPERIMENT METHODOLOGY

4.2.1 Motor Ability Facility

To determine the motor ability of passengers in a dynamic and/or capsizing environment a special purpose facility was designed and built. The special purpose facility is referred to as 1st MATE (First Motor Ability Testing Equipment).

4.2.1.1 1st MATE Operational Limits

To determine the operational limits of the facility, pilot studies were conducted on similar equipment including in-service vessels. The aim of the pilot study program is to develop a reference for the design approach used for the development of the 1st MATE facility.

The pilot study involved the investigation on the following items of equipment:

- Vessels, Merchant and Passenger - For vessel motions up to 8°, egress speeds were not significantly influenced;
- Ansett, Aircraft safety simulator - For mean lists between 8° to 12.5° small but noticeable influence on egress speeds were detected;
- Monash, inclined scaffolding - While volunteers could feel the influence of the mean list of 15°, the body was able to compensate due to external horizontal references and hence egress speeds were not altered;
- TNO Human Factors Motion Facility - For motions of approximately 20°, egress speeds were dramatically affected. For mean lists of approximately 30° the volunteer found it almost impossible to make unassisted forward progress.

In addition, Boltwood (1995) reported on past incidents:

- List 5-7°, passenger movement affected;
- Heeled 10°, passenger became frightened;
- List 15°, passengers experienced difficulty walking;
- List 12-15°, passengers jumped overboard;
- No panic observed due to list.

In summary the key area of concentration for the 1st MATE facility is between 15° and 20° and secondary concentration is between 20° and 35°.

4.2.1.2 1st MATE Configuration

The 1st MATE facility is shown in Figure 4.3 and Figure 4.4.

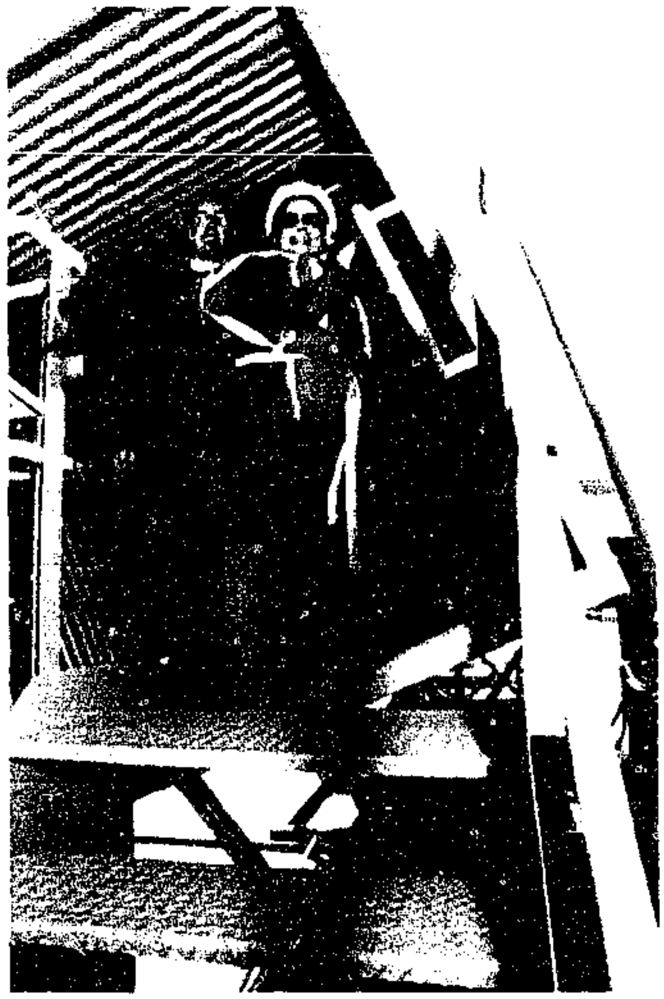


Figure 4.3 1st MATE Facility: Front Entrance

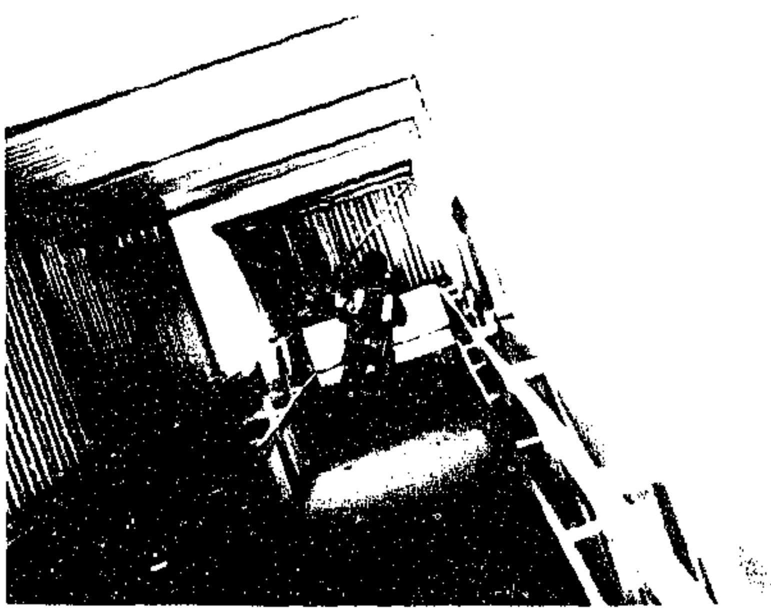


Figure 4.4 1st MATE Facility: Internal

The 1st MATE facility consists primarily of a corridor that is supported by two stationary pivot points along the longitudinal axis and third pivot point that is offset from the longitudinal axis and dynamically located by a single hydraulic ram. The corridor is 10m in length, 1.65m wide and the height from floor to ceiling is 2.0m. The floor is offset from the ground by approximately 1.0m and is supported by a grillage that has been specifically designed to allow the appropriate degrees of freedom required to realistically assess occupant egress. A volunteer on the facility was also involved in an incident on the Adriatic in December 1991 and commented that the 1st MATE facility was, 'more realistic than first thought,' and 'scary, even though only I was only in (1st Mate) for a short time.' The volunteer also commented that she, 'had to remind (herself) that it wasn't real.'

An extract from detail drawing M46-06 depicting motion limits of the 1st MATE is provided in Figure 4.5.

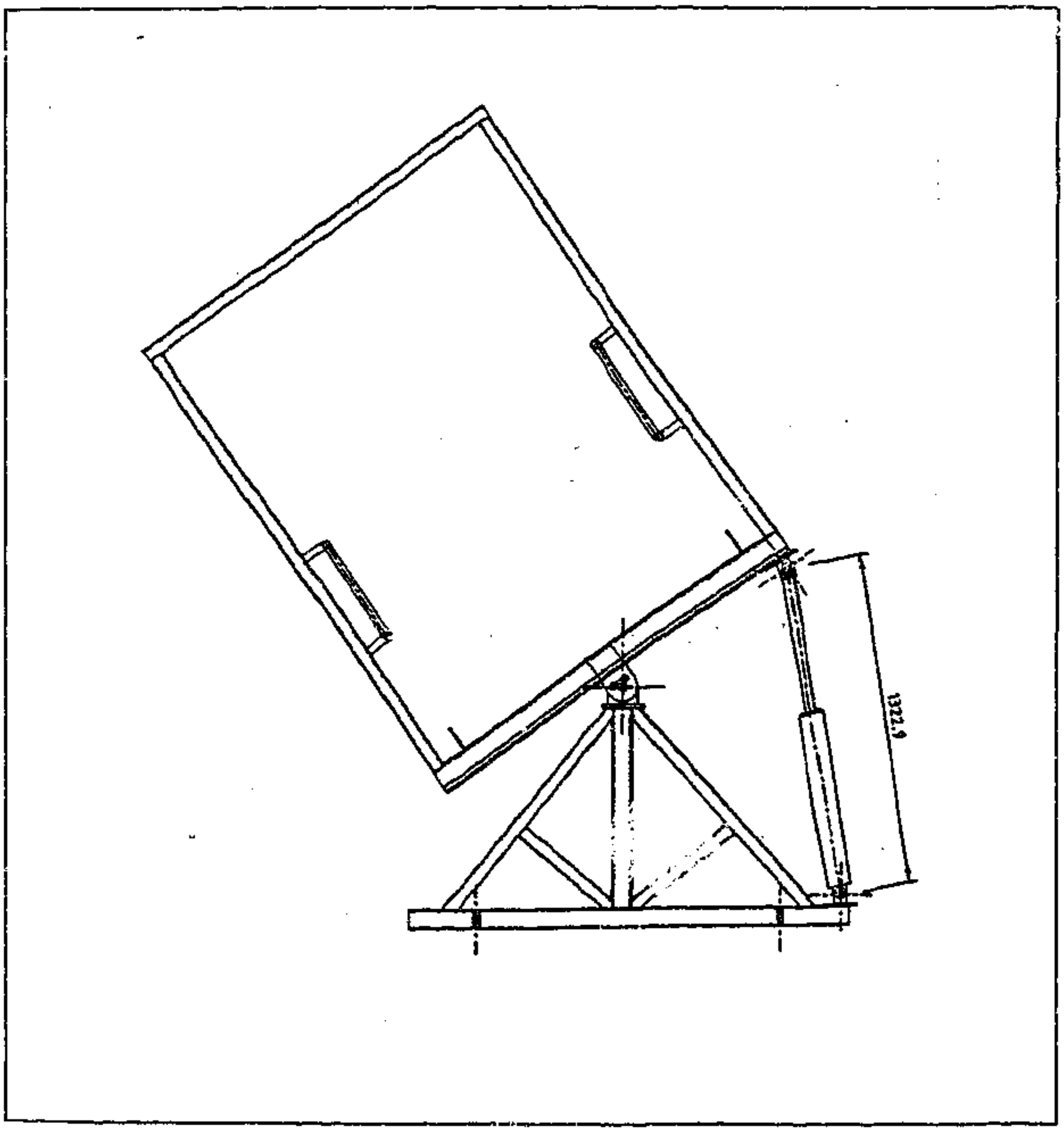


Figure 4.5 Detail Drawing of 1st MATE Facility

Access to the 1st MATE facility is via a built for purpose stairway. A separate module provides access to safety switches and computational hardware as well as a storage area. Qualitative tests at the Netherlands facility at TNO by Boer (1993) established that lighting will have no significant influence unless the facility is fully dark. As such a variable control on the lighting level has been excluded in this version of the facility.

4.2.1.3 Safety Aspects

The corridor and operating booth is fully enclosed to protect the occupants from outside environmental conditions. Video surveillance allows the operator to monitor the occupant behaviour during trials and hence allow for the provision of immediate intervention in the event of an unforeseen incident. Guardrails and non-slip flooring (steel checker plate) are provided to allow occupants to maintain a stable egress motion during the trials. As a precautionary measure the occupants are instructed to don lifejackets (for body protection) and helmets (for head protection). Occupants are not permitted to participate if footwear is deemed to be inappropriate and unsafe for the trials.

The testing program was conducted in such a way as to allow for the modification of test details (including increasing safety measures) based on gradually increasing knowledge of passenger egress. Put more simply, the safest tests were conducted first (i.e. small amplitude, low frequency motions; low mean angle of inclination; one occupant only) and based on the findings of the early tests the testing program was gradually made more demanding.

People with any health condition that could potentially be aggravated due to participation in these trials were excluded along with people under the age of 18.

Each occupant is informed of potential hazards associated with participation in these trials through an explanatory statement (Appendix 4) and is subsequently requested to sign consent form.

Although the 1st MATE facility was installed at a theme park and has been designed to AS3533 (Amusement rides and devices code)[9] it was operated as a research facility and occupants are made aware of this through the above-mentioned explanatory statement in accordance with Monash University ethical standards.

4.2.1.4 1st MATE Operation

The 1st MATE facility was operated by skilled research practitioners with an adequate understanding of the limitations of the facility and the goals of the research.

[9] See Australian Standards Non-Compliance section 10.7

The 1st MATE facility was designed to support 10 people during its operation. However the facility was limited to eight occupants at any one time during normal operation. Two positions on the facility remained available in the event of the extra requirement of live load capacity during an emergency. The facility was primarily subjected to less than two occupants for the majority of the operating life of the facility.

The facility is limited to maximum mean inclinations about the longitudinal axis (list) of 35°. The maximum dynamic motion about the mean list offset is 10°. The dynamic motions are be limited to sinusoidal oscillations of less than 0.5 Hz. Maximum angular accelerations of the facility are therefore be limited to 0.86 rad/s^2.

4.2.2 Environmental Conditions and Sample Characteristics

The safe/orderly evacuation analysis was carried out for a mixture of the following conditions:

- Mean List of 10, 15, 20, 25, 30 and 35 degrees
- Dynamic Frequency of 0.1,0.15,0.2 and 0.3 Hz
- Dynamic Amplitude of 0. 5,8,9 and 10 degrees

The environmental conditions for the tests conducted are described in Table 4.1

Table 4.1	Environmental Condition for 1st MATE Motor Ability Tests						
ID	List	Freq.	Amp.	n_{group}	n_{sample}	A	Er
Pilot Study							
1	0	0	0	1	15	0.00	0.00
2	5	0	0	1	15	0.86	0.47
3	10	0	0	1	15	1.70	0.93
4	15	0	0	1	15	2.54	1.39
Base Case (Normal Population, 18-65)							
5	10	0.2	9	1	35	3.48	1.79
6	15	0.3	5	1	47	3.71	2.12
7	15	0.15	9	1	58	4.15	2.50
8	15	0.2	9	1	43	4.27	2.46
9	15	0.1	10	1	63	4.22	2.44
10	20	0	0	1	41	3.36	1.90
11	20	0.1	8	1	49	4.67	2.49
12	20	0.2	5	1	67	4.30	2.24
13	20	0.3	5	1	64	4.50	2.51
14	20	0.15	9	1	52	4.92	2.67
15	20	0.2	9	1	36	5.04	2.73
16	20	0.2	5	1	49	4.30	2.45
17	25	0.3	5	1	42	5.26	2.83
18	30	0	0	1	60	4.91	2.75
Bottom Rail Only							
19	25	0.3	5	1	58	5.26	3.02
Carrying Child							
20	35	0	0	1	67	5.63	2.93
Group Flow							
21	20	0.2	5	2	62	4.30	2.44
22	25	0.2	5	2	14	5.06	2.99
23	25	0.3	5	4	67	5.26	2.93
24	30	0	0	2	46	4.91	2.86
Elderly (65-85)							
25	20	0	0	1	12	3.36	1.70
26	20	0.1	5	1	11	4.19	2.17
27	25	0	0	1	10	4.15	2.12
28	25	0.1	5	1	6	4.94	2.30
Disabled (Wheelchair)							
29	10	0	0	1	1	1.70	0.93
30	15	0	0	1	1	2.54	1.39
31	15	0.1	5	1	1	3.39	1.86
32	17.5	0	0	1	1	2.95	1.62
33	20	0	0	1	1	3.36	1.84
34	20	0.1	5	1	1	4.19	2.29

Note:
- List = Mean list angle (°)
- Freq. = Dynamic roll frequency (Hertz)
- Amp. = Dynamic roll amplitude (°)
- Group Size = Number of people on the 1st MATE facility.
- Sample Size = Number of measurements per condition.
- Er = Environmental Force Factor.
- A = Lateral Acceleration (m/s²)
- Gender = Percentage of the sample that are male.
- Age = Average age of the sample group.

The range of motor ability tests conducted using the 1st MATE facility is further summarised as follows:

- Evacuee groups of 1, 2 and 4 people;
- The number of people tested per test condition is between 14 and 67;
- Test conditions with more than 45 trials were used to develop empirical fit;
- Test conditions with less than 45 trials were performed for qualitative analysis.
- Test conditions were conducted for lateral accelerations (A) up to $5.63m/s^2$.
- Percentage of males varied from 44% to 94%. Due to time constraints tight controls on the gender population were not enforced. However the influence of gender is assessed and the resulting empirical fit to the data is corrected accordingly.
- The mean age of the sample for each test was predominantly between 30 and 35.
- A case study of the older population was assessed for a mean age of 72.
- A case study of young males of a mean age of 23 was also assessed representing the extreme age variation.

4.2.2.1 Scenario Assignment:

Each environmental condition assessed consists of four sub-conditions as follows;

- SC1 - inbound (i.e. walking towards a dead end with no horizontal references) with hand rails;
- SC2 - outbound (i.e. walking towards an open end with horizontal references) with hand rails;
- SC3- inbound without handrails;
- SC4 - outbound without handrails.

The sub-conditions were conducted in the same order for each test to ensure that the volunteers were not exposed to a significant risk of injury. The order of the listed sub-conditions is based on physical limitations of the facility and the requirement by safety authorities to allow the participants to become familiar with the facility prior to enforcing the more difficult 'without rails' restriction. The order of the listed sub-conditions means that subject has more experience in the facility for the 'outbound' condition than for the 'inbound' condition. This makes the interpretation of the influence of external horizontal references (i.e. the outbound case) difficult to separate from the influence of experience. To help provide a qualitative indication of the influence of experience and/or horizontal references on speed improvement the questionnaire asked the subject whether they found it any easier to walk inbound or outbound and why.

4.2.3 Motor Ability Trials Methodology

The detailed methodology for the motor ability trials is described in Appendix 6.

4.2.4 Safe and Orderly Evacuation Philosophy

The primary purpose of 1st MATE facility is to measure safe/orderly walking speeds of passengers in a simulated ship-sinking environment. While it should not be assumed that passengers would necessarily evacuate a ship in a safe/orderly manner, there are several reasons for adopting data that is obtained from safe/orderly walking speeds as follows:

- As identified by Harbst and Madsen (1993), qualitative assessments of both on land and at sea evacuations indicate that only a very small percentage of the population is likely to 'panic'. These qualitative assessments indicate that evacuees typically feel that the threat is less severe than it actually is; hence the normal reaction to an evacuation is to perform as though the threat is minimal. Saunders (1989) also found that real evacuations indicate that passengers will evacuate in the same fashion as they do in evacuation trials that is safe and orderly.
- Should passengers be forced to evacuate at speeds greater than a safe and orderly speed they expose themselves to greater risk of injury (which will ultimately lead to an increase in evacuation time which will not be modelled by an evacuation analysis). By adopting walking speeds that are not representative of safe/orderly practices the evacuation analysis will incorrectly conclude a lesser overall required evacuation time than is necessary.
- As the data is to be used to represent the required evacuation time for design purposes it is the responsibility of the designer to ensure that the evacuation procedure is as safe as reasonably practicable. This requires the designer to allow enough time for the passenger to evacuate without exposing the passenger to significant risk of injury. In severe dynamic conditions it is prudent that the design engineer adopt safe/orderly evacuation speeds to minimise exposure to injury.
- It is difficult to provide a prescriptive quantity to describe the safe and orderly speed that will minimise the risk of injury. However, by way of the approach adopted, the methodology intrinsically adopts a safe and orderly speed that is considered acceptable by the general public, provided that the sample population is representative of the commuting public as a whole.

Accordingly, the use of a safe/orderly evacuation velocity and the subsequent achieved evacuation velocity in simulations is a sound basis for defining safe/orderly evacuations in real circumstances. However, it is noted that some individuals may be overconfident and accordingly expose themselves to a high risk of injury. To ensure that the data is valid and conservative participants that run were omitted from the database. In the case where participants do not run yet still become unstable the walking speed will be reduced due to the recovery time such that the data set will be self-correcting. The above design philosophy is considered in the development of the details of the test procedure for single and multiple body flow as described in Appendix 6.

4.2.5 Questionnaire

A questionnaire was distributed for each participant in the motor ability trials. The questionnaire covered the following topics:

- *Demographic data* - The demographic data covered the following aspects that have the potential to influence the evacuation speed:
    - Age,
    - Gender,
    - Size (height and width),
    - Weight,
    - Handedness (left or right),
    - Shoe type (good or poor grip, hard or soft sole);
- *Physiological data* - In pilot studies it was identified that some occupants had feelings of nausea and dizziness in the various test facilities. It is noted that physiological factors that arise due to sea sickness may have some influence on evacuation performance and that those prone to feelings of seasickness may be also prone to instability for walking in the dynamic environment. Accordingly, middle ear conflicts resulting in seasickness may also cause stability and egress performance degradation. The survey was used to assess whether the occupant is prone to similar symptoms associated with seasickness in general and whether they experienced such phenomena within the 1st MATE facility. The symptoms assessed are as follows:
    - Dizziness,
    - Light-headedness,
    - Claustrophobia,
    - Walls distortion,
    - Nausea,
    - Seasickness;
- *Experience data*- It is possible that experience in the maritime area may influence the motor ability of passengers. To address this experience issue the following topics were discussed in the questionnaire:
    - Maritime experience,
    - Balance related experience.
- *Assistance data* - It was identified in pilot studies that the horizontal visual reference would have some impact on the motor ability of passengers. Participants claimed that while the adverse conditions were of concern they were able to compensate using the horizontal frame of reference. To assess this phenomena the participants were asked to identify which direction of transit was easier to cover and why. The inbound direction had no horizontal reference while the outbound had horizontal references at the exit.
- *Overturning Forces* - The lateral force required to tip the volunteers over was measured as a means of assessing the influence of human body strength on maintaining stability. Each volunteer

was asked to stand with feet shoulder width apart. A belt was attached at 40cm from the shoulder height of the volunteer (representing the approximate location of the centre of gravity of the average person). Attached to the belt was a spring force scale. The volunteer was asked to completely relax. The experimenter then gradually increased the lateral force until the person tipped over. This experiment was repeated on both sides of the body. A subsequent test was also completed with the volunteers instructed to "resist as much as possible while remaining perfectly vertical." The forces were recorded for each trial.

- *Walking Speed* - The time taken to walk 7.5m was recorded for each of the sub-conditions defined in Section 4.5. In addition the number of times handrails/kick rails were required was identified for the 'without rails' cases. The time taken to walk 9m on flat ground was also recorded as a reference to normal walking speed.

4.3 MOTOR ABILITY RESULTS

4.3.1 Demographic Data

The demographic data recorded for each of the motor ability trials conducted is recorded in Table 4.2.

4.3.2 Performance Data

Data such as the mean velocity ratio, percentage of the sample that refused entry without handrails, percentage of the sample that had at least one failure, and the average number of failures for the population that had at least one failure was measured for each of the motor ability trials conducted. Mean velocity ratios were measured for inward approach (no horizontal reference), outward approach (horizontal reference) and were also measured where volunteers were and were not allowed to use hand and kick rails. Summary performance data is documented in Table 4.3. The data was also adjusted to represent the velocity ratio of a population with a gender distribution of 50:50. This was achieved by separating the velocity ratios for males and females finding the average of the two resultant figures. Gender corrected data is documented in Table 4.4. The full database of data obtained is in Appendix 2.

Table 4.2	Demographic Data for Motor Ability Trials						
Condition	**Sample Size**	**Mean Age**	**% Male**	**Mean Height**	**Mean Weight**	**% Right**	**% Good Grip**
				Pilot Study			
1	15	40	-	-	-	-	-
2	15	40	100	-	-	-	-
3	15	40	100	-	-	-	-
4	15	40	100	-	-	-	-
				Base Case (Normal Population, 18-65)			
5	35	28	54	1718	68	97	82
6	47	30	65	1760	74	95	65
7	58	33	80	1730	80	92	85
8	43	35	62	1731	76	95	83
9	63	33	79	1760	75	95	89
10	41	33	66	1738	74	81	73
11	49	33	53	1735	70	91	71
12	67	34	30	1678	71	90	80
13	64	31	57	1722	74	94	58
14	52	31	56	1745	71	86	88
15	36	34	57	1722	72	80	86
16	49	32	75	1757	74	79	75
17	42	32	56	1745	70	91	62
18	60	36	71	1744	73	90	70
Average	**50**	**33**	**62%**	**1734**	**73**	**90**	**76**
				Bottom Rail Only			
19	58	31	70	1764	74	93	69
20	67	23	84	1724	69	84	66
				Bottom Rail Only			
21	62	32	71	1731	75	83	79
22	14	40	50	1728	78	93	86
23	67	23	94	1764	72	92	70
24	46	32	69	1761	76	82	82
				Carrying Child			
25	12	73	58	1685	69	92	75
26	11	72	64	1698	70	100	73
27	10	72	70	1695	69	100	70
28	6	71	50	1689	63	100	50
				Disabled (Wheelchair)			
29-34	1	22	100	1737	72	-	-

Note: % Male = Percentage of the population that is male
% Right = Percentage of the population that is right handed
% Good Grip = Percentage of the population describing shoe type as having good grip

Table 4.3		Motor Ability Performance Results									
ID	n_T	Environment		Failures			Vr				
		A	Er	$(n_T-n)/n_T$	$P(N_{MII}\geq 1)$	N_{MII}	rails		no rails		Avg
-	people	m/s^2	-	(%)	(%)	(MII)	in	out	in	out	-
					Pilot Study						
1	15	0.00	0.00	-	-	-	-	-	-	-	1
2	15	0.86	0.47	-	-	-	-	-	-	-	1
3	15	1.70	0.93	-	-	-	-	-	-	-	.99
4	15	2.54	1.39	-	-	-	-	-	-	-	.98
					Base Case (Normal Population, 18-65)						
5	35	3.48	1.79	0	63	1.43	.84	.88	.91	.94	.89
6	47	3.71	2.12	2	28	2.48	.79	.84	.83	.88	.83
7	58	4.15	2.50	2	65	1.57	.75	.77	.80	.86	.80
8	43	4.27	2.46	5	58	2.15	.74	.76	.76	.80	.76
9	63	4.22	2.44	0	53	1.87	.81	.85	.81	.81	.82
10	41	3.36	1.90	3	28	2.94	.95	.94	.83	.87	.90
11	49	4.67	2.49	2	67	2.58	.87	.92	.80	.84	.86
12	67	4.30	2.24	8	70	2.69	.84	.85	.73	.76	.80
13	64	4.50	2.51	28	49	1.91	.77	.78	.83	.87	.81
14	52	4.92	2.67	3	71	1.70	.76	.76	.74	.78	.76
15	36	5.04	2.73	0	83	1.85	.76	.76	.74	.78	.75
16	49	4.30	2.45	4	61	2.48	.87	.86	.80	.86	.85
17	42	5.26	2.83	37	63	3.03	.67	.70	.63	.68	.67
18	60	4.91	2.75	25	23	3.72	.77	.78	.65	.71	.73
					Bottom Rail Only						
19	58	5.26	3.02	-	-	-	.73	.79	.64	.67	.70
					Carrying Child						
20	67	5.63	2.93	40	76	5.07	.79	.75	.52	.54	.65
					Group Flow						
21	62	4.30	2.44	4	61	2.48	.87	.86	.80	.86	.85
22	14	5.06	2.99	-	-	-	.65	.68	-	-	.66
23	67	5.26	2.93	-	-	-	.88	.84	.85	.83	.85
24	46	4.91	2.86	-	-	-	.82	.80	-	-	.81
					Elderly (65-85)						
25	12	3.36	1.70	-	-	-	.56	.58	.52	.53	.55
26	11	4.19	2.17	-	-	-	.57	.59	.53	.59	.57
27	10	4.15	2.12	-	-	-	.56	.55	.60	.72	.58
28	6	4.94	2.30	-	-	-	.56	.55	.57	.58	.56
					Disabled (Wheelchair)						
29	1	1.70	0.93	-	-	-	-	-	-	-	.90
30	1	2.54	1.39	-	-	-	-	-	-	-	.93
31	1	3.39	1.86	-	-	-	-	-	-	-	.80
32	1	2.95	1.62	-	-	-	-	-	-	-	.89
33	1	3.36	1.84	-	-	-	-	-	-	-	.70
34	1	4.19	2.29	-	-	-	-	-	-	-	.60

Note:
- n_T = Total number of participants in trials with handrails (SC1 and SC2)
- n = Number of participants in trials with no handrails (SC3 and SC4)
- A = Lateral acceleration at the centre of gravity of the occupant
- Fr = Environmental Force Factor
- $(n_T-n)/n_T$ = Percentage of the population to refuse to attempt to conduct the trial without use of handrails
- $P(N_{MII}\geq 1)$ = Percentage of the population to have at least one failure
- N_{MII} = Average number of failures for the participants that have at least one failure
- Vr = Mean Velocity Ratio
- rails = Population were instructed to use hand and kick ails
- no rails = Population were instructed not to use hand rails
- in = Population walked inbound (no horizontal reference)
- out = Population walked outbound (horizontal reference)

Table 4.4 Motor Ability Performance Results - Gender Corrected (Base Case Only)

ID	n	Environment		Vr				
		A	Er	rails		no rails		Avg
		m/s^2		in	out	in	out	
5	35	3.48	1.79	.84	.87	.92	.92	.89
6	47	3.71	2.12	.78	.82	.82	.86	.82
7	58	4.15	2.50	.75	.75	.77	.83	.78
8	43	4.27	2.46	.73	.74	.74	.79	.75
9	63	4.22	2.44	.80	.84	.79	.82	.81
10	41	3.36	1.90	.96	.94	.85	.87	.90
11	49	4.67	2.49	.87	.91	.79	.84	.85
12	67	4.30	2.24	.83	.84	.72	.76	.79
13	64	4.50	2.51	.76	.77	.80	.85	.80
14	52	4.92	2.67	.75	.75	.74	.77	.75
15	36	5.04	2.73	.76	.75	.74	.73	.74
16	49	4.30	2.45	.85	.83	.82	.86	.84
17	42	5.26	2.83	.66	.69	.60	.66	.65
18	60	4.91	2.75	.73	.75	.63	.69	.70

Note:
n = Sample size
A = Lateral acceleration at the centre of gravity of the occupant
Er = Environmental Force Factor
Vr = Mean Velocity Ratio
rails = Population were instructed to use hand and kick ails
no rails = Population were instructed not to use hand rails
in = Population walked inbound (no horizontal reference)
out = Population walked outbound (horizontal reference)

4.4 DISCUSSION OF KEY RELATIONSHIPS

The key motor ability relationships are based on the impact of environmental accelerations and forces on walking speed and stability. These relationships are examined in the following sections.

4.4.1 Velocity Ratio versus Environment

The walking speed of each of the evacuees was determined in dynamic and static conditions and converted to the velocity ratio. The mean velocity ratio was determined for each condition. The list and roll parameters were converted to the environmental force factor and the lateral acceleration as reported in Section 4.3.2. The impact of varying environmental forces on velocity ratio is shown in the Figures 4.6 and 4.7. Only data points with more than 30 volunteers were considered in this evaluation. The correlation coefficient, R^2, between the factors is 0.91.

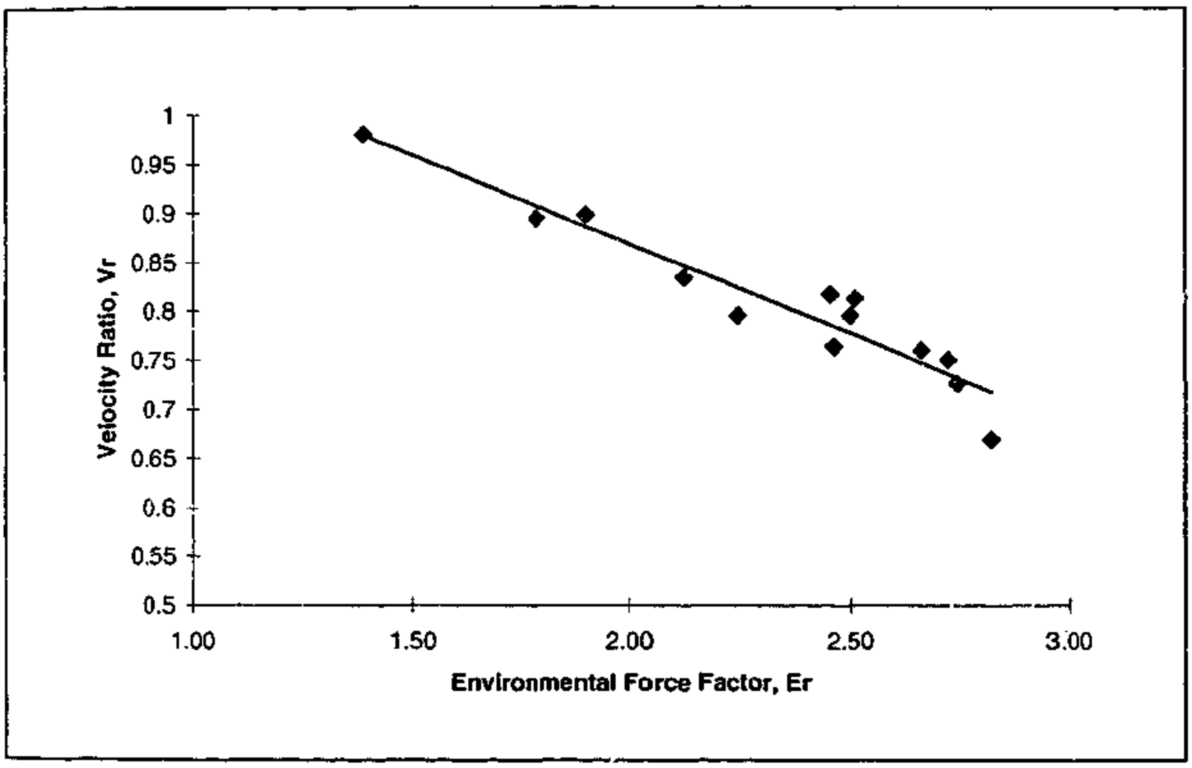


Figure 4.6 Environmental Forces versus Velocity Ratio

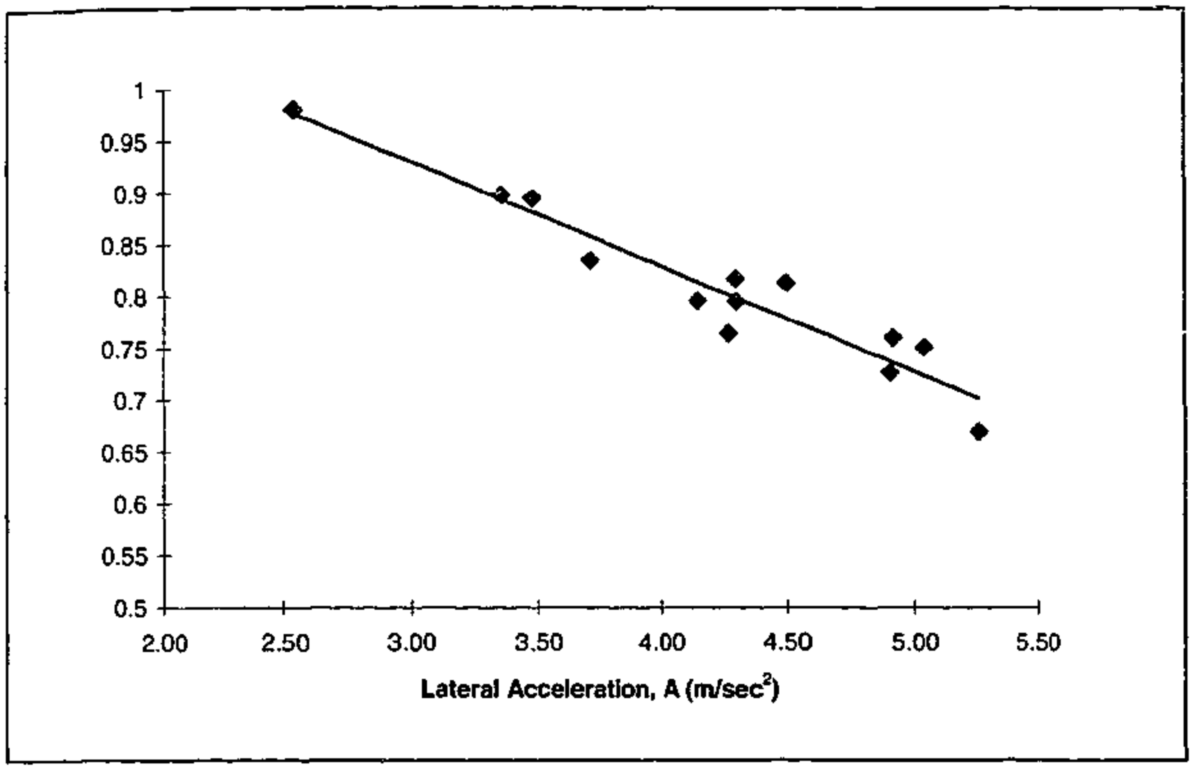


Figure 4.7 Velocity Ratio versus Lateral Acceleration

The linear least squares relationship between the velocity ratio and environmental force factor is as follows:

$$Vr = 1.23 - 0.18.E_r \quad (R^2=0.91) \qquad (4.17)$$

The linear least squares relationship between the velocity ratio and lateral acceleration estimate is as follows:

$$Vr = 1.23 - 0.10.A \quad (R^2=0.92) \qquad (4.18)$$

4.4.2 Tipping Coefficient

The required lateral tipping force was measured for 240 of the volunteers that participated. Based on the tipping coefficient the predicted tipping force was also calculated as:

$$F_t = (l/h).m.g \qquad (4.19)$$

Where Ft = Tipping Force
l = half stance width
h = height of the vertical centre of gravity of the volunteer
m = mass of the volunteer

g = gravitational acceleration

A comparison of the predicted required lateral tipping force against that measured showed a poor correlation when the person was relaxed (R^2 =0.059). When the person was instructed to resist yet remain vertical there was a much stronger correlation between predicted and measured lateral tipping forces (R^2 =0.374) where the intercept passes through zero. That is 37% of the variation of the measured tipping force is accounted for by the differences in the predicted tipping force. The comparison is shown in Figure 4.8. To better visualise the relationship between the predicted and measured tipping forces the data was divided into groups of 30 in ascending order of force magnitude. Figure 4.9 demonstrates that the average calculated tipping force systematically under predicts the measured tipping force by 15%.

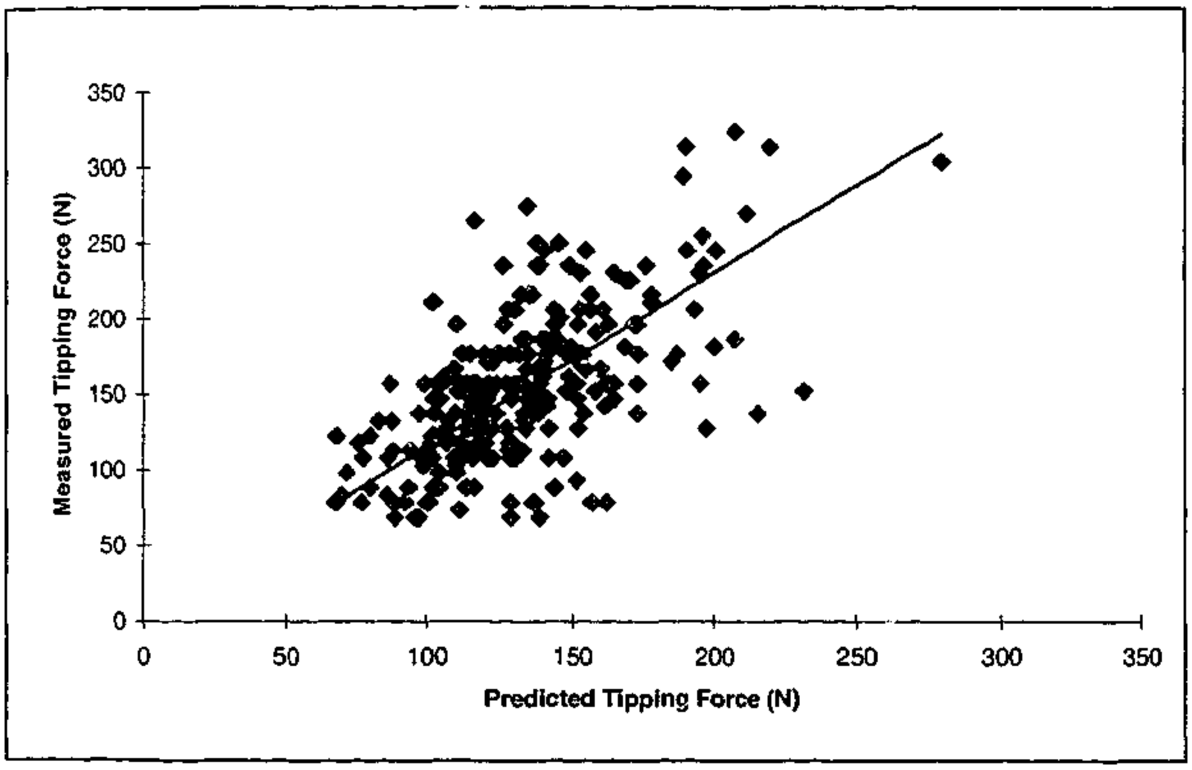


Figure 4.8 Tipping Coefficients - Predicted versus Measured

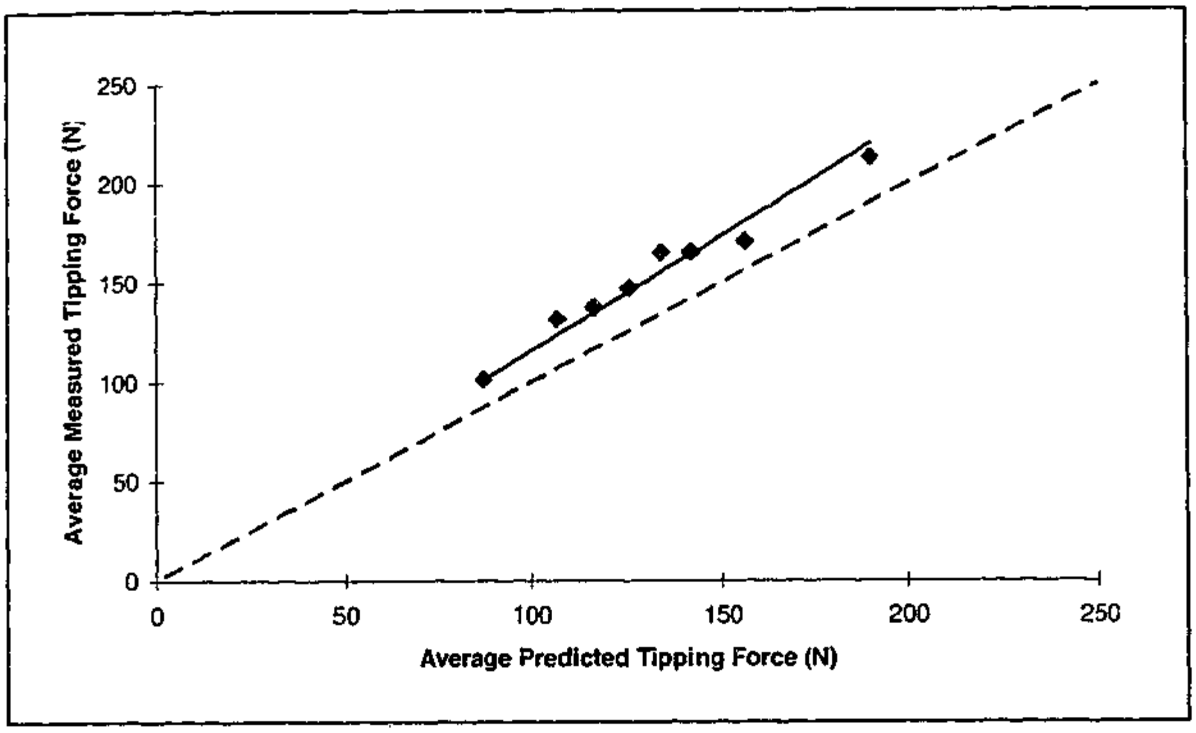


Figure 4.9 Tipping Coefficients - Predicted versus Measured (30 Volunteers per Sample)

The linear relationship (forced through zero) is:

$$F'_t = 1.15\,F_t = 1.15(l/h).m.g \qquad (4.20)$$

Where, F'_t = Measured Tipping Force

For the resisting scenario there is evidence of significant influences on resisting force of factors not considered by the predictor. Possible factors include:

- Leaning against pull (i.e. not vertical aligned);
- Injury causing inability to remain stiff (i.e. protecting injury);
- Changing position of centre of gravity.

The possible reasons for poor correlation for the relaxed scenario include:

- Increased percentage error in measurement of forces (i.e. lower forces);
- Increased opportunity for misinterpretation of instruction.

Even under supervision and instructions there was only limited correlation between the predicted and measured forces for the lateral tipping trials for the resisting scenario. In addition the systematic 15% under prediction using the tipping coefficient method indicates that the volunteers may have been optimising there body form to counter the lateral forces. In the situation where the volunteer has significantly more freedom on body form in response to lateral forces, such as free walking, it is clear that there will be significant scatter in the response of volunteer. Hence, for the purposes of developing supporting data for maritime specific evacuation models, a statistical approach should be adopted rather than attempting to model explicitly the performance of each individual. Accordingly empirical models based on the statistics of a sample population are more appropriate. The statistical approach is consistent with the application of human factors for other components of evacuation models (such as influence of congestion on walking speeds) and is suitable for the stochastic approach commonly applied.

A relationship between the force required to cause a single stability event and the rate of instabilities has been established empirically yet has not been developed fully theoretically. Crossland and Rich (2000) implied that the rate of instabilities is dependant purely on the number of incidences per unit time where the observed accelerations acting on the body exceed the acceleration limit identified by the tipping coefficient.

However data collected for this thesis indicates that the velocity ratio and the rate of instabilities is not as dependent on the frequencies of excessive accelerations as may be implied. This is evidenced by the following observations:

- Where there is no vibration component, instabilities are still observed;
- Where there is a vibration component, multiple incidences may occur for a single acceleration exceedance event;
- Alternatively, in some incidences where the acceleration threshold is exceeded the volunteer does not show signs of any instability.

The observations are dependant on human factors such as caution, fear, co-ordination, skill, experience and the general ability of the body to adapt to the environment. These factors were not included in the theoretical formulation of motion-induced interruptions as applied by Crossland and Rich (2000) and their predecessors. It is noted that Graham (1990) introduced the use of probabilistic approaches for application of motion induced interruption theory for spectral sea state conditions defined in the frequency domain. However, in the approach adopted by Graham (1990), only the environmental accelerations were handled in a probabilistic manner and the tipping threshold was assigned in a deterministic form (either empirically or theoretically defined).

At this point it is worth noting how the tipping coefficient threshold is positioned relative to the results gathered for this thesis. The average measured and predicted tipping thresholds are as follows:

h	$= 0.67*1.737m = 1.164m$
l	$= 0.213m$
A_t	$= (l/h)g = (0.215/1.164)9.81 = 1.814\ m/s^2$
F_t'	$= 153kg$
m	$= 72.2kg$
A_t'	$= F_t'/m = 153/72.2 = 2.12\ m/s^2$

Where,	h	= Average height of VCG of Passenger Sample (m)
	l	= Average ½ Stance Width of Passenger Sample (m)
	A_t	= Predicted Acceleration Tipping Threshold (m/s^2)
	A_t'	= Measured Acceleration Tipping Threshold (m/s^2)
	F_t'	= Average Measured Tipping Force (N)
	m	= Average of Passenger Sample (m)

When reference is made to Figure 4.10 it can be seen that the measured and predicted tipping thresholds coincide directly with the point where the lateral accelerations start to impact on the walking speeds. In addition the changes in the velocity ratio beyond the tipping threshold is significant. This provides increased confidence with the modelling approach adopted and, in particular, the experimental procedure adopted. However it emphasises the need to develop a probabilistic description of the tipping threshold.

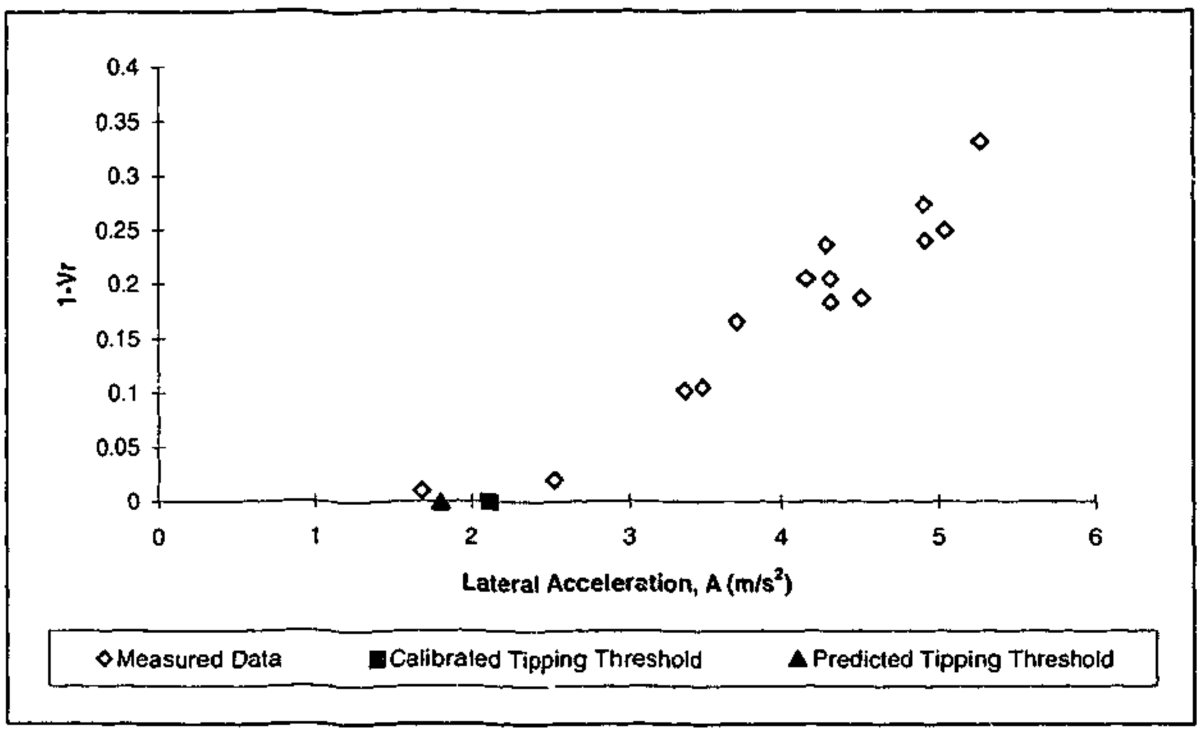


Figure 4.10 Comparison of Deterministic Tipping Thresholds with Lateral Acceleration

4.4.3 Stability versus Environment

Instability of passengers walking was measured as the incident where a volunteer required the use of the handrail or kick rail to prevent falling. In a moving environment it is assumed that this incident is caused by lateral accelerations exceeding the tipping coefficient. In static environments with a mean list, the cause of instability is more difficult to interpret. Observations from video records indicate that the volunteers were momentarily misaligned with the vertical axis, such that the component of gravity acting laterally on the body increases and causes failure.

It is noted that some passengers found walking in the corridor with full use of handrails very difficult and chose not to participate in the trials that required no use of handrails on the basis that they considered it highly likely that they may get injured in such a trial. Accordingly, the process of participation is self-selecting and may contribute to bias in the results. It is therefore assumed that the number of failures that would occur for those who did not participate would be on the upper bound of the number of failures measured for those who did participate. Accordingly, for the purposes of identifying a trend between the rate of failures and the environmental condition, it is assumed that those who did not participate will have 1.85 times as many failures as those who did participate and had at least one failure. The method of calculating the failure rate is as follows:

$$MII_{rate} = 60.N_{MII}[n + 1.85(n_T-n)]/(T.n_T) \qquad (4.21)$$

Where, MII_{rate} = Number of failures per minute per person;

N_{MII} = Number of failures per test per person;

n = Number of participants per scenario without handrails;

n_T = Number of participants per scenario with handrails;

T = Time taken to conduct test.

A power relationship was observed between the incidence of failures and the environmental conditions considered. The number of failures measured as a function of acceleration did not correlate as well as the velocity ratio. However, the correlation was still relatively high, $R^2 = 0.67$. The relationship observed, where the number of volunteers per environmental condition was greater than 44, is described as follows:

$$MII_{rate} = 0.151.A^{3.002} \qquad (R^2=0.67) \qquad (4.22)$$

Where, MII_{rate} =Motion Induced Interruption Rate (Number of failures per minute)

A = Lateral Acceleration

The relationship observed for all base case conditions tested is described as follows:

$$MII_{rate} = 0.212.A^{2.745} \qquad (R^2=0.67) \qquad (4.23)$$

Figure 4.11 presents the MII data with the least squares best-fit power relationship.

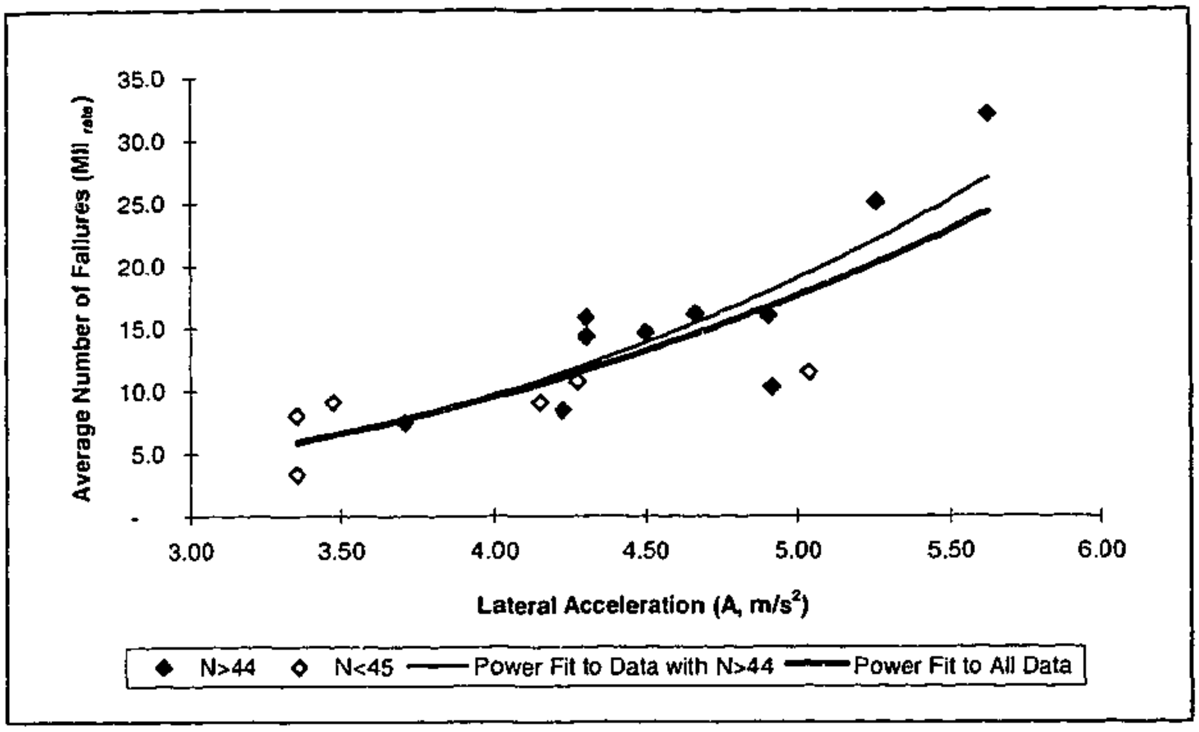


Figure 4.11 MII_{rate} as a function of Lateral Acceleration

The average rate of occurrence of failures may be broken down into the percentage of people that experience failures (i.e. $P(N_{MII}\geq 1)$) and the average number of failures for each person that experiences a failure (N_{MII}). This is stated as follows:

$$MII_{rate} = 60.N_{MII}.P(N_{MII}\geq 1)/T_{WAVES} \quad (4.24)$$

Where, $T_{WAVES} = T_{CALM}+D_{MII}.N_{MII}.P(N_{MII}\geq 1)$

And, T_{WAVES} = Time taken to complete the task on a dynamic, capsizing surface;

T_{CALM} = Time taken to complete the task on a horizontal, stationary surface;

N_{MII} = Average number of failures for each person that experiences at least one failure during the completion of the task;

$P(N_{MII}\geq 1)$ = Percentage of people that experience failures;

D_{MII} = Average duration of each failure.

As the environmental conditions worsen it is expected that the number of people that experience failures will increase as well as the average number of failures that the each person experiences. Due to the potential for people to modify their stance and centre of gravity it is anticipated that the number of people that experience failures at the tipping threshold is minimal. An analysis of the data in terms of percentage of people to experience failures indicates that the mean tipping threshold for a sample population is approximately twice that of the idealised tipping threshold. That is, 50% of the population will have at least one failure (or chose not to conduct the test) at a lateral acceleration of 4.13 m/s^2 (i.e. tipping coefficient, l/h = 0.42). This is shown in Figure 4.12 with a cumulative normal distribution fit and a standard deviation of 25% of the mean value.

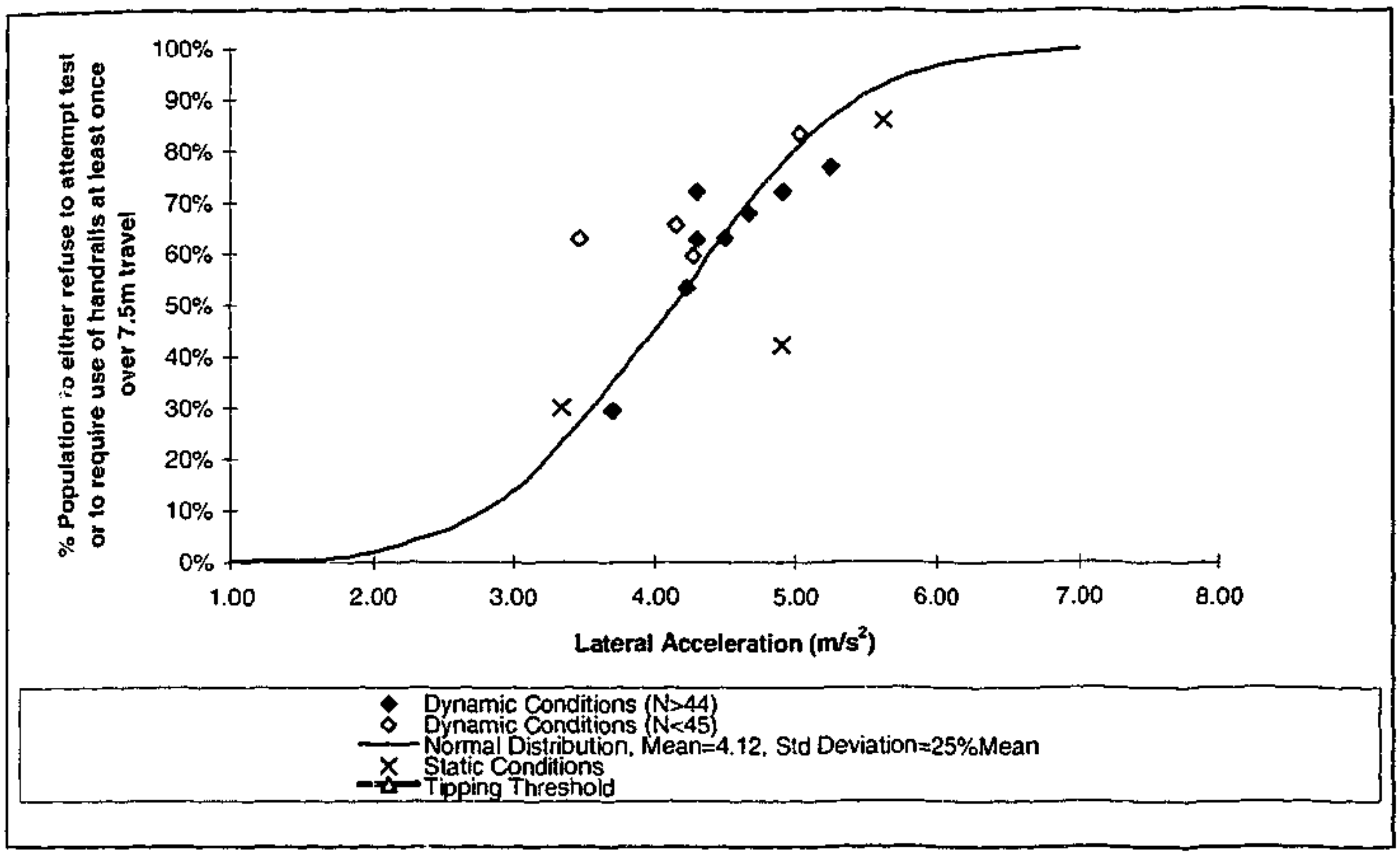


Figure 4.12 Percentage that Experience Failures as a function of Lateral Acceleration

(Including people that chose not to attempt the trial without handrails)

An analysis of the number of failures per metre of travel distance for the population that breached the tipping threshold was conducted on the data gathered for this thesis. The number of failures per person per metre trended with the lateral acceleration caused by the mean list rather than the combined lateral acceleration caused by list and roll. It is assumed that the roll coupled with list is sufficient to cause a single failure event but recovery and repeat failures in a single wave cycle are dependant on the mean angle of inclination of the deck. A cumulative normal distribution fit with a mean list acceleration 4.13 m/s^2 and a standard deviation of 60% of the mean value provided a good approximation to the date observed. This is shown in Figure 4.13.

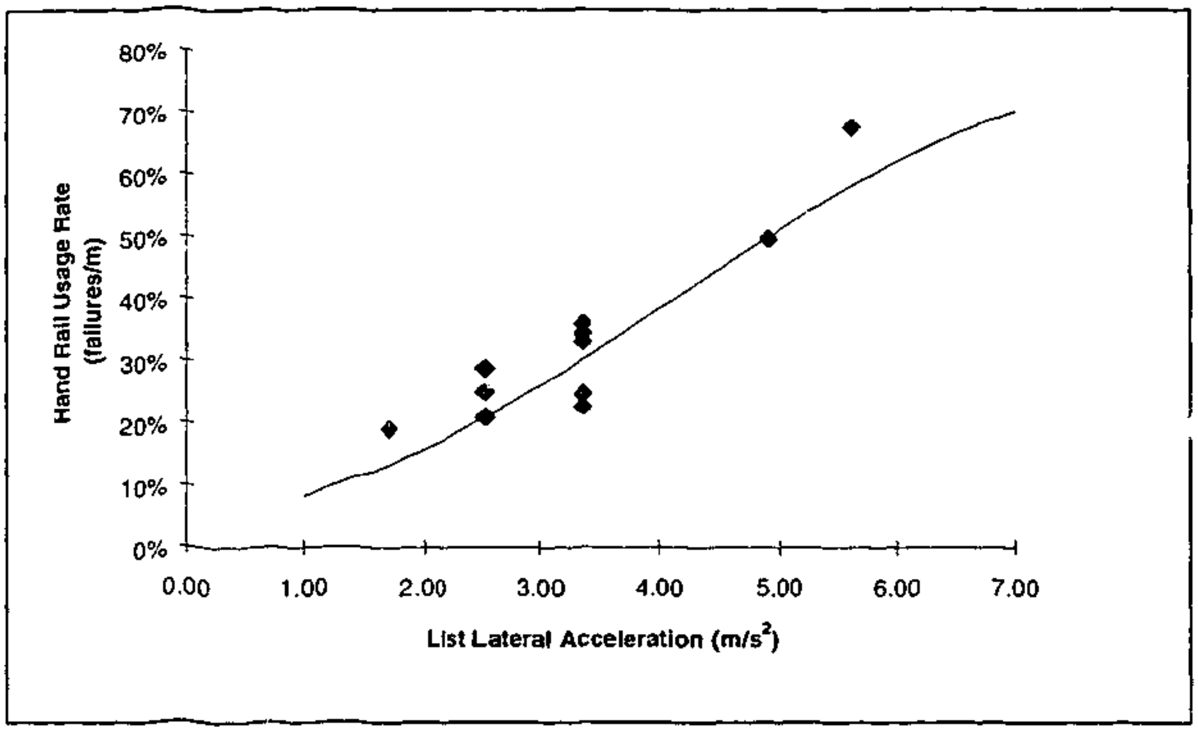


Figure 4.13 Number of Failures as a function of List Lateral Acceleration

(Excluding those with no failures)

Crossland and Rich (2000) proposed a relationship between stability (MII) and velocity ratio (task effectiveness). However the relationship is dependent on the duration of the failure event (D_{MII}). In other words the velocity ratio is dependant not only on whether a failure is observed but also on the duration of the momentary pausing that is caused to recover from the failure. While Crossland and Rich (2000) provided MII durations for a number of tasks, no durations were determined for walking tasks due to the complexity of measuring the associated recovery time.

Similarly, for the experiments of this thesis no failure (MII) durations were recorded directly hence the correlation between instabilities and walking speeds cannot be directly measured.

For four tasks other than walking Crossland and Rich (2000) observed a large single peak in the probability distribution for MII durations of the order of 2.5 seconds with 95% of MII durations being less than the zero crossing period tested (9 seconds). Using the relationship developed by Crossland and Rich (2000) the velocity ratio may be correlated with the number of stability failures per minute (MII_{rate}) as follows:

$$\overline{V_r} = 1 - MII_{rate} \cdot D_{MII}/60 \qquad (4.25)$$

Or, $$D_{MII} = 60(1-Vr)/MII_{rate} \qquad (4.26)$$

Where, D_{MII} = constant

For the experiments conducted for this thesis the failure duration (D_{MII}) was determined from equation 4.26 as ranging from 0.54 to 1.44 seconds over 15 conditions, which is of the order of magnitude expected. However, when the velocity ratio predicted (Vr), using a constant failure duration (average D_{MII} = 1 second) and the measured number of failures (MII_{rate}^{*}), was compared to the measured velocity ratio (Vr*) there was poor correlation (R^2=0.386) for conditions with greater than 30 participants. This appears to be due to the large variation of the failure duration (D_{MII}) between environmental conditions. The comparison is presented in Figure 4.14. The calculated failure duration, (D_{MII}) from equation 4.25 was compared with the lateral acceleration (A) to identify whether it took longer for an individual to recover from a failure in more severe conditions. The correlation between failure duration and lateral acceleration was poor (R^2=0.02). The comparison is shown in Figure 4.15.

The mechanisms that caused the failure duration are examined further to provide improved confidence in the results obtained. The examination is based on the following assumptions:

- The volunteer will act as a spring (with a mass and stiffness) rather than a simple rigid body;
- The person's stiffness can be directly derived from the force that is required to cause instability and the person's half stance (i.e. the instability is caused when the persons centre of gravity is moved outside the half stance);
- The recovery time will be half the person's natural period (i.e. the person's centre of gravity will return back above the middle of the half stance after half of the natural period).

Given that the body will overturn when the centre of gravity is moved further than the half stance width then this will be the displacement at the applied maximum force. Hence the stiffness may be written as:

$$k = F/l \qquad (4.26)$$

Based an assessment of 146 volunteers, the mean population lateral force and half stance were 155N and 215mm respectively. Accordingly the mean lateral stiffness was 721N/m.

The half natural period of the body is estimated as:

$$T_{1/2} = \tfrac{1}{2}\, 2.\pi \sqrt{(m/k)} \qquad (4.27)$$

From the sample population measured the mean mass of the population was 72 kg. Hence the mean half natural period of the population is 0.99 second. The half period determined is consistent with the calibrated failure duration. However, it is not regarded that the evidence herein is sufficient to conclusively establish that the failure duration may be directly determined from the half natural period. Rather the evidence put forward provides increased confidence in the value determined for the mean calibrated failure duration and provides a further support for the motion induced interruption approach as a whole.

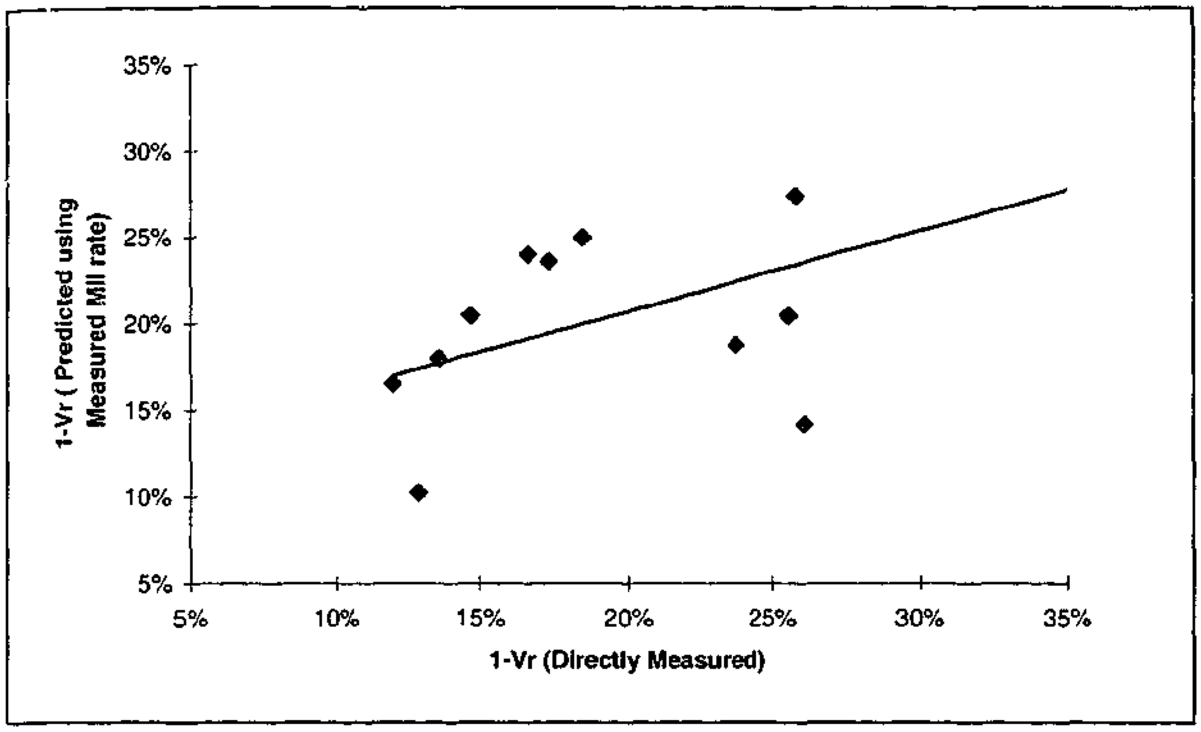


Figure 4.14 **Predicted Velocity Ratio versus Measured Velocity Ratio** *(from Measured MII_{rate})*

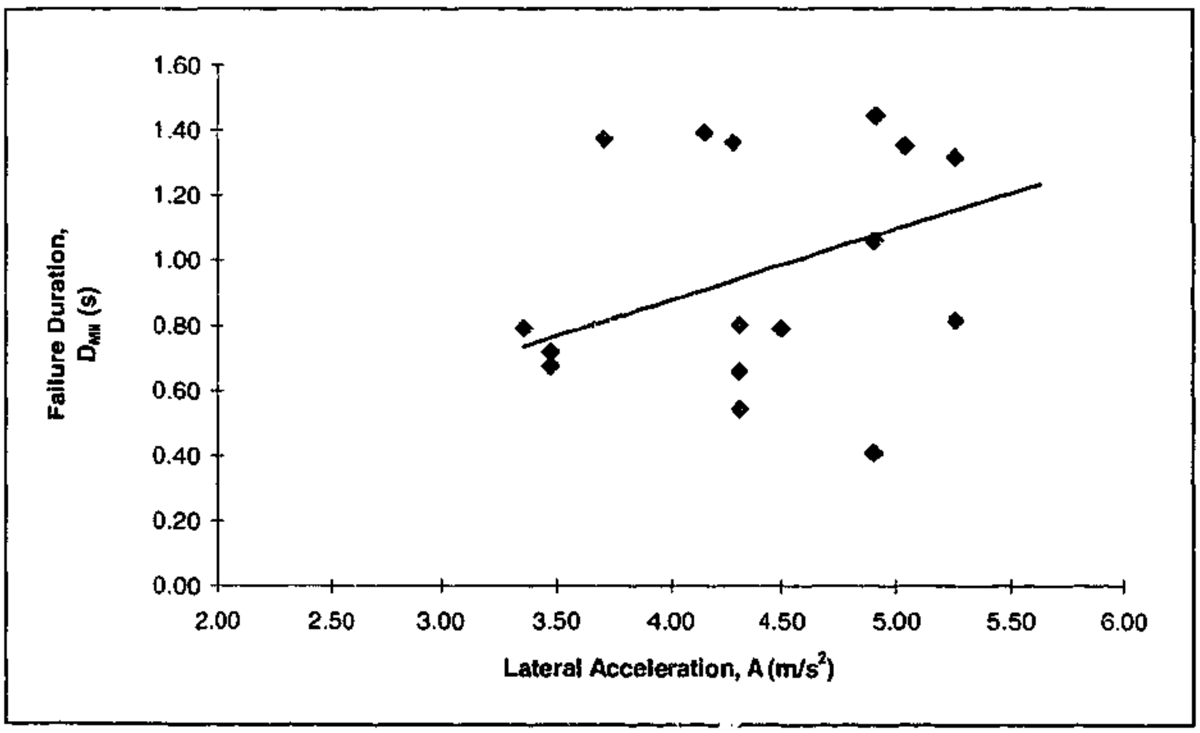


Figure 4.15 **Measured Failure Duration versus Predicted Failure Duration (Method 1)**

An alternative approach to determine the failure duration is to determine the time taken to complete the task (walk 7.5m) in dynamic conditions less the time taken to complete the task in static conditions, all divided by the total number of failures recorded.

$$D_{MII} = (T_{WAVES}-T_{CALM})/N_{MII\,(d=7.5m)} \tag{4.28}$$

Where T_{WAVES} = Time taken to Walk 7.5m in dynamic/capsizing conditions (s)

T_{CALM} = Time taken to walk 7.5m in static/horizontal conditions (s)

$N_{MII(d=7.5m)}$= Number of MIIs in 7.5m per person

For this method of determining the failure duration only those that actually recorded failures were included in the analysis, whereas the previous method incorporates the performance of all participants. For this approach the failure duration was determined on the basis of each individual and subsequently averaged for each condition.

For the base case condition the average failure duration calculated using the second method was found to exhibit a strong relationship with the lateral acceleration. This relationship is presented in Figure 4.16. A cumulative normal distribution based on a mean acceleration of 2 times the tipping threshold acceleration (2.12m/s^2) and a standard deviation of 25% of the mean is also displayed on Figure 4.16. The distribution is multiplied by 2 seconds, which represents an upper bound estimate of the failure duration.

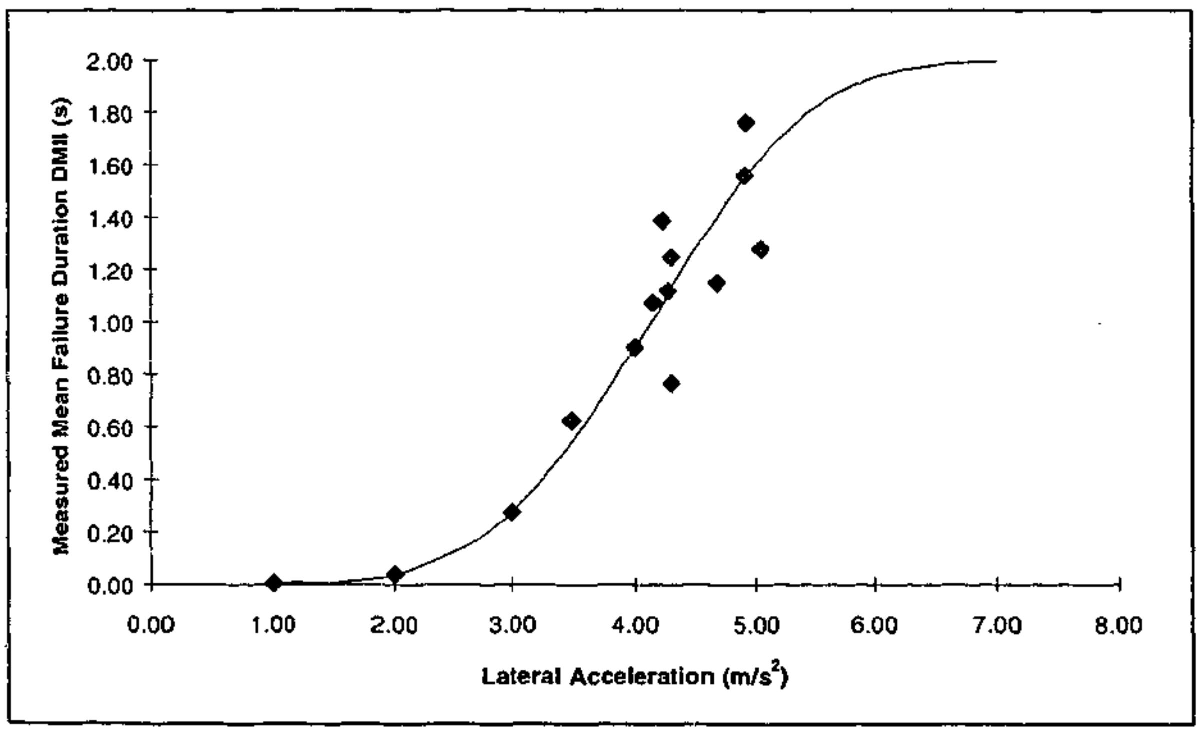


Figure 4.16 Measured Failure Duration as a Function of Lateral Acceleration (Method 2)

It is noted that it is not anticipated that failure duration measurements will provide a complete description of the deterioration in walking speed in a dynamic environment for the following reasons:

- There is no record of near misses;
- Volunteers can slow down to avoid failure;
- Different combinations of roll frequency, amplitude and capsize may influence the number of failures observed;
- Consideration of those that chose not to complete the trials provides a best guess estimate of the likely observed number of failures only.

Despite this it is noted that, when a constant failure duration, D_{MII}, of 0.97 second is used with the empirical power fit as described by equation 4.22, the MII approach predicts the velocity ratio very well ($R^2 = 0.92$). That is:

$$V_r = 1\text{-}MII_{rate}(A).D_{MII}/60 \qquad (4.29)$$

Where, $MII_{rate} = 0.151A^{3.002}$ and $D_{MII} = 0.97$

This relationship may be written as:

$$V_r = 1\text{-}0.151A^{3.002}.(0.97/60) \qquad (4.30)$$

Or, $$1\text{-}V_r = 0.00244A^{3.002} \qquad R^2\text{=}0.92 \qquad (4.31)$$

Using a power fit of the same form to directly predict the best empirical relationship between the lateral acceleration (A) and the velocity ratio (V_r) the following relationship is obtained:

$$1\text{-}V_r = 0.0017.A^{3.234} \qquad R^2\text{=}0.95 \qquad (4.32)$$

The method using the empirical fit to the number of failures (MII_{rate}) compares well to the best least squares fit obtained by direct correlation. This becomes clear when reference is made to Figure 4.17. It is noted, that the form of the empirical model predicted using the MII approach provides a better fit than a simple linear regression and matches the data points that were not used in the linear regression due to lack of data subjects.

The predicted acceleration dependant failure duration, number of failures and number of occupants to have at least one failure are combined to form an alternative probabilistic estimate of the failure rate as described in equation 4.24. It is noted that the predictor underestimates the failure rate calculated from equation 4.21. However it does provide a reasonable match for the measured velocity ratio when applied in equation 4.25. A comparison of the approaches is shown in Figures 4.18 and 4.19.

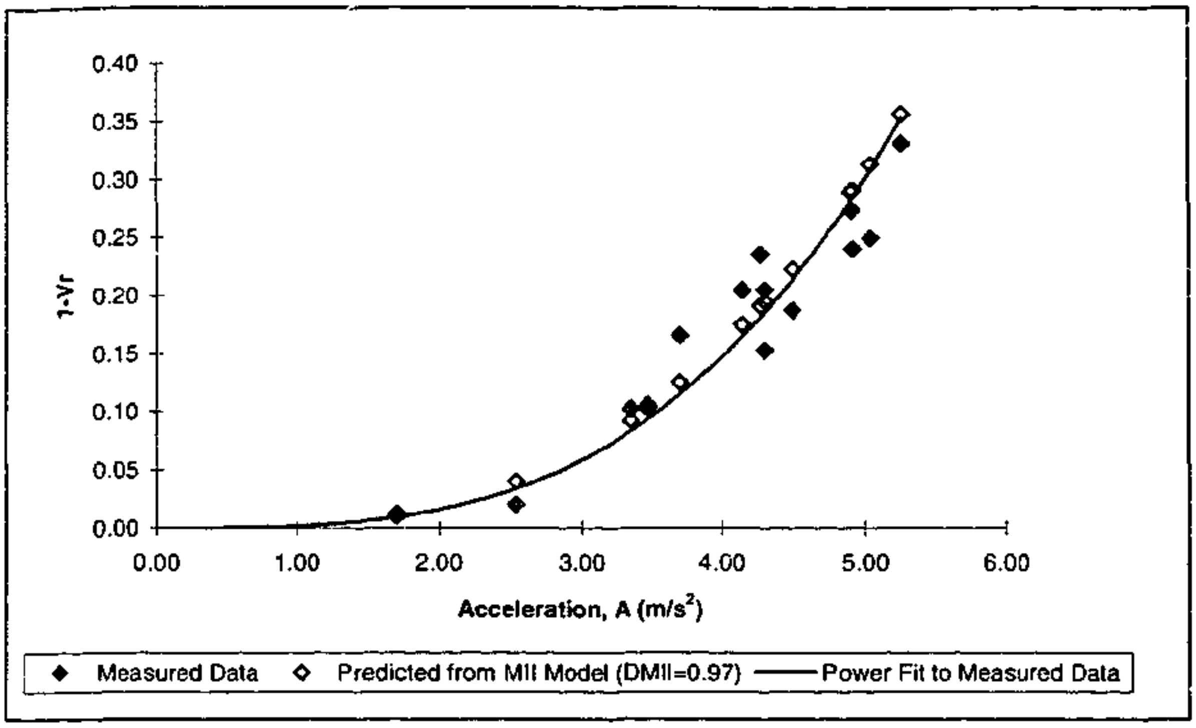


Figure 4.17 Predicted Velocity Ratio as a Function of Lateral Acceleration

Based on a Constant Failure Duration (D_{MII} = 1sec) and the Least Squares Power Fit to Motion Induced Interruption Rate.

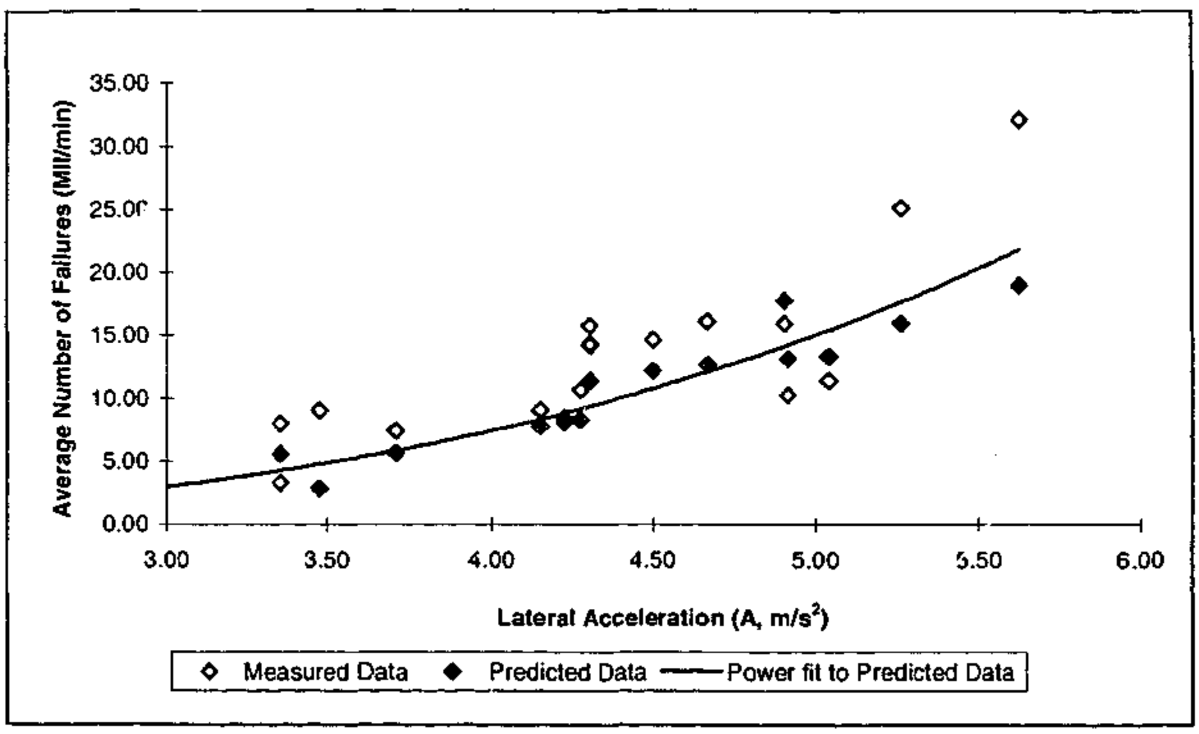


Figure 4.18 MII_{RATE} as a function of Lateral Acceleration (Probabilistic Approach)

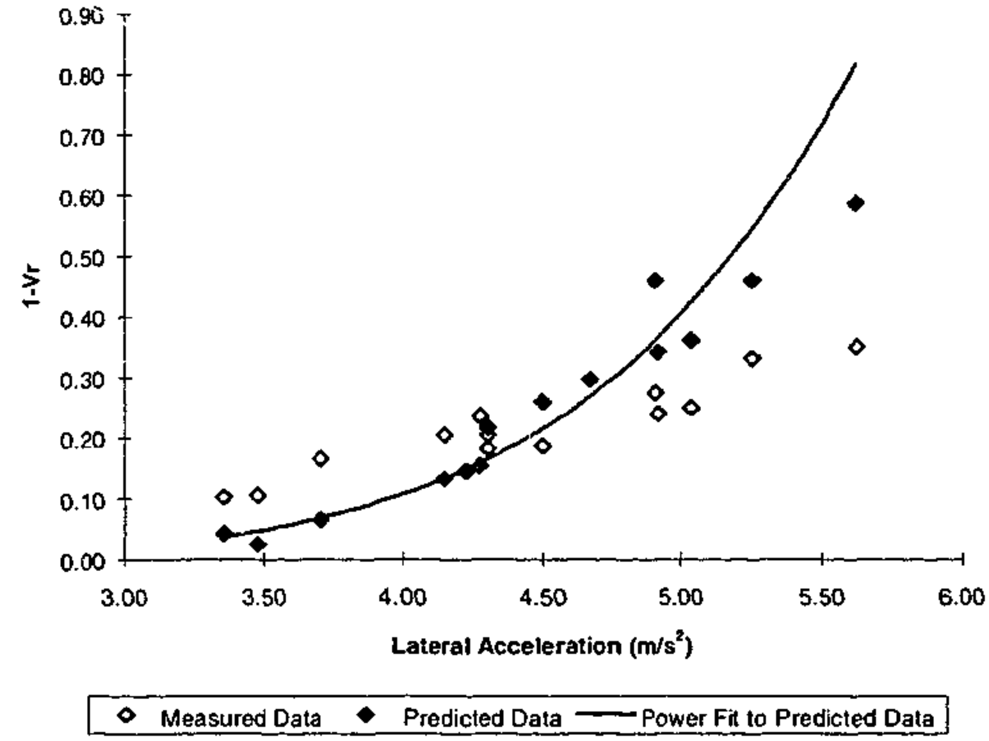


Figure 4.19 Velocity Ratio as a function of Lateral Acceleration

(Probabilistic Approach)

4.4.4 Comparison of Findings with Published Data

The reduction in walking speed as determined in this thesis is compared against the performance degradation for a range of alternative maritime operational tasks that have been previously published in Figure 4.20. Typical operational tasks assessed include the following as defined by Crossland and Rich (2000):

- Standing aft;
- Loading;
- Standing arms aloft;
- Standing athwartships.

Hosada and Kunitake (1985) broke down tasks into 'heavy' and 'light' work. Cox and Lloyd (1977) report the degradation in performance due to 'Roll.' Schreckenberg et al (2001) also provided an empirical approximation fo performance degradation due to roll up to 20°.

All the approaches described in published literature to date overestimate significantly the impact of vessel motions and capsize on the degradation of walking speeds. Recently Bles, Nooy and Boer (2001) published findings of similar evacuation trials as those conducted within this thesis. It is noted that the trials consisted of less people and less severe environmental conditions as those assessed herein. Furthermore path lengths were smaller as were corridor widths. A comparison of the data by

Bles, Nooy and Boer (2001) with the data collected for this thesis is provided in Figure 4.21. The data by Bles, Nooy and Boer (2001) exhibits a greater impact of motions and capsize on walking speeds than observed in the data obtained for this thesis. The difference between the results is most likely due to the following differences in facility set up and test procedures.

- The facility by Bles, Nooy and Boer (2001) only had approximately 1.6m of corridor length where walking speeds are measured. Accordingly the walking acceleration and deceleration may have an increased impact on overall performance. Conversely the work in this thesis is based on a walking distance of 7.5m of walking length.
- It appears as though the procedure by Bles, Nooy and Boer (2001) is based on volunteers having the same psychological and motivational status for the normal walking case (static horizontal deck) and the dynamic case (capsizing moving deck). The work conducted in this thesis was aimed at attempting to include changes in the psychological and motivational status of passengers between the static non-evacuation condition on a horizontal surface and the dynamic/capsizing emergency condition during evacuation. Accordingly many volunteers walked casually for the normal condition and walked with purpose but safely in the 1st MATE facility under dynamic conditions. Accordingly, for less extreme environmental conditions many passengers walked faster than their on land walking speed.

It is considered that the work in this thesis is therefore more 'realistic,' than the work by Bles, Nooy and Boer (2001) and accordingly more suitable for the application of proving the hypothesis posed for this thesis. Despite this, the work by Bles, Nooy and Boer (2001) provides a suitable conservative estimate for less extreme environmental conditions and in particular emphasises the influence vessel motions on egress through confined spaces. It is further noted that the work by Bles, Nooy and Boer (2001) extends egress through stairs and in pitch motions. Based on the findings in this thesis, the work by Bles, Nooy and Boer (2001) on pitch motions and stairwell can be reasonably extrapolated to more extreme conditions not previously tested.

The acceleration threshold due to coefficients of friction of 0.3, 0.5 and 0.7 are documented in Figure 4.22. Section 4.1 presents a discussion of the range of coefficients of friction with 0.2-0.4 representing wet, highly slippery deck, 0.5 representing the typical requirement for on land structures and 0.7 as the typical requirement for a dry naval deck. The observations of the performance of passengers indicated that a predominant cause of failure for the majority of tests was tipping rather than sliding. However for the most severe conditions tested and for passengers with leather sole shoes many passengers were slipping. Figure 4.22 shows that for a coefficient of friction of approximately 0.5 slipping would only be expected for the most severe condition tested which is consistent with the visual observations made during testing.

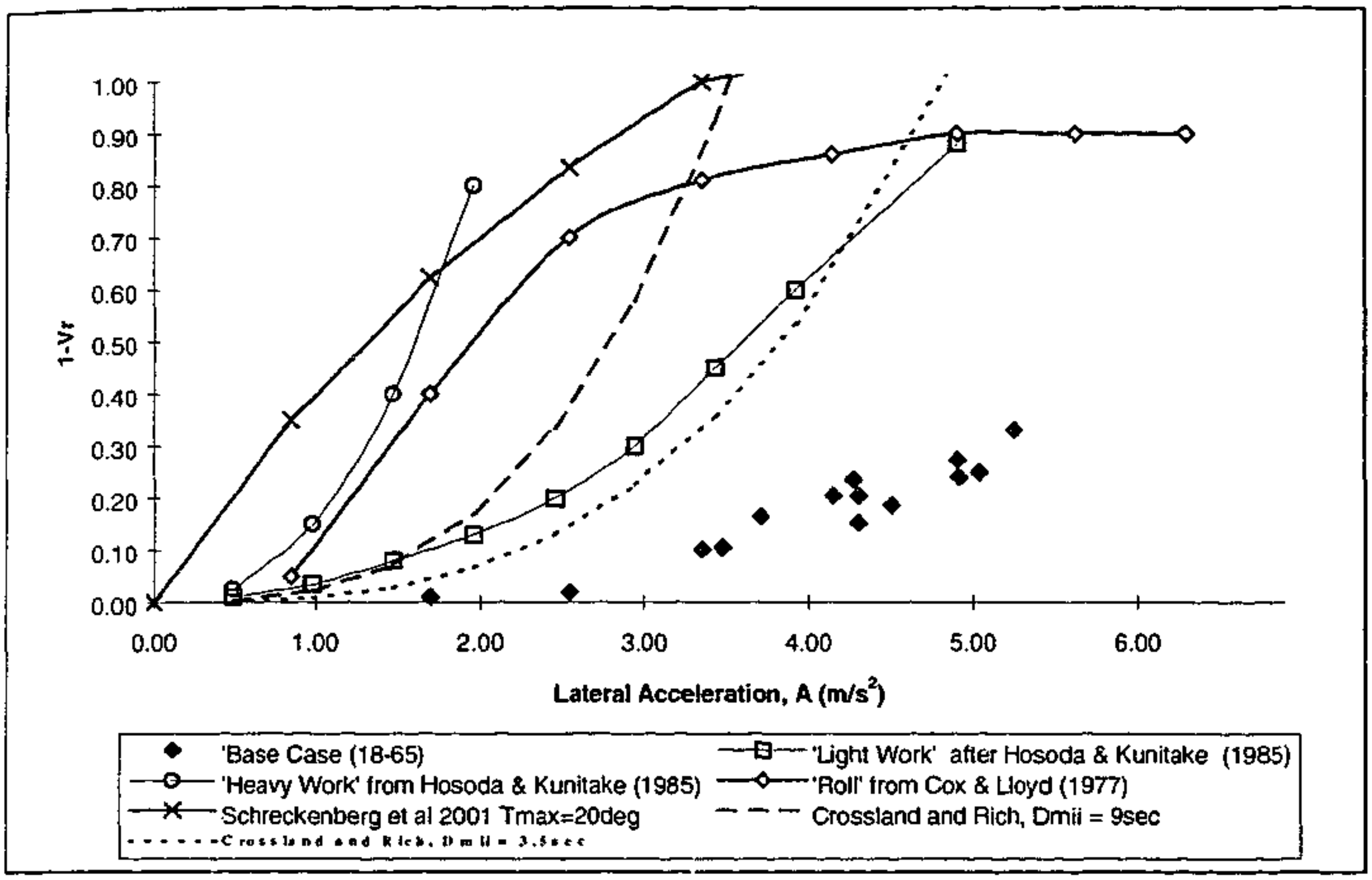


Figure 4.20 **Comparison of Velocity Ratio Degradation with Published Data**

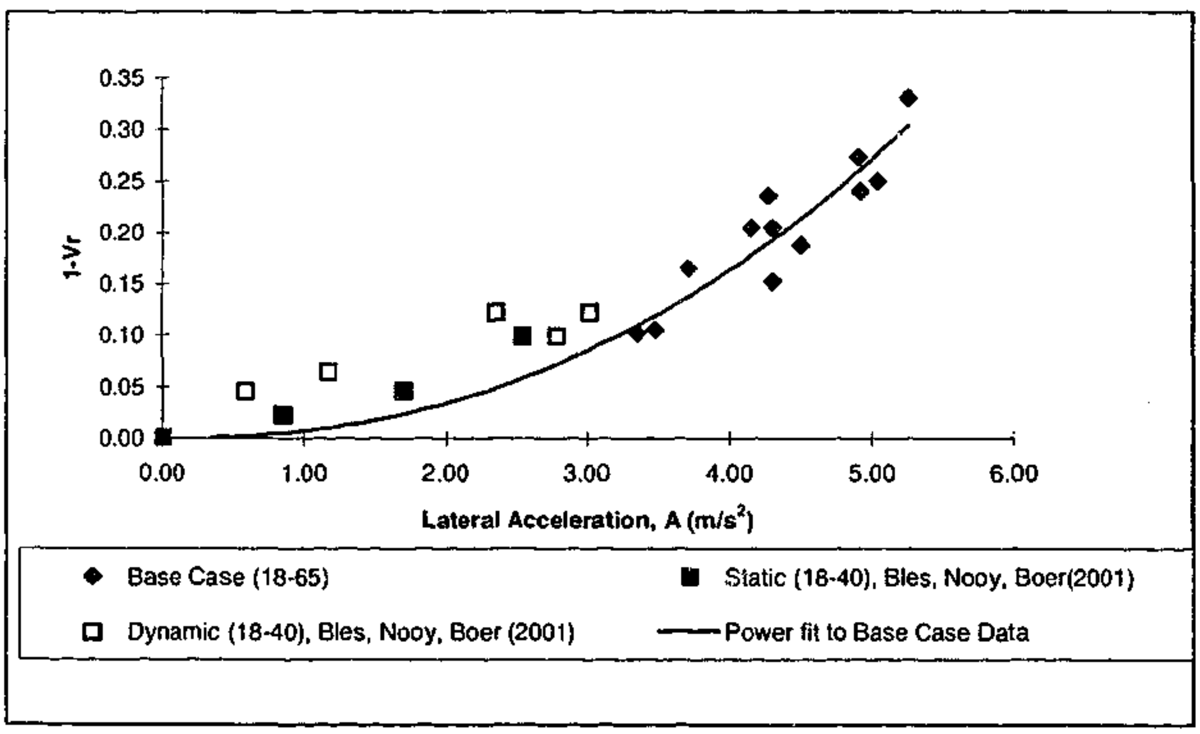


Figure 4.21 **Velocity Ratio Determined from Bles, Nooy and Boer (2001)**

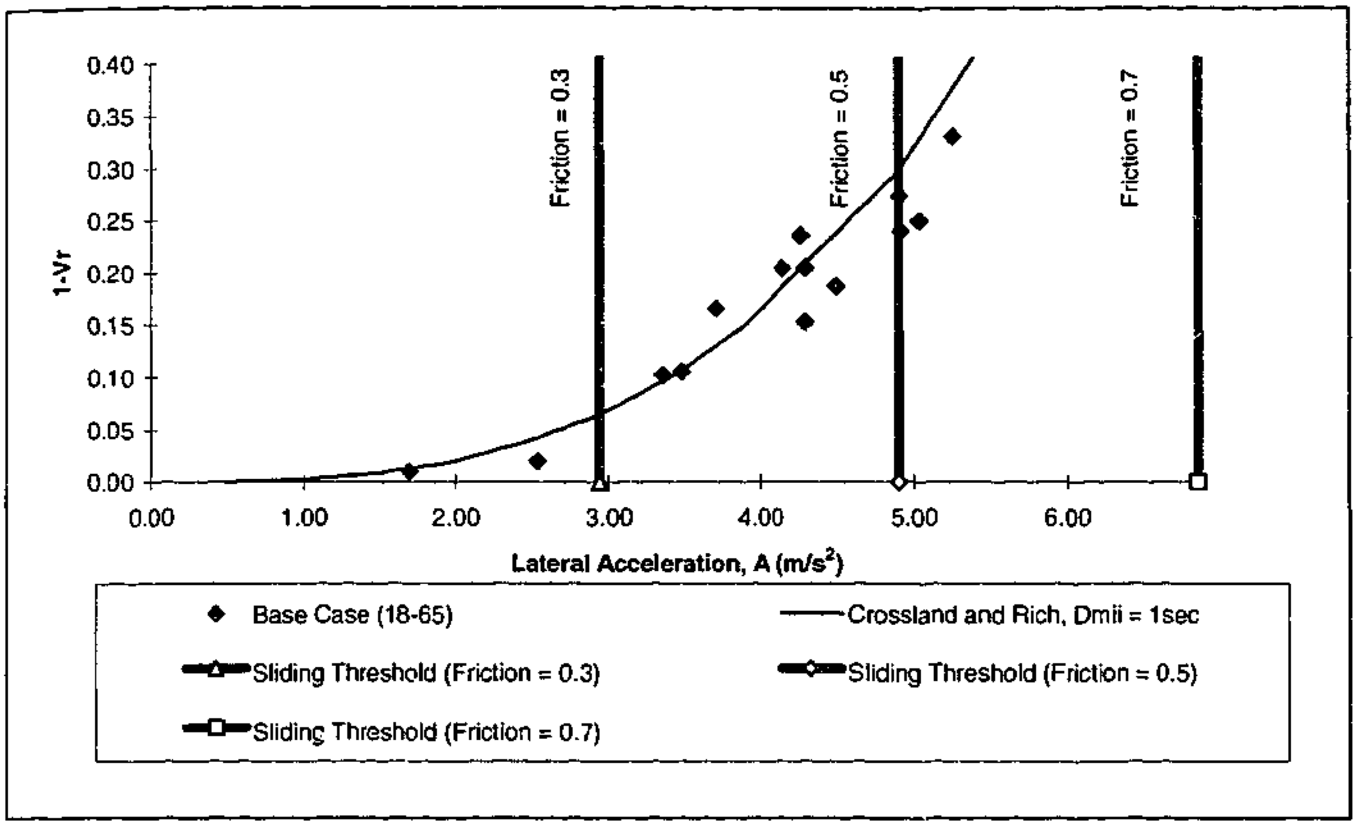


Figure 4.22 Acceleration Thresholds due to Surface Coefficients of Friction 0.3, 0.5 and 0.7

4.5 SUB-CONDITIONS

Four sub-conditions have been assessed through the motor ability trials. These have been identified and discussed in Section 4.2.2.1. A comparison of these sub-conditions using the student T test indicated that there was a noticeable statistical difference between the mean walking speeds of each of the sub-conditions tested. This difference is documented in Table 4.5.

Table 4.5	**Comparison of Subconditions**			
General Statistics				
Subcondition	*1*	2	*3*	*4*
Mean Vr	0.813	0.834	0.776	0.817
Standard Deviation	0.221	0.236	0.248	0.269
Paired Student T Test				
Comparison	*1 : 2*	*1 : 3*	*2 : 4*	*3 : 4*
T statistic	-4.382	4.936	2.186	-7.445
Significance Level	>0.01	>0.01	>0.05	>0.01
Ratio	0.98	1.05	1.02	0.95
Note: Sample size was limited to 650 volunteers from over 15 conditions. Where there was data missing from any particular sub-condition the sample was removed. For confidence level = 0.05, $t_{critical}$ = 1.796; = 0.01, $t_{critical}$ = 2.718				

The T statistics indicate that the hypothesis that "the difference between the mean of any of the sub-conditions is zero (i.e. that the differences observed are merely due to random error)" should be rejected. It is therefore accepted that the following hypotheses in the capsizing ship environment is statistically valid:

- The combined existence of an exit, horizontal references and limited experience can increase the walking speed of evacuees (by 2-5%);
- The removal of supporting structures (such as handrails and kick rails) will reduce walking speeds (by 2-5%).

Other observations are as follows:

- The best sub-condition (highest recorded velocity ratios) is where the person has both the availability of supporting structures combined with the existence of an exit, horizontal references and some experience. (Subcondition 1, SC1, mean Vr = 0.83);
- The worst sub-condition where none of the above conditions exist (Subcondition 3, SC3, mean Vr = 0.78).

It is noted that for subcondition 3, the volunteers have had some limited experience within the motion simulator (1st mate) where they have had access to the handrails (i.e. sub-conditions 1 and 2). Although the velocity ratio for sub-condition 3 is the lowest of all categories tested, there is the potential for the mean velocity ratio to be lower (i.e. where the evacuee has no experience at all and has no access to handrails). Due to safety testing protocols this more severe sub-condition was unable to be tested.

However it may be argued that the passengers would have the opportunity to gain experience to the same level as that tested within the first few wave cycles of the evacuation process. Accordingly, over the duration of the evacuation the associated error in total evacuation time would be minimal. In addition the evacuee may even increase walking speeds further after the first few wave cycles (due to refinement in walking style/increased confidence) such that the estimates provided through the testing program provide a conservative estimate for design purposes.

For the purposes of analysis of the velocity ratio, Vr, as a function of the environmental conditions, Er or A, the measured velocity ratios of all the sub-conditions have been combined. That is,

$$Vr_{average} = (Vr_{SC1} + Vr_{SC2} + Vr_{SC3} + Vr_{SC4})/4 \qquad (4.33)$$

The basis for combining the velocity ratios of the sub-conditions is to reduce experimental error as well as to simplify the design procedure. Where the evacuation designer is required to explicitly model the sub-conditions tested it is recommended that the empirical formulae developed be modified by a sub-condition 'performance' factor, ξ_{SCi}.

This is stated as follows:

$$Vr_{SCn} = \xi_{SCi} . Vr_{total.} \qquad i = 1,2..4 \qquad (4.34)$$

Where $\xi_{SC1} = 1.00$

$\xi_{SC2} = 1.03$

$\xi_{SC3} = 0.96$

$\xi_{SC4} = 1.01$

The above performance factors were derived directly from the mean velocity ratios for the entire observed data set and not derived as the mean of the volunteer performance factors.

4.6 CASE STUDIES

It is recognised that passengers of cruise ships and ferries will include members of the population outside the range of the base case population range tested. In addition it is also recognised that these individuals may have considerable potential to interact with other passengers such as to impact significantly on overall evacuation times. These individuals were excluded from the regular testing schedule on health and safety grounds. However focussed case studies were performed to provide a means of estimating the degree of variability from the normal population to the 'high risk' passenger categories. The case studies focussed on the elderly, disabled and the guardian's of infants. Other case studies included the influence of group interaction and physiological factors. In addition the influence of gender was also assessed.

The case studies conducted fit broadly into the following three categories:

- Physical Factors - While there are many physical factors that can influence the ability of passengers to egress in a sinking ship condition only three can be readily identified from vessel passenger records as follows:
  - Age,
  - Gender,
  - Disability;
- Interaction – In addition to the physical parameters of the individual the interaction between people may also influence the motor ability performance of evacuees. Two case study trials were established to identify the influence of interaction between individuals as follows:
  - Adult - Adult Interaction,
  - Adult - Infant Interaction;
- Physiological Factors

4.6.1 Physical Factor: Age

The passenger mobility trials conducted as part of this research program focussed on participants from 18 to 65 years of age due to University Ethics Committee requirements. The goal of the base case program was to assess a high volume of volunteers to increase the confidence in mobility statistics and to provide a sound basis for the development of ship evacuation models. However, it is recognised that passenger vessels often have to cater to elderly passengers (>65) and in many cases focus on elderly passengers as core business. Figure 4.23 indicates the difference between the age distribution of the mobility test participants and the age distribution of an overnight ferry with sleeping quarters operating in Australian waters (vessel capacity > 1000 passengers). The comparison provides evidence of the noticeable difference in age distributions between the two cases. Accordingly, a focussed case study was conducted to identify the influence of vessel motions on a limited number of able-bodied elderly passengers.

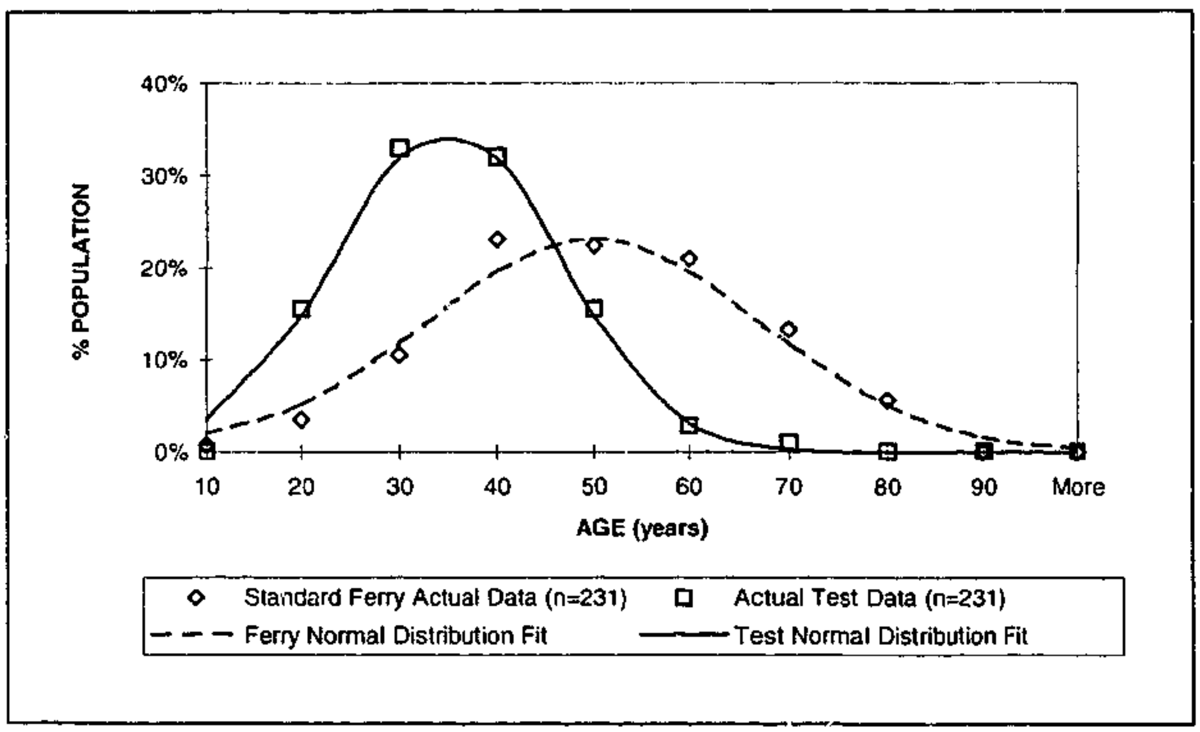


Figure 4.23 Age Distribution of Ferry Passengers and Test Participants

A small sample of fit elderly citizens (members of a bush dance club) aged between 65 and 80 were assessed for a range of environmental conditions as presented in Figure 4.24. The tests indicated that maritime specific environmental conditions significantly influence the motor ability of the elderly passengers tested. In addition the elderly passengers (aged 65-80) were influenced more considerably than the bulk population tested (aged 18-65). It is interesting to note that the gradual worsening of performance against environmental force factor was not noted for the elderly population. It appears that the elderly population are considerably influenced by mild conditions and settle to a perceived 'safe walking speed limit'. Once this 'safe walking speed limit' is achieved the elderly do not appear to compensate further even for worsening conditions. The elderly 'safe walking speed limit' appears to intersect with the walking speed reduction factor of the base case population (aged 18-65) at the most severe conditions tested.

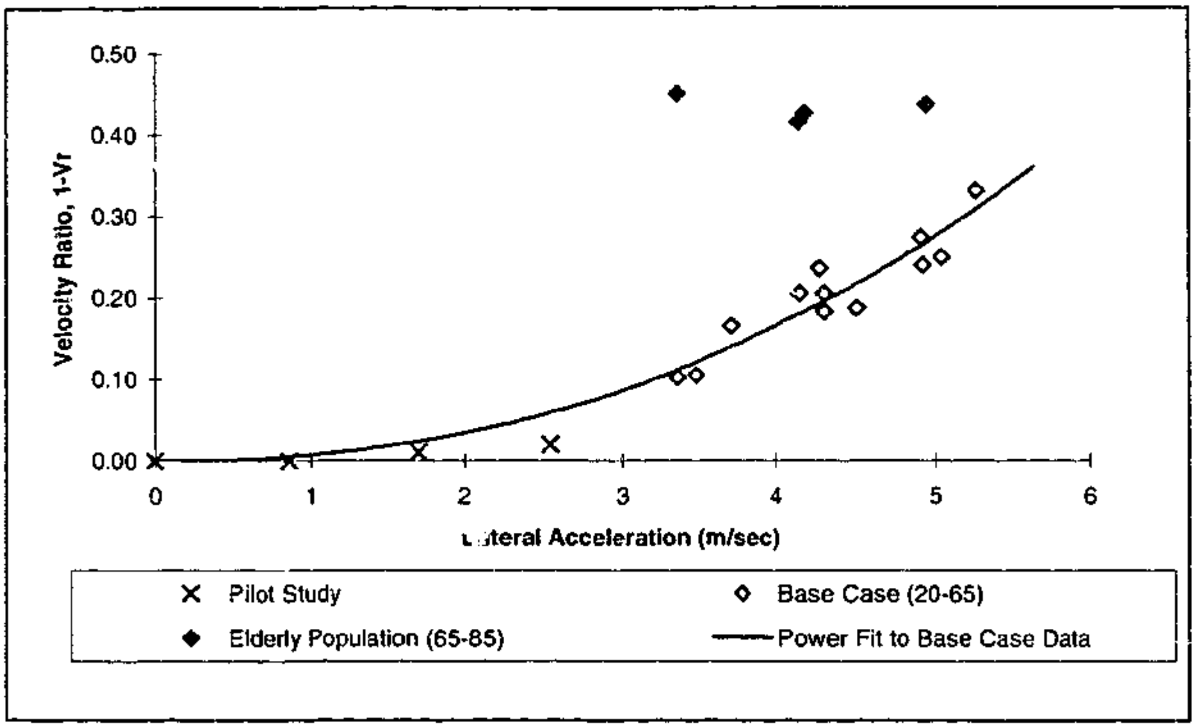


Figure 4.24 Motor Ability of Elderly in a Dynamic Environment

To quantify the influence of age on walking speeds in a dynamic environment, the reduction in walking speed with age for the entire population tested was assessed. Due to testing requirements very few participants were tested for a range of conditions. That is, for the majority of the tests each volunteer was only subject to one environmental condition. To allow for consideration of the bulk of the data gathered in the assessment of age impact, the dynamic walking speed for each environmental condition was normalised using the mean velocity ratio (refer equation 4.32). For conditions where only a specific age subset was considered (i.e. the elderly group aged 65-80) the normalised dynamic velocity would be biased by the age distribution if the 'measured' mean velocity ratio were used. Accordingly 'predicted' mean velocity ratio (based on equation 4.32) was used to normalise the dynamic walking speed. That is,

$$\overline{V\delta}_{m,n} = Vd_{m,n} / Vr_{Mllm} \qquad (4.35)$$

Where,

$\overline{V\delta}_{m,n}$ = normalised dynamic velocity (for condition m, person n)

$Vd_{m,n}$ = dynamic velocity (for condition m, person n)

Vr_{MHm} = predicted mean velocity ratio, (for condition m)

= $1\text{-}0.001423.A_m^{3.335}$ (refer Equation 4.26)

$\overline{Vr_m}$ = measured mean velocity ratio, (for condition m)

= $\sum_{n=1}^{i} Vd_{m,n}/Vs_n$

$\overline{Vs_n}$ = static velocity, level ground (for person n)

A_m = lateral acceleration (for condition m)

An assessment of the normalised dynamic velocity for the population aged 18-65 indicated only a minor influence on motor ability due to age variation. Figure 4.25.

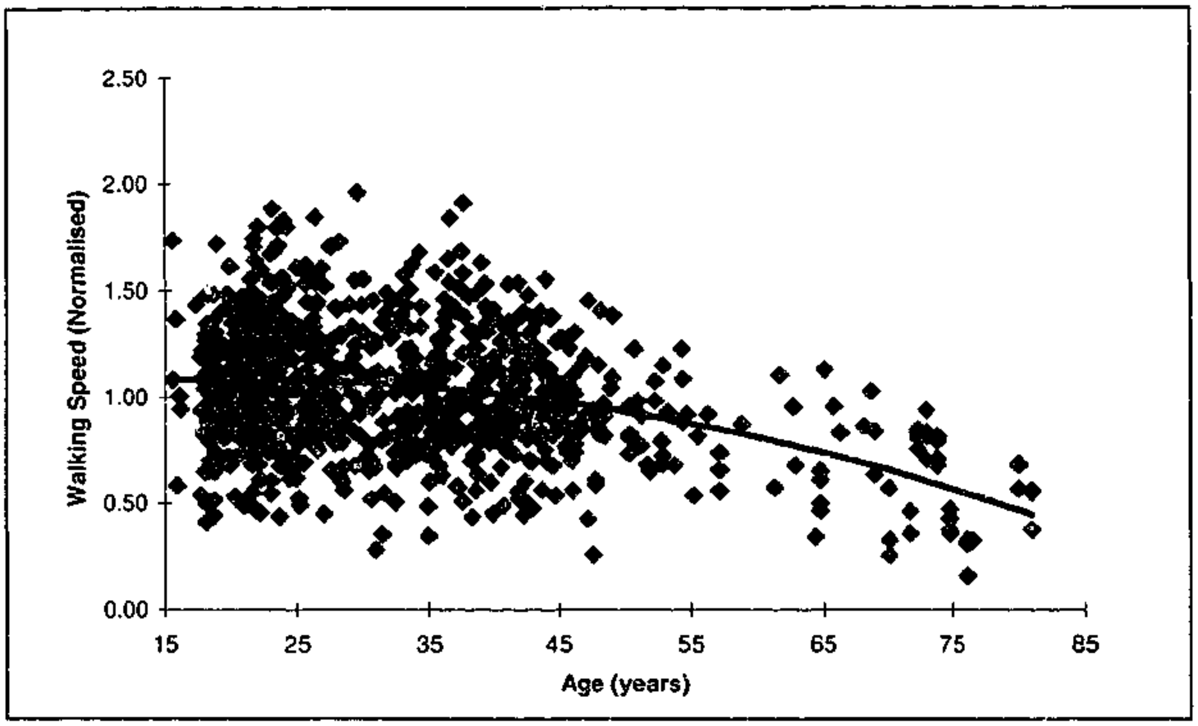


Figure 4.25 Influence of Age on Motor Ability in a Dynamic Environment (n=730)

However when the participants from the elderly case study are considered a gradual downward trend with increasing age is observed. This trend is shown in Figure 4.26 along with the change in static walking speed with age for comparison. For Figure 4.26 the normalised dynamic and static walking speed has been averaged based on the bins designated in Table 4.6.

Table 4.6	Influence of Age on Walking Speed			
Bin	Age	Count	Average Normalised Walking Speed	
			Static	Dynamic
1	< 25	316	1.01	1.08
2	25-40	336	1.01	1.05
3	40-55	182	0.99	0.97
4	55-70	28	0.92	0.75
5	70-85	34*	0.85	0.57

* Up to four conditions per individual (12 individuals only)

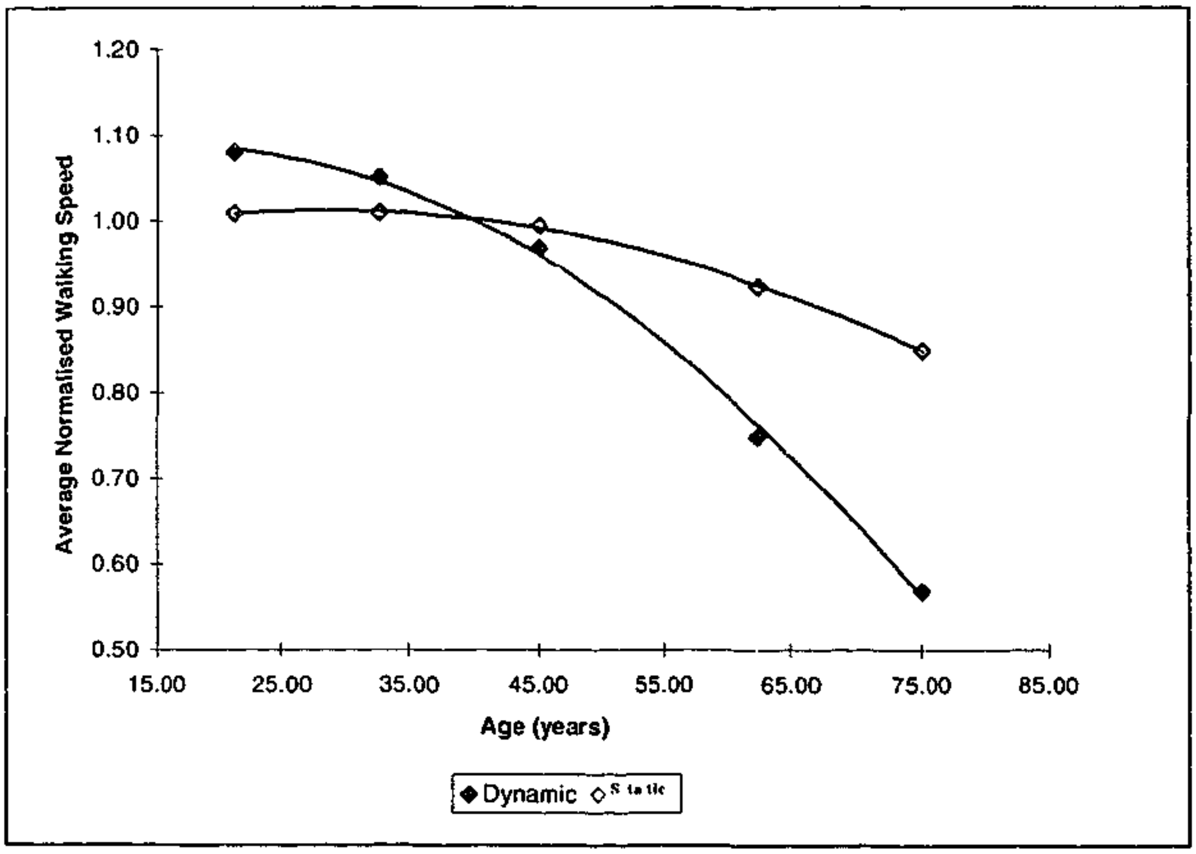


Figure 4.26 Influence of Age on Performance

The polynomial least square equation of best fit for the influence of age on velocity ratio is as follows:

$$\xi_{age} = Vr_m/Vr_{m=0} = -0.000169\ Age_m^2 + -0.00661\ Age_m + 1.021 \qquad (4.36)$$

Where, Age = mean age of the population (years)

A Student T test was conducted to determine whether there is a statistically significant difference between mean velocity ratio data observed for the elderly population and the velocity ratio predicted based on equation 4.32. The analysis indicated that for the mid range lateral acceleration conditions (conditions 3.3-4.2) there is a significant difference between the mean velocity ratio predicted from equation 4.32 and the mean velocity ratio determined for the elderly population (based on a significance level of 0.05). The results of the Student T test are presented in Table 4.7.

Table 4.7	**Elderly Walking Speed versus Predicted Walking Speed**			
General Statistics				
Condition	*1*	*2*	*3*	*4*
Mean Velocity Ratio (Vr)	0.571	0.584	0.555	0.556
Standard Deviation (S)	0.099	0.154	0.138	0.165
Lateral Acceleration (A, m/s^2)	3.36	4.19	4.15	4.94
Predicted Vr (Eqn 4.26)	0.919	0.831	0.837	0.706
Sample Size (n)	12	11	10	6
Student T Test: $Vr_{elderly} \neq Vr_{base}$				
T statistic (T)	12.167	5.329	6.453	2.239
Significance Level (α)	>0.05	>0.05	>0.05	>0.05
T critical ($t_{\alpha/2}$)	2.593	2.634	2.685	3.163
Is $T > t_{\alpha/2}$?	✓	✓	✓	×

4.6.2 Physical Factor: Gender

65% of the volunteers for the motor ability tests were male. Analysis of the results of 970 adult males and females for 21 different conditions indicated that males had an average dynamic walking speed that is faster than females. Table 4.8 provides results of the Student T test based on the gender of the participants. The analysis indicates that the hypothesis (i.e. that the male walking speed is equal to the female walking speed) may be rejected for all sub-conditions and the combined condition at the 0.01 level of significance. Accordingly the true mean walking speed of males is likely to be greater than the walking speed of females in a dynamic environment.

Table 4.8	**Male Walking Speed versus Female Walking Speed**				
General Statistics (Vr_{male}/Vr_{female})					
Condition	*SC1*	*SC2*	*SC3*	*SC4*	*all*
Average Ratio	1.12	1.16	1.11	1.10	1.13
Maximum Ratio	1.39	1.38	1.35	1.35	1.26
Minimum Ratio	0.95	0.98	0.81	0.91	0.97
Standard Deviation (S)	0.116	0.114	0.144	.110	0.090
Sample Size (n)	21	21	19	19	21
Student T Test: $Vr_{male}/Vr_{female} \neq 1$					
T statistic (T)	4.58	6.42	3.23	3.99	6.47+
Significance Level (α)	>0.01	>0.01	>0.01	>0.01	>0.01
T critical ($t_{\alpha/2}$)	3.15	3.15	3.20	3.20	3.15
Is $T > t_{\alpha/2}$?	✓	✓	✓	✓	✓

The total velocity ratio may be described by the female and male velocity ratios as follows:

$$Vr = G.Vr_{male} + (1-G).Vr_{female} \quad (4.37)$$

Where, G = % population tested that is male

$= N_{male} / N_{total}$

Based on the ratio presented in Table 4.8 ($Vr_{male} / Vr_{female} = 1.13$) the equation 4.37 may be written as follows:

$$Vr = 1.13G.Vr_{female} + (1\text{-}G).Vr_{female} \quad (4.38)$$

$$= Vr_{female}\,(0.13G+1)$$

The base case investigations on mobility were conducted with an overall gender distribution of 60% male to 40% female (G_0=60%). On the basis of the base case gender distribution and equation 4.38 the following equation may be used to convert from the base case conditions (subscript 0) to a different gender distribution (subscript i):

$$\xi_{gender} = Vr_i / Vr_0 = Vr_{female}\,(0.13G_i+1) / Vr_{female}\,(0.13G_0+1) \quad (4.39)$$

$$= (0.13G_i+1) / (0.13x0.6+1)$$

$$= (0.13G_i+1) / 1.078$$

Accordingly,

$$Vr_i = Vr_0\,(0.13G_i+1) / 1.078 \quad (4.40)$$

4.6.3 Physical Factor: Disability

A case study was performed on a single 23-year-old paraplegic with a L1 (Lumber one) incomplete spinal injury. The individual represents a fit and agile wheel chair user and has represented Australia in wheelchair basketball. The wheel chair is described as a super light sports chair designed for agility and control. The case study represents an upper bound estimate for evacuation of paraplegics in maritime conditions. The study identified that wheelchair operators are influenced significantly more by maritime environmental conditions than the able bodied population. Figure 4.27 indicates that the upper bound estimate of wheel chair operator performance based on an array of static and dynamic conditions is significantly less than the mean population performance for a similar range of condi s.

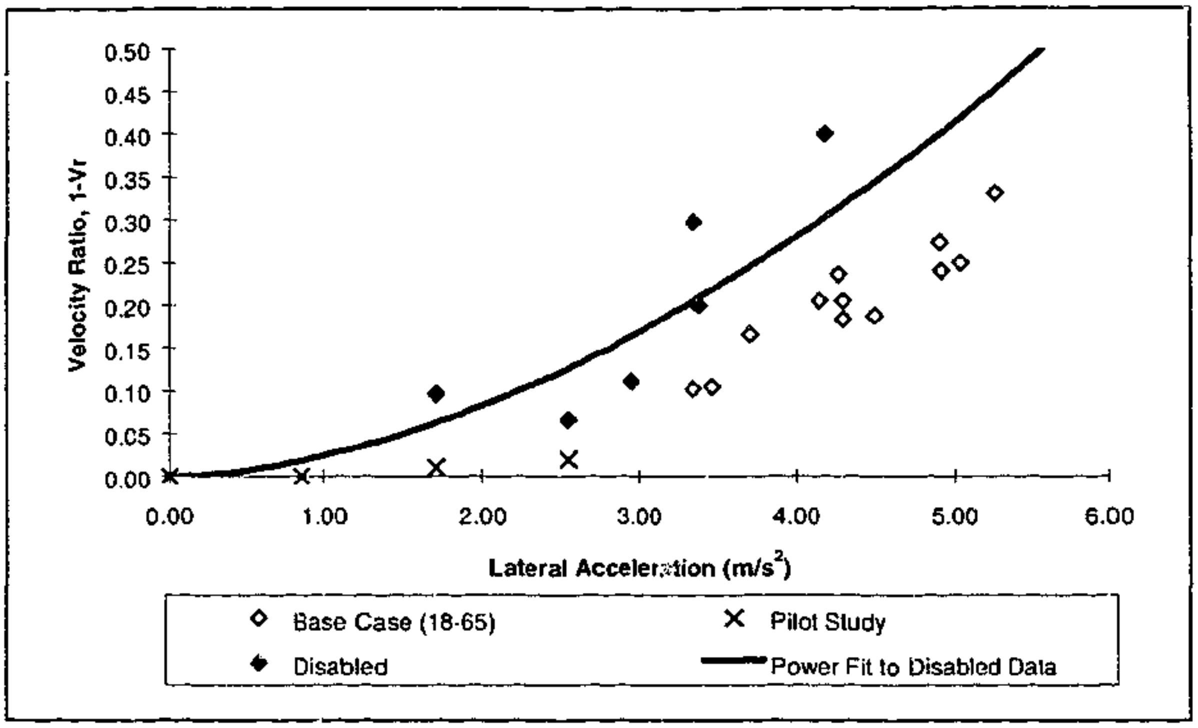


Figure 4.27 Upper-bound Motor Ability of Disabled in a Dynamic Environment

4.6.4 Interaction: Adult-Adult

Adult-Adult interaction includes counter and group flow as a function of population density. The following two scenarios were assessed to identify the influence of group flow and counter flow:

Case 1: Static List = 30°, Roll Amplitude = 0°,
Lateral Acceleration = 4.91m/s^2,
Number of People = 44

Case 2: Static List = 25°, Roll Amplitude = 5°, Frequency = 3 Hz,
Lateral Acceleration = 5.26 m/s^2
Number of People = 38

The trials were conducted for the following approach arrangements:

Approach 1: Approach 1 consists of a single person in the forward direction, with no people in the opposing direction. This approach arrangement is the base case arrangement adopted for all the tests completed. The total number of people involved in this encounter is one.

Approach 2: Approach 2 consists of a single person in the forward direction, with a single person in the opposing direction. The total number of people involved in this encounter is two.

Approach 3: Approach 3 consists of a two people in the forward direction, two people in the opposing direction. The total number of people involved in this encounter is four.

Approach 4: Approach 4 consists of a two people in the forward direction, and no people in the opposing direction. The total number of people involved in this encounter is two.

Approach 5: Approach 5 consists of a four people in the forward direction, and no people in the opposing direction. The total number of people involved in this encounter is four.

Group flow trials are classified as the condition with multiple people walking in same direction with no people in the opposing direction (i.e. approaches 1, 4 and 5). Counter flow trials include scenarios with people approaching in the opposing direction (i.e. approaches 2 and 3). The findings are presented in Table 4.9 and Figure 4.28

Table 4.9	**Group and Counter Flow**							
	Population		Velocity Ratio		Case Normalised Velocity Ratio		Equivalent Static Velocity = Vr x 1.4m/s	
Case	#/test	Density (ρ)	1	2	1	2	1	2
Approach 1 (Single)	1	0.44	0.81	0.86	1.00	1.00	1.40	1.40
Approach 2 (Counter)	2	0.53	0.74	0.78	0.91	0.90	1.28	1.265
Approach 3 (Counter)	4	1.07	-	0.68	-	0.79	-	1.11
Approach 4 (Group)	2	0.89	0.68	73	0.84	0.85	1.18	1.19
Approach 5 (Group)	4	1.78	-	59	-	0.68	-	0.95
Notes: Density determined from equation 4.41.								

The population density was determined as a function of the non-encounter and encounter lengths as well as the corridor width. The encounter length is the length over which the counter flow interaction is anticipated to occur. The non-encounter length is the length over which no counter flow interaction is anticipated to occur. For the 7.5m walkway and a single encounter event, the encounter length was estimated at 1.5m long. The non-encounter length was therefore 6m long. Where there was no counter flow the non-encounter length was 7.5m long. Accordingly the density was determined as follows:

$$\rho = \delta/(\delta+\zeta)\, n_g/(\zeta w) + \zeta/(\delta+\zeta)\, (n_c + n_g)/(\zeta w) \qquad (4.41)$$

Where, ρ = average density over the length of the corridor

δ = non-encounter length

ζ = encounter length

w = width of corridor

n_g = number of people walking the same direction as the individual under examination

n_c = number of people walking the opposing direction as the individual under examination

The population density used for this analysis is presented in Table 4.9.

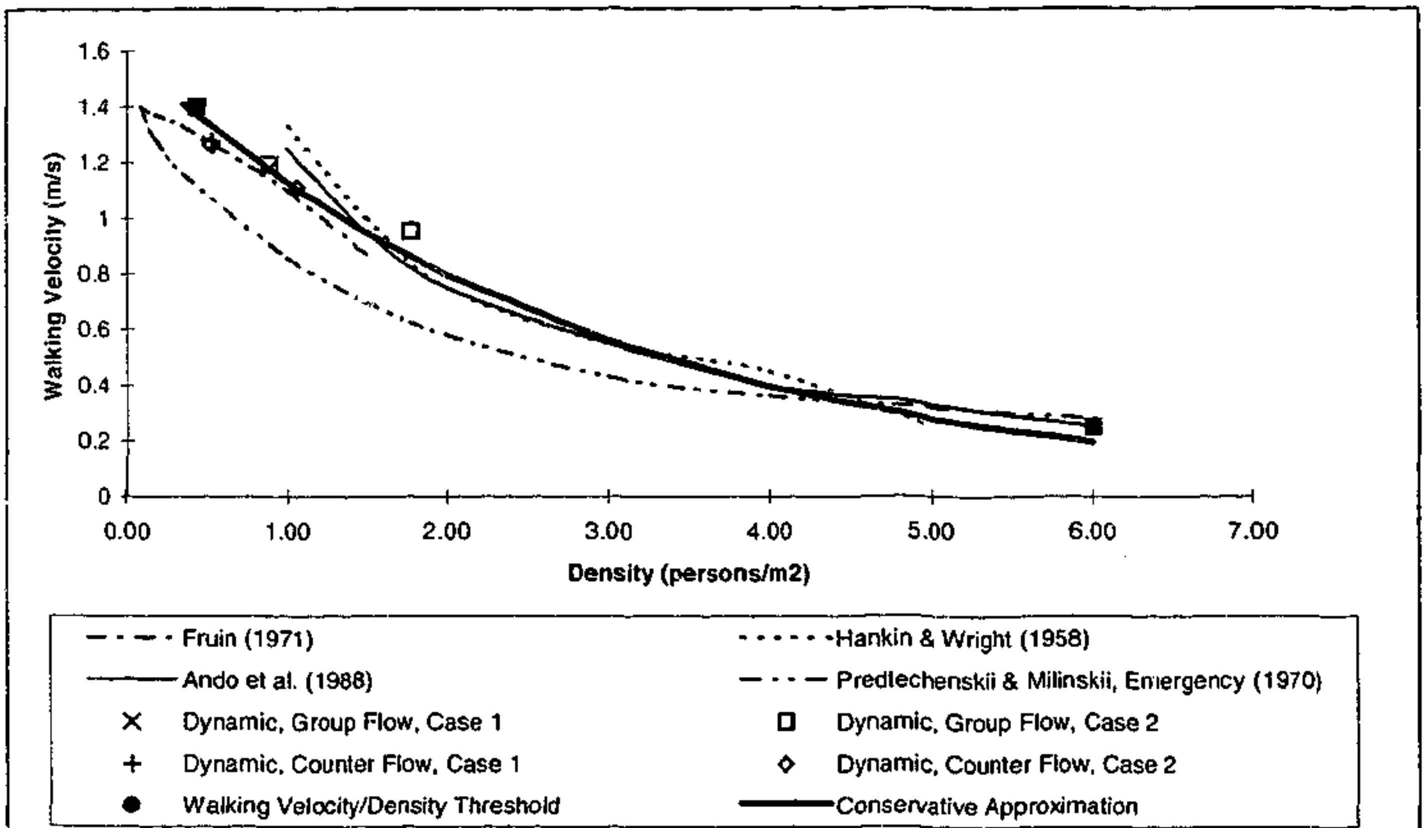


Figure 4.28 Counter and Group Flow in a Dynamic Environment

Figure 4.28 presents the walking velocity of the population as a function of population density in the dynamic/capsizing environment for group and counter flow. The figure also presents the walking speed as a function of population density for static flat walking conditions as collated by Thompson &

Marchent. The comparison indicates that mean walking velocity of a population is more sensitive to population density in a dynamic, capsizing environment than on a static, horizontal surface in the group flow scenario for small crowd densities. The curve describing walking speed in the dynamic conditions intercepts the curve developed by Ando et al (1988) and Hankin & Wright (1958) for static/horizontal conditions at a density of approximately 1.5 people/m^2. For densities greater than this it is anticipated that group flow trends in the dynamic environment will not exceed that determined for static/horizontal conditions.

The estimate of walking velocity for a horizontal flat surface as predicted by Fruin (1971) for (presented by Thompson & Marchent) provided a good match with the mean walking speed in dynamic/capsizing conditions as determined by in this thesis for counter flow conditions.

It is noted that the work by in this thesis does not extend to high-density populations. For the purposes of comparison it has been assumed that 'body arching' or jamming as described by Thompson & Marchent will occur at the same high crowd concentrations for both dynamic/capsizing and static/horizontal conditions. For the purposes of this investigation, the density at which jamming occurs will be referred to as the walking velocity/density threshold. Based on the work by Ando et al (1988), the velocity/density threshold is determined as approximately 0.25m/s at 6 people/m^2 on a static/horizontal walkway. The least squares best fit exponential curve between the observed data for the dynamic counter flow scenario (Case 2) and the velocity/density threshold identified by Ando et al (1988) has a regression coefficient $R^2 = 1$ to three significant figures. The equation of best fit is as follows:

$$\xi_{congestion} = (1.6e^{-.35\rho}) / \overline{V_n} \qquad (4.42)$$

Where, $\overline{V_n}$ = Average walking speed on static horizontal walkway (m/sec)

$\xi_{congestion}$ = Congestion performance factor

ρ = Population density (crowd/m^2)

The curve described in equation 4.42 fits the trend described by Fruin (1971) where ρ is less than 1.5 people/m^2 and the trend by Ando et al (1988) where ρ>1.5people/m^2 indicating that best fit equation to the data observed provides an adequate description of the influence of congestion on dynamic/capsizing and static/horizontal conditions.

4.6.5 Interaction: Adult-Infant

An assessment of the ability of adults to support infants (3.6kg) during the evacuation of a passenger vessel was conducted for extreme environmental conditions (35° list). Over 65 adults were tested (aged between 20 and 25) for this scenario. The study indicated that while the evacuees had difficulty maintaining stability the motor ability performance was equivalent to the motor ability without the infant present. The results are presented in Figure 4.29.

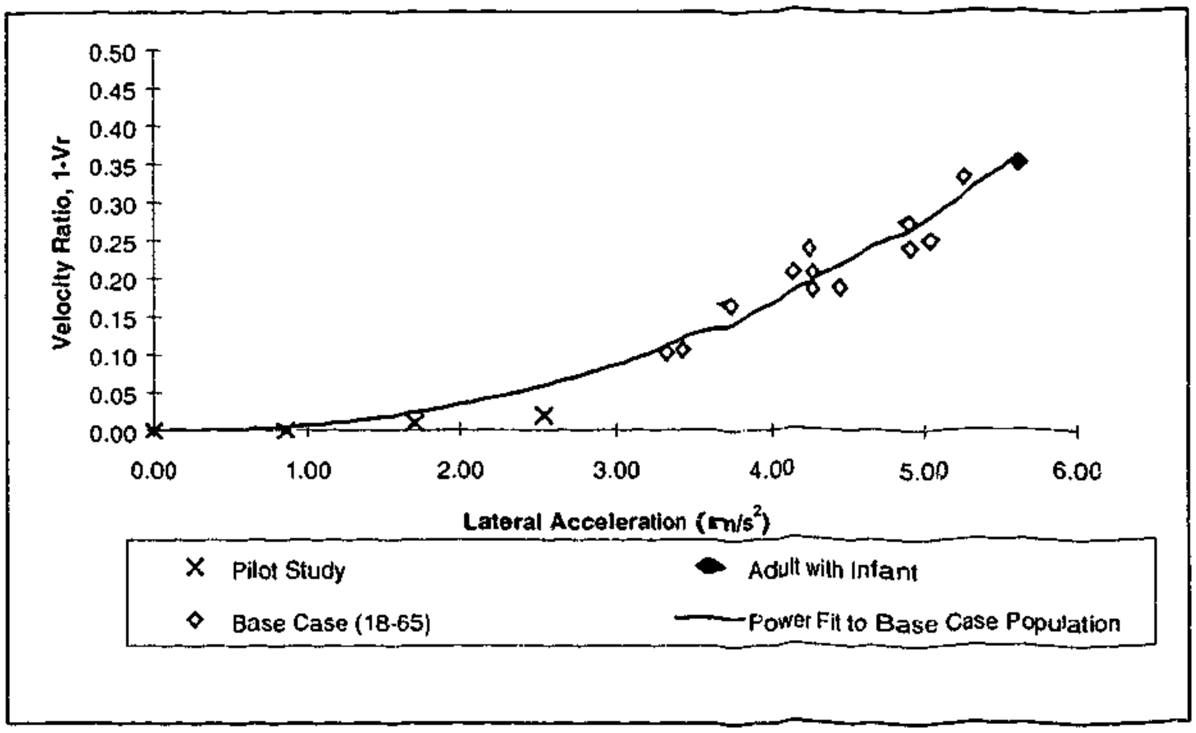


Figure 4.29 Infant Support in a Dynamic Environment

A Student T Test was conducted to confirm that the prediction of equation 4.32 for the base case scenario is suitable for use with adults carrying infants in extreme listing conditions.

Table 4.10 Infant Carrying Walking Speed versus Predicted Walking Speed		
General Statistics		
Condition	*1*	
Mean Velocity Ratio (Vr) as measured	0.65	
Standard Deviation (S)	0.165	
Lateral Acceleration (A)	5.63	
Predicted Velocity Ratio, Vr (eqn 4.32)	0.55	
Age Correction Factor, ξ_{age} (eqn 4.36) ($Age_i = 23$, $Age_0 = 32$)	1.054	
Gender Correction Factor, ξ_{gender} (eqn 4.39) ($G_i = 84\%$, $G_0 = 60\%$)	1.029	
Corrected Vr	0.60	
Sample Size (n)	67	
Student T Test: $Vr_{with\ infant} \neq Vr_{base\ case}$		
T statistic (T)	2.72381	2.72381
Significance Level (α)	>0.05	>0.01
T critical ($t_{\alpha/2}$)	2.293	2.904
Is $T > t_{\alpha/2}$?	✓	×

The Student T test indicates that the hypothesis that, 'the corrected base case equation gives the true mean for people carrying infants,' should be rejected at the 0.05 significance level but not rejected at the 0.01 significance level. Accordingly, the true mean is not likely to be predicted for people carrying infants using the corrected base case equation. However the equation provides a suitable and conservative estimate of the mean velocity ratio.

4.6.6 Physiological Parameters

Pilot studies on the 1st MATE test facilities indicated that a number of evacuees were experiencing feelings of discomfort in the moving facility. These feelings of discomfort were likened to the early stage feelings of kinetosis (or sea sickness). The propensity of different characteristic groups to develop seasickness has been well researched such that a relationship between propensity to seasickness and motor ability provides a good means of assessing evacuation performance.

The rating system used to quantify the influence of vessel motions and capsize on the above listed physiological parameters presented in Table 4.11.

Table 4.11	**Level of Physiological Symptoms Experience During Test**					
Severity Level	None	Low	Moderate	High	Very High	Extreme
Ranking, r	0	1	2	3	4	5

The overall ranking used to define the severity of symptoms for each individual is as follows:

$$R_t = \text{maximum}(r) \qquad (4.43)$$

Where, $r = r_i$

i = symptom identifier

= 1,2..5

And, 1 = Dizziness Identifier

2 = Light-headedness Identifier

3 = Claustrophobia Identifier

4 = Visual distortion Identifier

5 = General Discomfort Identifier

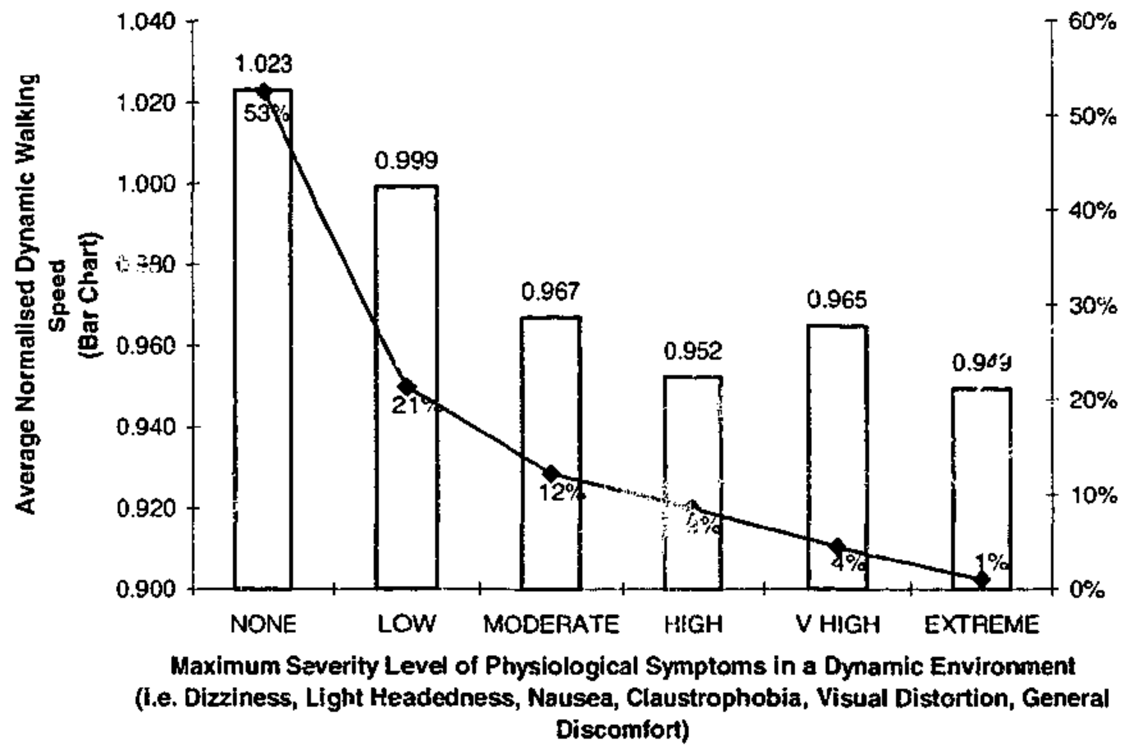


Figure 4.30 Physiological Effects in a Dynamic Environment

Figure 4.30 presents a comparison of the averaged normalised dynamic walking speed of evacuees for each severity level ranking. A least squares linear regression fit was conducted with consideration of all severity levels with over 30 volunteers. The best fit resulted with a regression coefficient R^2=0.983 and the following empirical approximation:

$$\xi_{kinetosis} = -0.0244\,Rt + 1.0219 \qquad (4.44)$$

From Figure 4.30 a general trend of decreasing normalised walking speed with increasing physiological symptoms is observed. A Student T Test was carried out between the empirical fit and the data obtained for all severity levels (including those with less than 30 volunteers). In addition a T test was also conducted to identify whether volunteers with severity levels at moderate to high levels have a different dynamic walking speed to those with low or negligible severity levels.

Table 4.12	**Comparison of Walking Speed for Increasing Seasickness Severity**					
General Statistics $\xi_{kinetosis}$						
Severity Level	***None***	***Low***	***Mod***	***High***	***V. High***	***Extreme***
Maximum Ranking	0	1	2	3	4	5
Average Normalised Dynamic Walking Speed	1.023	0.999	0.967	0.952	0.965	0.949
Standard Deviation (S)	0.235	0.239	0.214	0.219	0.204	0.104
Sample Size (n)	259	105	60	42	22	5
T critical ($t_{\alpha/2}$, α=5%)	2.25	2.27	2.30	2.33	2.41	3.50
T critical ($t_{\alpha/2}$, α=10%)	1.97	1.98	2.00	2.02	2.08	2.78
Student T Test: $\xi_{kinetosis}' = \xi_{kinetosis}$						
T statistic (T)	0.07	0.06	0.22	0.10	0.93	1.06
Is T < $t_{\alpha/2}$? (α=5%)	✓	✓	✓	✓	✓	✓
Is T < $t_{\alpha/2}$? (α=10%)	✓	✓	✓	✓	✓	✓
Student T Test: $\xi_{kinetosis}' \neq 1$						
T statistic (T)	1.57	0.04	1.20	1.42	0.81	1.09
Is T > $t_{\alpha/2}$? (α=5%)	×	×	×	×	×	×
Is T > $t_{\alpha/2}$? (α=10%)	×	×	×	×	×	×

The Student T test indicates that the true mean of the normalised walking speed is likely to be equal to that predicted by the empirical fit of equation 4.44. However the Student T test also indicates that normalised walking speed may also be described by $Vd_{R_t=i} = 1$. Accordingly the above data does not provide conclusive evidence of a difference between walking speeds based on physiological discomfort caused by vessel dynamic motions.

4.6.7 Summary of Results

The key findings relating to motor ability in the marine environment are summarised as follows:

- Linear regression provides a good fit to the velocity ratio (Vr) data measured as a function of environmental force factor (Er) and/or the lateral acceleration;
- The mean velocity ratio (Vr) of a population may be accurately estimated from the environmental force factor (Er) without the direct explicit use of the number of failures (MII_{rate}) and failure duration (D_{MII});
- A more accurate and simpler prediction of the velocity ratio (Vr) of a population may be estimated from the lateral acceleration (A) without the direct explicit use of the number of failures (MII_{rate}) and failure duration (D_{MII});
- The calculated failure duration is equivalent to the half natural period of the volunteer (D_{MII} = 1 second) providing increased confidence in the experimental approach adopted;
- Explicitly using the actual measured estimates of the number of failures, $MII_{rate}(A)$, with a constant failure duration, D_{MII}, provides a poor means of estimating the velocity ratio (Vr);
- Using empirical estimates of the number of failures, $MII_{rate}(A)$ with a constant (calibrated) failure duration, D_{MII}, provides a very good means of estimating the velocity ratio, Vr;
- The probabilistic approach provides a rational basis for consideration of human factors in the estimation of motion-induced interruptions and ultimately the velocity ratio. The approach based on failure events and failure durations indicated a reasonable match with the velocity ratio measured.
- The implication of the probabilistic approach for future applications is that it can no longer be assumed that a single failure will occur when the lateral accelerations due to a particular wave peak exceed a preset deterministic tipping threshold. The results of this thesis provide evidence that multiple failures can occur for a single exceedence of a tipping threshold and that the tipping threshold itself should be considered as a probabilistic rather than deterministic term.
- This finding has particular relevance to operational tasks for naval and commercial operations as assessed by Crossland and Rich (2000) and Graham (1990) where the consequence of a single failure event becomes mission critical.
- Furthermore, the results indicate that the theoretically tipping coefficient based on rigid body theory does provide a suitable conservative boundary for the general population.
- However, it also indicates that the variability in the performance of individuals can be dramatic such that a highly trained, skilled or experienced person has the potential to perform operational tasks significantly better than predicted by the theoretical rigid body approach.
- Consequently the use of the rigid body theory may be overconservative and restrict the potential design of vessels and/or operations when the designed based on rigid body theory.

- Furthermore the large variability between people indicates that empirically derived deterministic coefficients must be based on a suitable number of people (over 30) that represent human performance requirements for the specified operation.
- However, for the evacuation of passenger ships, a failure event may simply indicate a requirement for handrails and while failure events will slow down the passenger, forward progress is still achievable with the use of handrails.
- It is noted that a simple empirical estimate of the motion induced interruption rate provides a better fit to the velocity ratio data for the range of conditions tested, when a constant failure duration rate is applied, than the full breakdown of the terms.
- Furthermore the least squares power fit to the velocity ratio provides the best fit to the velocity ratio data measured. When compared to alternative models.

For the purposes of this thesis, the number of failures or duration of failures is not required to substantiate the hypothesis. Accordingly, the parametric study described in Section 6 utilises the least squares power fit to the velocity ratio data as described in equation 4.32 rather than the more complex breakdown of terms described.

The motor ability trials have identified a number of human factors that influence the walking speed of evacuees in a dynamic sinking ship environment. These are summarised as in the Table 4.13

Table 4.13 Findings on Motor Ability in a Dynamic/Capsizing Environment			
Topic	**General Finding**	**Eqn**	**Section**
	Design Relationship		
Design Walking Speed	$V = \xi_{DC}.\xi_{Sci}.\xi_{age}.\xi_{gender}.\xi_{congestion}.\xi_{infant}.\xi_{kinetosis}.Vn$ $V > 0.2$	-	-
	Supporting Relationships		
Dynamic/Capsizing Performance Factor	$\xi_{DC} = Vr_{power} = 1\text{-}0.0017.A^{3.234}$	4.32	4.4.3
Sub-condition Performance Factors (ξ_{SCi})	$\xi_{SC1} = 1.00$ $\xi_{SC2} = 1.03$ $\xi_{SC3} = 0.96$ $\xi_{SC4} = 1.01$	4.34	4.5
Age Performance Factor (ξ_{age})	$\xi_{age} = -0.000169\ Age^2 + 0.00661\ Age + 1.021$	4.36	4.6.1
Gender Performance Factor (ξ_{gender})	$\xi_{gender} = (0.13G+1) / 1.078$	4.39	4.6.2
Congestion Performance Factor ($\xi_{congestion}$)	$\xi_{congestion} = 1.6e^{-.35\rho}/Vn$	4.42	4.6.4
Infant Carrying Performance Factor (ξ_{infant})	$\xi_{infant} = 1$	-	4.6.5
Kinetosis Performance Factor ($\xi_{kinetosis}$)	$\xi_{kinetosis} = -0.0244\ Rt + 1.0219$ $= 1$	4.44	4.6.6
	Other Background Relationships		
Tipping Force (F_t)	$F_t = (l/h).m.g$ $F'_t = 1.15\ F_t$	4.19 4.20	4.3.3.1
Velocity Ratio (Vr)	$Vr = V_d/V_n$ $Vr_{linear} = 1.23 - 0.10.A$ $Vr_{MII} = 1\text{-}MII_{rate}(A).D_{MII}/60$ $Vr_{power} = 1\text{-}0.0017.A^{3.234}$	4.03 4.18 4.29 4.32	4.1.4 4.3.3.2 4.3.3.4 4.3.3.4
Moment Induced Interruption Rate (MII_{rate})	$MII_{rate}(A) = 0.151.A^{3.002}$	4.22	4.4.3
Average Duration of MII (D_{MII})	$D_{MII} = 0.97$ s (average)	4.29	4.4.3
Acceleration Tipping Threshold (A_t)	$A_t = 2.12\ m/s^2$	-	4.4.2

4.6.8 Design Guide

Brumley and Koss (2000c) developed a design guide for special groups including the disabled and elderly on the basis of the research described in this thesis. The guide is based four stages described as follows:

- *Stage 1: Negligible accelerations* - Where lateral accelerations are less than that caused by a 5 degrees static list they are classified as having a negligible impact on walking speed of the elderly and disabled;
- *Stage 2: Transitional accelerations* - It is noted that the velocity ratio of the mid age population is described well using a linear least squares fit for lateral accelerations greater than or equal to 2.54m/s^2. Based on this observation it has been assumed that a linear transition will also be applicable to the special groups category. Accordingly the design guide is based on a linear transition between 5 degree static list limit and the significant acceleration threshold;
- *Stage 3: Significant accelerations* - The impact of significant accelerations is based on the following premises:
  - The elderly population respond to significant accelerations by adopting a constant velocity ratio. This is supported by the observation that the elderly adopted a constant safe walking velocity ratio in all conditions with static list greater than or equal to 20 degrees (with or without a dynamic roll component),
  - A lateral acceleration which causes a noticeable influence on the velocity ratio of the mid age population is a as significant accelerations,
  - The mid age population velocity ratio was only noticeably influenced for lateral accelerations equivalent or greater than that produced by a static list of 15 degrees (i.e. lateral acceleration of 2.54 m/s^2).

  Hence, the design guide is based on a constant velocity ratio for significant accelerations (i.e. greater than 2.54 m/s^2).
- *Stage 4: Extreme accelerations* - For accelerations greater than that tested it is assumed that the performance of the elderly and disabled will be equivalent to that of the worst performer in the elderly group tested (Vr=0.2).

The guide developed by Brumley and Koss (2000c) is recast in Figure 4.31 in terms of lateral acceleration and velocity ratio.

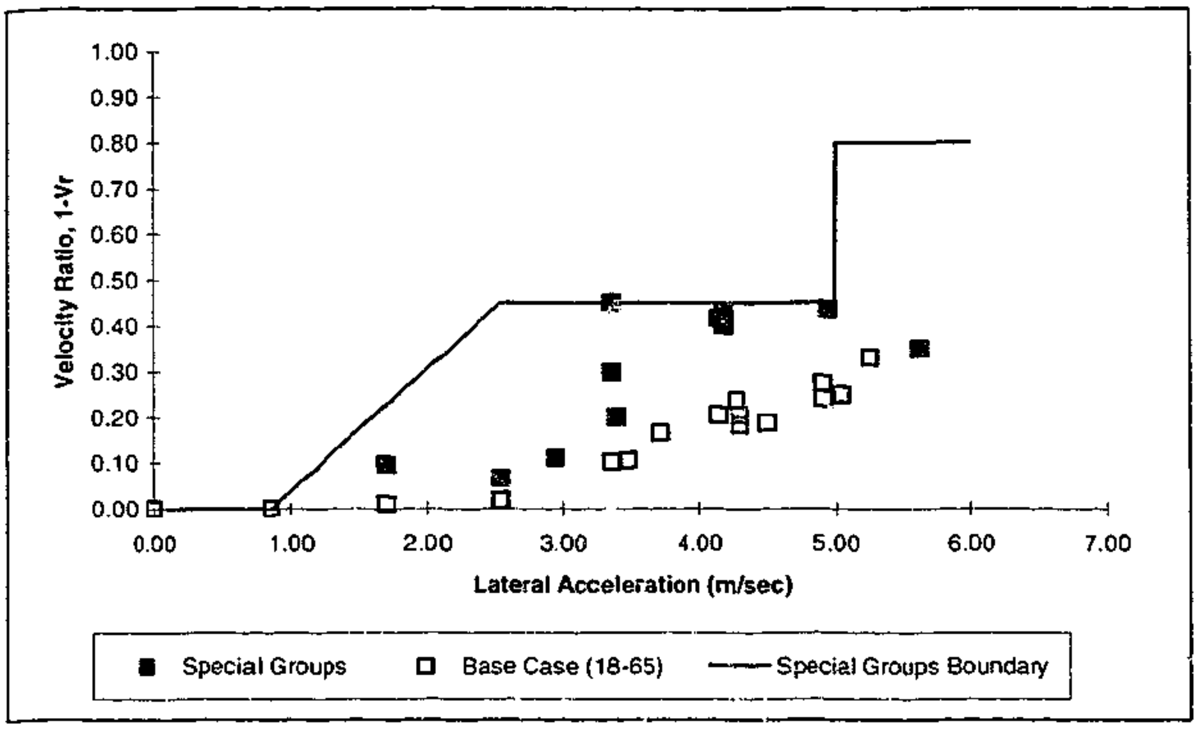


Figure 4.31 Special Groups Design Guide

4.6.9 Limitations

There are number of limitations placed on the application of the empirical design curves and coefficients derived herein. These may be summarised as follows:

- Only list and roll were considered;
- There is some variation in population characteristics between tests;
- Some conditions only had small sample sizes;
- Case studies only had small sample sizes;
- Some conditions did not represent typical gender distribution;
- Children were not assessed;
- Movement up/down stairs was not considered;
- Movement around stationary objects was not considered;
- Congestion was only considered for low-density situations.

Despite these limitations, the trends to the data observed are consistent with similar models developed for the assessment of performance degradation in a dynamic environment. The data obtained for the base case (population ages 18-65) has been performed for large sample sizes and an extensive and range of conditions such that this data is suitable for the requirements of this thesis.

4.6.10 Assumptions

A number of assumptions have been used to develop the empirical design curves and coefficients as follows:

- List and roll will be the most frequently occurring conditions and will have the biggest impact on motor ability. The rationale for this assumption is discussed in Section 4.1.3 and confirmed by Graham (1990)
- The mechanisms that influence list and roll are the same as those that influence other degrees of freedom. While the rationale for a similar influence from pitch motions can be readily argued it is noted that qualitative observations in the pitch environment (TNO facility) indicated that the passenger will be forced to undertake 'uphill' and 'downhill' walking operations depending on the part of the wave cycle and mean trim. These uphill/downhill-walking motions can expend considerable energy such that fatigue considerations may play an important factor. The issue of fatigue is less likely to influence the roll/list walking environment as the direction of motion runs parallel to the angular axis of motion. Fatigue has not been addressed in this thesis. While it is recommended that the models adopted be applied to other degrees of freedom in the absence of more comprehensive data, it is noted that fatigue should also be addressed for pitch motions.
- It is assumed that high levels of congestion will influence the walking speed considerably more than vessel motions. The SFPE (1995) Handbook of Fire Protection Engineering indicated that the walking speed in the optimum crowd density is 50% of the walking speed in minimal density conditions, while in crush conditions the walking speed is less than 25% that of the minimal density. The worst-case reduction of the mean walking speed due to environmental motions measured is approximately 65% of normal walking conditions.
- The population assessed represent the typical passenger distribution. It is recognised that the typical distribution of passengers on a seagoing passenger vessel may be considerably different from the sample set assessed. In particular, many vessels are marketed to the elderly and quite often vessels will be occupied by a significant contingent of children (for field excursions etc). The disabled represent another group that must be considered. While case studies have been conducted to assess these representative groups, the sample sizes were limited. Despite this limitation there is sufficient evidence to suggest that the bulk of the seafaring population is represented by the data obtained and that the elderly/disabled and children may be catered for by conservative design curves tailored from case studies.
- The physical parameters of the average Australian are representative of populations elsewhere in the world. In the area of human factors in evacuation it is often argued that there is some difference between the performances of people from different cultural, religious and/or racial origins. Smith (1997) found that in the case of motion sickness there is also evidence that racial background may influence the susceptibility of an individual to low frequency vibration. The demographics of the population assessed, while representing the typical Australian distribution,

may be somewhat different to the population of a different country. The use of the static walking speed in the velocity ratio may go some way to working against this bias. However there is no guarantee that this will counter the differences between the sample set and other likely populations. In particular it is noted that the static walking speed did little to reduce the differences between male and female in walking speeds. Despite these difficulties data on walking speeds for evacuation (for on land structures) is commonly applied across borders and for different demographic subsets.

- The performance of a small sample set of elderly is representative of the elderly population - the data on walking speed of elderly is represented by a sample size of less than 15 people. Accordingly the confidence interval on the mean velocity ratio for the ranging environmental conditions is significantly larger than for the normal population set. Despite this, the clear difference in average walking speeds between the elderly and the normal population is sufficiently large to demand a different set of design conditions for this subset. The data gathered is significantly more than any like subset currently in existence in the public domain and accordingly it provides a good estimate of the influence of such conditions on the poorer performing members of the evacuating population.
- The simulated environment is sufficient to replicate the impact of the real environment. While it is clear that the '1st Mate' environmental simulator does not model all the relevant factors in evacuation of a sinking vessel, such as the associated fear and anxiety, reports from participants that have either had experience in a sinking environment or have had naval experience have indicated that the simulation is 'very real.' In addition, the motions of the vessel did have some physiological influence on some participants such that they felt mild nausea and some anxiety and to that end had a desire to complete the task. Finally, rather than a requirement for substantial cognitive processes, the testing performance is influenced significantly by the physical motions and physical performance. Accordingly, the relative impact of psychological factors is reduced.

While there may be reasonable scope for arguing against the above assumptions it should be borne in mind that the principal hypothesis put forward in this thesis is that ***'Maritime specific features have a significant influence on the evacuation analysis outcomes of passenger vessels: These features should be considered in the early stage of design.'*** The assumptions put forward and the limitations of the models developed are reasonable within the scope of the proposed thesis. Accordingly the empirical models developed provide a good approximation of some representative maritime specific features with which to compare against standard evacuation analysis procedures.

5. WAY FINDING ON PASSENGER SHIPS

5.1 WAY FINDING ANALYSIS

5.1.1 Overview

A particular area requiring increased information is that of how people select the appropriate evacuation destination when confronted with an emergency situation. Lovas (1994a) identified that very little has been written about detailed models of way finding behaviour. Prior to this thesis no quantitative data existed in the public domain on the distinct nature of destination selection during evacuation in the maritime scenario. In particular the no quantitative data was available to support the idealisation that all passengers will select the assigned muster station as the first destination during an evacuation. On the contrary Boltwood (1995) provided qualitative evidence from past incidents that passengers have had difficulty finding lifeboats and that some did not know where lifejackets were held. Furthermore, unlike the evacuation of buildings, the safest location on the vessel depends on the particular threat, the purpose and size of the vessel and the evacuation policy of the ship management. This section provides an overview of the existing theories on way finding during evacuation along with the development of a new theory for the description of destination selection in the maritime environment based on the findings field surveys of a range of vessels conducted for this thesis.

5.1.2 Physical System

For the purposes of an evacuation analysis assessment Timmermans et al (1992) and Passini (1984) defined specific factors relevant to way finding behaviour that are of interest as follows:

- Goal selection - selection of task to be achieved;
- Destination selection - selection of desired destination to achieve task;
- Global route selection - selection of overall route to take to get to destination;
- Local route selection - selection of minor perturbations in global route based on local conditions/signs etc.

A factor that can assist in the goal and destination selection of evacuations is passenger knowledge of safety requirements. IMO (2001a) required that passengers be informed of the location of their life vests as well as the location of their muster areas. However, Boltwood (1995) identified that in past incidents passengers have difficulty finding lifeboats and that some did not know where lifejackets were held.

Passengers can be informed of their requirements in a number of different ways depending on the type and duration of the journey. Aircraft style demonstrations, practice evacuations, audible information systems, continuous video demonstrations, colourful pictorial placards and written information bulletins can be used individually or as a combination.

Global and local route selection due to signage, lighting, familiarity, crowd flows and hazards has been researched significantly for on-land buildings and many of the principals adopted are common with maritime evacuations. However the goal and destination selection for the maritime scenario may be quite different to on-land scenarios, accordingly this is examined in more detail in this section.

Ozel (1993) discussed the influence of cognitive factors on way finding during the evacuation of buildings. Ozel (1993) identified, 'several characteristics of the physical environment that effect people's spatial behaviour and way finding,' as follows:

- Visual access to other areas of the building;
- Physical or functional differentiation of building parts (lobbies and atriums etc.);
- Signage for identification and direction purposes;
- Plan configuration.

Furthermore Ozel (1993) identified the following emergency design concepts that interact most with the environmental cognitive variables:

- Separation of exits;
- Arrangement of exits;

- Capacity of exits;
- Exit signage.

Ozel (1993) claimed the evacuation research literature provides ample evidence that most people have difficulty with spatial orientation because of the complexity of the built environment. Furthermore he claims that signage does not overcome users' problem with spatial orientation and way finding. Ozel (1993) claimed that, 'cognitive mapping must be considered a factor in emergency egress behaviour.'

Boer (1993) investigated the effectiveness of direction cues (signs etc.) isolated from other cues (crew directions, seeing where others go) in a simulated ship environment. Boer (1993) found that evacuation signs do a good job of communicating muster stations and 20 out of 21 read the safety instructions. Of those investigated, 35% knew the name of their muster station; 55% could not tell what the alarm was for; 72% of those that didn't know what the alarm was for suggested they would ask others, ask crew, find an exit and go to deck; and 20% lost their way in the drill (i.e. The passengers moved to a place where no-one was waiting for them). A relationship between not knowing the muster station and losing their way could not be confirmed. In the crew only area muster the evacuation took twice the muster time when occupants had not practiced a muster and had little layout familiarity and started from their cabin. The crew-only area evacuation took four times the approximated muster time when the occupants had practiced muster and had layout familiarity but started in a public area. For the public area muster the evacuation took twice the muster time when occupants had not practiced a muster and had little layout familiarity and started from their cabin. In addition the time taken when occupants had practiced the muster, had layout familiarity and started in a public area was equivalent to the anticipated evacuation time in the public area muster. Boer (1993) recommended that the safety awareness of the average passenger be investigated for a number of different vessels.

A transnational BritEuram programme on the evacuation of passenger ships is currently ongoing and includes the following participants: TNO Human Factors Research Institute (TNO); Det Norske Veritas (DNV); Danish Maritime Institute (DMI); Kungliga Tekniska Hogskolan (KTH); Quasar Consultants; and Scandlines.

The research includes a study on the effects of new design features such as intuitive systems for guiding passengers; and corridors and stairs that offer an improved walking surface in a typical condition of a ship - a moving environment. These effects were assessed under realistic ship motion and behavioural conditions. From the research program Boer and Vredeveldt (1999) presented the findings of trials investigating three alternative way-finding systems including the following:

- Existing IMO compliant way finding system;
- Directional information along the skirting board;
- Electrical system programmable in direction.

Almost 300 volunteers evacuated the imitated interior of a ship. People moving in groups and as individuals were assessed. The study identified that the system with directional information along the skirting board was favourable when compared against the existing IMO compliant system because it leads to a reduction in way-finding errors. The programmable system was considered a failure. Boer and Vredeveldt (1999) discussed the following factors relating to the systems:

- Clarity, including line of sight consideration, adequate luminance, and a good ratio of 'signals' (evacuation signs) to 'noise' (advertisements);
- Technical robustness;
- Programmable direction including situation awareness at ships bridge.

In particular Boer and Vredeveldt (1999) noted that the location of doors was, 'the main source of way-finding errors.'

5.1.3 Dependant Variables

As stated previously, two major way finding parameters that may be specific to maritime scenarios are:

- *Goal Selection* - The goal of the evacuee can be described by the actions category as discussed in the Section 2.3.2.3. In particular the goal parameter may be described as the percentage of the population that would carryout a specific goal. For example Harbst and Madsen (1993) defined the goals of evacuees, after acceptance of need for evacuation, as:
    - Evacuate 10%;
    - Attack Threat 5%;
    - Warn Others 10%;
    - Wait for Others 60%;
    - Paralysed 12-14%;
    - Panic 1-3%.
- *Destination selection* - once passengers have decided to evacuate they are required to select exactly where they will evacuate. Passengers may decide to evacuate to the following locations based on the level of safety knowledge available:
    - Cabin;
    - Crew/Bridge;
    - Children's Supervised Area;
    - Foyer/Reception;
    - Outer Deck/Nearest Exit;
    - Upper Decks;
    - Lower Decks/Car Deck;
    - Wrong Muster/Assembly Area;
    - Assigned Muster/Assembly Area;
    - Embarkation Deck;
    - Overboard.

Prior to the work of this thesis no data had been gathered on the destination selection. Accordingly, evacuation models typically assume that when passengers evacuate they will choose the correct evacuation destination.

5.1.4 Independent Variables

The independent variables that influence the destination selection are as follows:

- *Safety Knowledge System* - type of system rated against the information triangle as discussed in Thygerson (1977) and shown in Figure 5.1. This may be measured by assessing the percentage of the population that claim to have reviewed the safety system.
- *Passenger Experience* - previous opportunities to learn the safety system. This may be measured as the percentage of the population that have travelled on the same form of transport on prior occasions.

The passenger experience and safety system is typically dependant on the conditions of the trip such as the target population, transit route, likely environmental conditions and duration of each journey.

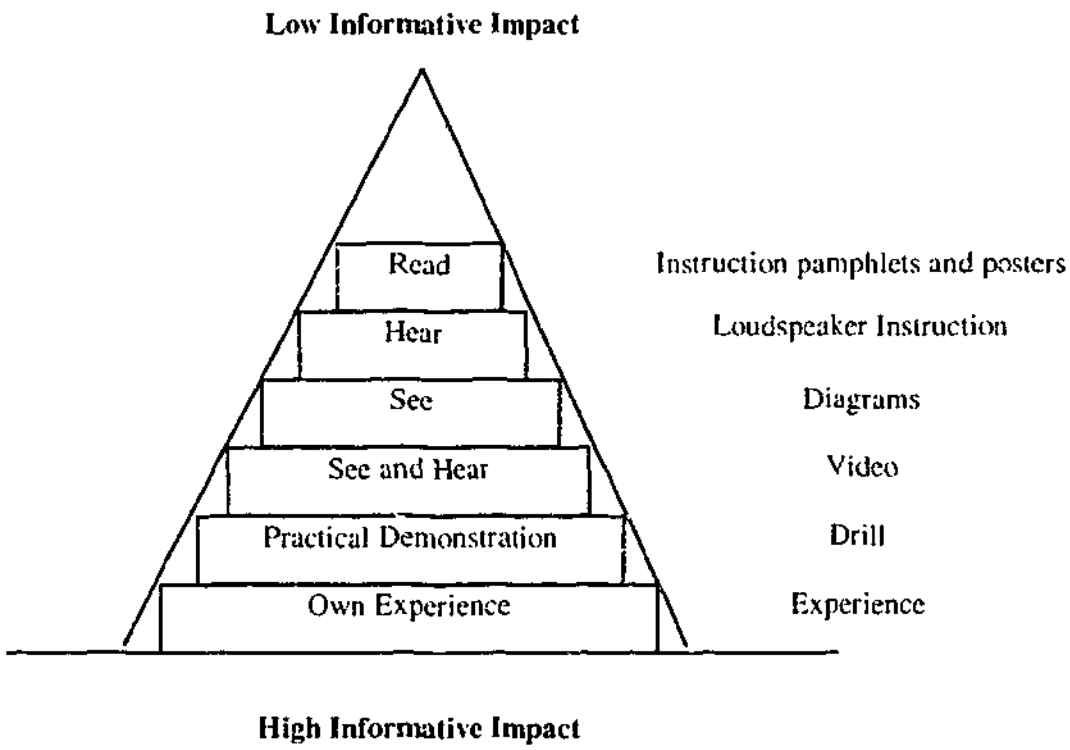


Figure 5.1 Information Triangle, after Thygerson (1977)

5.1.5 Lifejacket Storage Policy on Way Finding

5.1.5.1 Overview

The philosophy on lifejackets can vary between services and is dependant on the safety management of the particular vessel. The two major and quite different philosophies are as follows:

- Near Passengers;
- Near Muster/Assembly Station.

5.1.5.2 Near Passengers

On smaller vessels this usually means under seats or in overhead compartments; on larger vessels this means in cabins (under bed, in wardrobe).

Advantages:

- More intuitive for passengers;
- Passengers can put jackets on in dramatically advancing conditions;
- Better storage alternative;
- Less demanding on crew.

Disadvantages:

- Crew do not get opportunity to review donning of each passenger;
- More likely to be damaged/stolen;
- Harder to maintain;
- Passengers away from their assigned location are required to egress into dangerous areas;
- Causes counter flow and egress confusion.

5.1.5.3 Near Muster Stations

On smaller and larger vessels alike the jackets are stored in safety lockers near the muster stations.

Advantages:

- Crew review donning of each passenger;
- Less opportunity for jackets to be lost or stolen;
- All passengers egress to a like location;

Disadvantages:

- Passengers get confused where lifejackets are distributed;
- Passengers must wait for crew to administer - takes time;
- Takes up expensive floor space;
- Passengers are required to go to their assigned muster station not necessarily the nearest one.

5.1.6 Vessel Characterisation

Harbst and Madsen (1993) categorised vessels based on the various operational constraints as follows:

Table 5.1	Vessel Categories, after Harbst and Madsen (1993)
Category A	Short Duration Transit - Ships without sleeping passengers where the trip itself only lasts a few hours or less.
Category B	Sightseeing Cruises - normally in coastal areas, lakes and rivers
Category C	Long Duration Cruises - travelling times of 8-24 hours where sleeping accommodation is provided in the form of cabins
Category D	Multi-night Cruises - typically design for vacation purposes

Harbst and Madsen (1993) also identified the various forms of safety media that is appropriate for various categories of transport:

Table 5.2 Media System Allocation, after Harbst and Madsen (1993)

Id	Media System	Vessel Category
1	On back of ticket, boarding cards, menus etc	ABCD
2	Posters on car deck	AC
3	Video on general information screen	ACD
4	Ship cinemas	ACD
5	Loud speakers	BCD
6	Poster at all evacuations stations	ABCD
7	Practice drills	D (often A, C)
8	Competitions	ACD

For the purpose of this investigation the level of previous experience and safety system was assessed against the type of vessel according to the method developed by Harbst and Madsen (1993) as described above.

5.1.7 Formulation of Mathematical Model

The probability that a passenger will correctly select the assigned muster/assembly destination (S_m) is a function of a quantifiable parameter describing the safety information system in place on board a vessel described as follows:

$$S_m = f(I_s) \qquad (5.02a)$$

Where,

S_m = Percentage of the population that select the assigned muster/assembly area as the first destination in an evacuation;

I_s = Safety information system parameter;

$$I_s = f(m_s, e_x); \qquad (5.02b)$$

m_s = Media system;

e_x = Percentage of the population with passenger maritime experience;

$f(\ )$ = Undefined function;

And where,

$$m_s = f(L_a, A_d, N_p) \qquad (5.02c)$$

L_a = Percentage of the population that examine the ship layout,

A_d = Percentage of the population that listen to the announcement/drill,

N_p = Percentage of the population that examine the notices/pamphlets.

5.2 WAY FINDING EXPERIMENTS

5.2.1 Methodology

To determine the influence of safety media systems and experience safety knowledge on passenger vessels a series of interviews and questionnaire were distributed. The surveys were conducted using the following methodology as part of this research:

- Smaller Vessels:
  - Wait for passengers to board and be seated,
  - Approach each passenger and request their participation,
  - On positive response distribute survey,
  - Explain passenger requirements,
  - Collect on completion;
- Overseas Ferry:
  - On boarding request that passengers participate in survey,
  - Collect completed form pursers office;
- Cruise Ship:
  - Distribute surveys in cabin while passengers at first port of call,
  - Collect surveys from vessel administration.

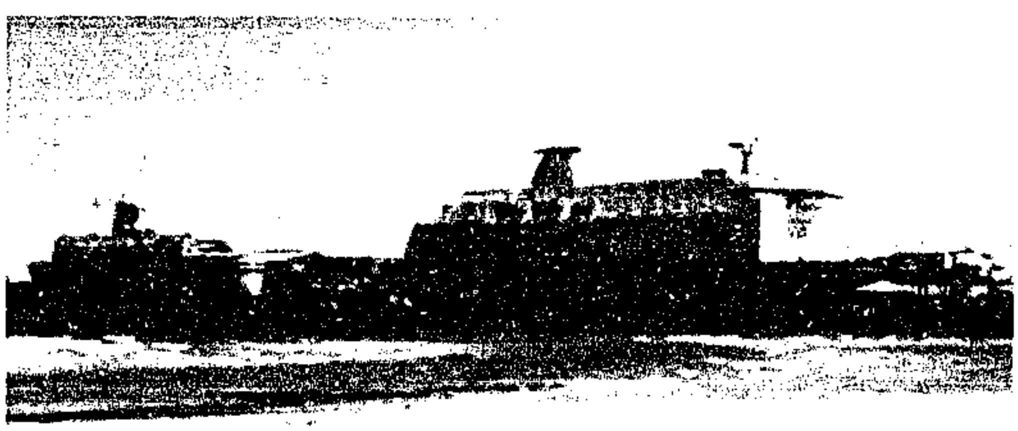


Figure 5.2 Cruise Ship and Overseas Ferry Moored at Station Pier, Melbourne.

5.2.2 Questionnaire Description

The questionnaire was designed to cover the following issues:

- Age;
- Gender;
- Previous travel on the vessel in question;
- Previous travel on other vessels;
- Travel companions;
- Hearing/ listening/ understanding safety announcements and drills;
- Viewing bulletins, pamphlets and ship layouts;
- Perceived safest location;
- Preferred first destination in an emergency;
- Confusion about ship layout;
- Lifejacket storage;
- Reference to companions and safety notices.

5.2.2 1 General Introduction

In circumstances where the survey is distributed prior to boarding there is potential for passengers to read and complete the survey prior to the opportunity for the media system to be effective. In an attempt to prevent this from occurring written warnings were issued on the envelope and on the front page of the survey. The front-page warning was as follows:

> *'IT IS ESSENTIAL FOR THE SUCCESS OF THIS SURVEY THAT YOU DO NOT READ OR COMPLETE THIS SURVEY UNTIL 8.00 P.M.*
>
> *DO NOT READ PAGE TWO UNTIL YOU HAVE COMPLETED THIS PAGE*
>
> *THIS SURVEY IS A MEMORY BASED SURVEY - PLEASE DO NOT REFER TO SAFETY NOTICES OR WITH YOUR COMPANIONS UNTIL YOU HAVE COMPLETED THIS SURVEY.'*

5.2.2.2 Demographic Data

Demographic parameters are required to ascertain whether any correlation exists between safety knowledge, experience and easily obtainable demographic data. This correlation enables vessel designers to consider the target group and from that ascertain their likely knowledge and experience and hence what their likely route choice will be. Demographic data included age, gender and first language.

5.2.2.3 *Previous Travel*

Experience on previous vessels can be categorised as follows:

- *Travel on the vessel in question* - This is a measure of the amount of experience a particular person may have. People who have travelled on the particular vessel before may be less likely to listen to safety information yet they still may know the correct evacuation destination.
- *Travel on other vessels* - This is also a measure of the amount of experience a particular person may have. People who have travelled on other vessels previously may be less likely to listen to safety information yet they still may know the correct evacuation destination or procedure.

The questions relevant to previous travel were phrased as follows:

> *'Have you travelled on the {VESSEL NAME} before?*
>
> > *If yes, approximately how many times?*
>
> *Have you travelled on any other passenger ship?*
>
> > *If yes, was there a safety announcement?'*

5.2.2.4 *Travel companions*

By determining the number of companions a particular person has and comparing their knowledge to the volunteer the data set can be extended to increase confidence in the implication of the data trends. The question on travelling companions was phrased as follows:

> *'How many people are you travelling with (do not include yourself)?*
>
> *How well do you think your travelling companions know the safety procedures?*
>
> > *a. better than me,* *b. the same as me,*
> >
> > *c. worse than me.*
>
> *How well do you think your travelling companions know the ship?*
>
> > *a. better than me,* *b. the same as me,*
> >
> > *c. worse than me.'*

5.2.2.5 *Hearing/ Listening/ Understanding safety announcements and drills*

A measure of hearing/listening/understanding safety announcements helps ascertain how effective a particular method of transferring safety knowledge. In particular it assesses how responsive passengers are to that media. The questions on understanding announcements and drills were phrased as follows:

'Do you remember hearing the safety announcement? (if no, go to 9)

or

Did you attend the safety briefing? (if no, go to 9)

Did you listen to the safety announcement?

a. yes, very carefully	*b. yes, most of it*
c. yes, some of it	*d. no*

Did you understand the safety announcement?

a. yes, it seemed straight forward	*b. yes, but could have been better*
c. yes, but some things were confusing	*d. no, I was confused'*

5.2.2.6 Viewing Bulletins, Pamphlets and Ship Layouts

A measure of the level of revision by participants of passive safety media helps to ascertain how effective a particular method of transferring safety knowledge. In particular it provides a form of assessment on how responsive passengers are to that media.

'Have you looked at a layout of the ship?

a. yes, in detail	*b. yes, briefly*
c. no, but I know where one is	*d. no, where are they?'*

Have you read the safety notice on the back of your door or wall?

a. yes, in detail	*b. yes, briefly*
c. no.	*if no, why not?*

Have you read the safety pamphlet given to you on boarding?

a. yes, in detail	*b. yes, briefly*
c. no.	*if no, why not?'*

5.2.2.7 Perceived Safest Location

Knowledge of the perceived safest location provides a measured to assess how well people absorb the information provided in the safety media and their trust in the information provided.

'Where do you think the safest place is on a ship during an emergency? '

5.2.2.8 Preferred First Destination in an Emergency

A measure of the preferred first destination in an emergency gives an indication of the extent to which people will proceed to non-intuitive destinations based on guidance from safety media.

'Where is the first place you would go in the event of an emergency?'

5.2.2.9 Confusion About Ship Layout

A measure of the passenger confusion about the ship provides a mechanism for assessing the effect of a confusing layout of a ship on passengers' response to information media.

'Do you get confused about your location on the ship?

a. yes, very often *b. yes, sometimes*

c. no, never'

5.2.2.10 Lifejacket Storage

Knowledge of lifejacket storage locations provides a mechanism to identify and quantify the affects of 'near person' and 'near muster' life jacket storage philosophies on passenger life jacket location knowledge.

'Where is your life jacket stored?'

5.2.2.11 Muster Station

The muster station is the principle information that is conveyed through safety media. However it is typically only allocated on the back door of the cabin. The most accurate measure of the effectiveness of the safety system is the percentage of the population that knows their muster station.

'Do you know your muster station number?

if no, do you think your travelling companion does?

if yes, what is it?'

5.2.2.12 Signage Location

The location of emergency exits influences the ability for passengers to make way to their muster station from their cabin. The effectiveness of signage location may be assessed through correlation with the percentage of the population that notices emergency exits in general activities.

'Did you notice any emergency exit signs on the way to your cabin?'

5.2.2.13 Alcohol Consumption

Many passenger ferries and cruise ships supply alcohol to their commuters and in some cases this is a significant reason for transit by these commuters. To calibrate the data obtained against other data sets it is important to have an indication of the level of alcohol consumed and the relationship between alcohol consumption and the influence of safety media systems.

'How many alcoholic drinks do you intend to have during your journey?'

5.2.2.14 Reference to Companions and Safety Notices

As the survey was conducted as a memory based survey, passengers who referred to information media or companions while filling out the survey were excluded.

'Did prior knowledge of this survey influence your answers to any of the questions?

Which questions?'

5.2.3 Vessel Characteristics

To assess the implications of different media systems, four alternative ship scenarios were assessed to represent the range of passenger safety knowledge models that exist in the present market of passenger sea transportation systems. The ship scenarios are described in Table 5.3:

Table 5.3	Vessel Category For Ships Surveyed
Transit Ferry (Category A)	An hourly service used for predominately for public transport. The service is aimed at providing a cheap transport alternative between two very densely populated suburbs. The service has no active safety media system. The passive media system is a notice and layout located in several areas about the ship. The majority of passengers are frequent users
Bay Ferry (Category B	An hourly service used equally for transport and tourism. The service has a car deck for the motorist and connects to small tourism towns along a major scenic route. The active safety media system is a general announcement at departure. The survey was conducted without the full compliment of speakers active. The vessel also has a passive safety media system consisting of notices and layouts located about the ship. As the service is aimed at both the travelling public and the tourism market a large proportion of the passengers had travelled on the service before.
Long Duration Transit Ferry (Category C)	A daily service used equally for transport and tourism. The service has several car decks for the motorist and connects two large cities. The active safety media system is a general announcement at departure. The vessel also has a passive safety media system consisting of notices and layouts located in each cabin as well as at several locations about the ship. Each passenger is also supplied with safety information pamphlets prior to boarding. As the service is aimed at both the travelling public and the tourism market a moderate proportion of the passengers had travelled on the service before.
Multi-night Cruise Ship (Category D)	The cruise ship is a specialised service aimed specifically at the tourism market. The service conducts journeys ranging from days to weeks in duration. The active safety media system consists of a safety drill where passengers are guided to their muster station. The vessel also has a passive safety media system consisting of notices and layouts located in each cabin as well as at several location about the ship. As the service is aimed specifically at the tourism industry only few passengers had used this service before.

5.2.4 Safety System

The four scenarios each consist of different levels of safety media information systems due to the target population, the transit route, the likely environmental conditions and duration of each journey. These safety systems have been rated below:

Table 5.4	**Safety System Rating**
Rating 1	This consists of actively informing passengers of their requirements through demonstration. This form of information transfer is typically performed on journeys that are expected to take more than 24 hours (Category D). The information is supplemented by passive information media such as notices in cabins and about the ship.
Rating 2	This consists of actively informing passengers of their requirements through audio announcement at all locations on the vessel. This form of information transfer is typically performed on journeys that are expected to take more than 6 hours and less than 24 hours (Category C). The information is supplemented by passive information media such as notices in cabins and about the ship as well as pamphlets handed out prior to boarding.
Rating 3	This consists of actively informing passengers of their requirements through audio announcement in selected locations on the vessel only. This form of information transfer is typically performed on journeys that are expected to take less than 6 hours and on routes that are a considerable distance from regular traffic and land (Category B). The occupants of these vessels spend the majority of their time in common areas (i.e. no cabins) and are within close proximity to muster stations. The information is supplemented by passive information such as notices about the ship.
Rating 4	This consists only of passively informing passengers of their requirements with notices about the ship. This form of information transfer is typically performed on journeys that are expected to take less than 2 hours and on routes that are within close proximity to regular traffic and land (*Category A*). The occupants of these vessels spend the majority of their time in common areas (i.e. no cabins) and are within close proximity to muster stations.

5.3 DESTINATION AND WAY FINDING RESULTS

A pilot study was conducted to ensure that the questions were sufficiently comprehensive and that the passengers easily interpreted them. The pilot study consisted of two components as follows

- Unobtrusive Survey - Due to time limitations an unobtrusive survey was required to ensure that the population questioned in the survey was representative of the entire vessel population. The unobtrusive survey included demographic data such as age, gender and travelling group size. The survey consisted of unobtrusive observation of the passengers with estimates by the researcher of the various demographic data. The vessel population consisted of approximately 200 passengers. The unobtrusive survey included 92 of these;
- Obtrusive Survey - The obtrusive survey covered many of the questions described in Section 5.1. A sample copy is attached in Appendix 7. Issues covered included:
  - Demographic data,
  - Number of travelling companions,
  - Heard/listen/understand announcement,
  - Noticed exit signs,
  - Reliance on companions,
  - Confusion about location,
  - Perceived safest location in an emergency.

A comparison between the obtrusive and unobtrusive surveys for the pilot study indicates that the obtrusive survey represents a valid subset of the vessel population as shown in Table 5.5. A full list of the pilot study results along with the results of the detailed survey is documented in Table 5.6.

Table 5.5 Pilot Study Demographic Data		
	Obtrusive (n=42)	**Unobtrusive (n=92)**
Age (Mean)	40	38
Gender (% males)	59%	54%
Travelling Group Size (Mode)	2	2

Table 5.6 Detailed Survey Results							
Question Reference Response (n=612)		A n=233	B n=225	C(p) n=42	C(i) n=77	C(ii) n=64	D n=35
1.	Mean Age	43	47	40	48	45	54
2.	% Male	41	52	59	31	35	51
3a.	% Travelled Same	81	51	-	48	73	6
3b.	Number of time %<5	45	77	-	83	94	100
4.	% Travelled Other	81	79	-	69	77	80
4a.	Announcement	49	48	-	56	56	76
5.	% Travelling Alone	21	11	20	3	6	6
6.	# Companions (Mode)	1.8	-	2	2.3	3.4	2.7
7.	Hear/Attend Briefing	-	44	90	100	100	97
8.	Listen a,b	-	34	69	75	63	91
9.	Understand a,b	-	26	88	90	86	94
10.	Layout a,b	38	51	79	99	95	100
11.	Safest Place						
	Muster/Assembly Area	16	21	28	39	36	41
	Embarkation/Lifeboats	8	2	10	9	9	6
	Foyer/Reception	0	0	5	5	4	3
	Outside Deck/Exit	36	20	28	17	30	29
	Lower/Car Deck	4	8	0	0	0	0
	Upper Deck	18	34	10	4	5	6
	Cabin	0	0	0	3	0	3
	Crew/Bridge	6	-	0	0	5	6
	Don't know	9	20	18	22	12	6
	Overboard	3	1	0	0	0	0
12.	1st Destination						
	Muster/Assembly Area	30	41	-	79	78	82
	Embarkation/Lifeboats	6	4	-	6	3	3
	Foyer/Reception	0	0	-	1	5	3
	Outside/Deck/Exit	29	22	-	6	8	12
	Lower/Car Deck	1	5	-	0	0	0
	Upper Deck	10	22	-	1	0	0
	Cabin/Seat	0	0	-	1	2	0
	Crew/Bridge	13	-	-	3	2	0
	Don't know	5	12	-	1	4	0
	Overboard	6	3	-	0	0	0
13.	Confused a	0	0	10	5	2	21
	b	0	0	51	68	67	65
	c	100	100	39	25	32	16
14.	LJ Location Correct	72	54	-	58	51	100
15.	Companion Safety a	-	-	18	15	5	0
	b	-	-	61	64	68	91
	c	-	-	21	21	26	9
16.	Companion-Ship a	-	-	-	29	22	16
	b	-	-	-	55	70	72
	c	-	-	-	26	8	13
17.	Correct Muster Station	30	41	-	79	78	82
18.	Notice Exit Signs	-	-	63	83	86	88
19.	Refer Notice a	7	4	-	49	25	32
	b	14	21	-	35	62	47
	c	77	74	-	16	13	21
20.	Refer Pamphlet a	-	-	-	29	24	30
	b	-	-	-	36	43	48
	c	-	-	-	35	33	18
21.	Cheat	-	-	-	11	0	12

Note: n = sample size
For a description of vessel types refer to Table 5.3.
For question details refer to Appendix 7
For vessel C, i = 1st trip to destination, ii = return trip from destination, p=pilot study

5.3.1 Key Results

Tables 5.7 and 5.8 below show the utilisation of media and the travel experience of passengers based on the information gathered through the surveys conducted.

Table 5.7 Utilisation of Media Systems

Vessel Category	Description	Media Utilisation Parameter (%)			
		L_a	A_d	N_p	$^1/_3(L_a + A_d + N_p)$
A	Notices about Ship Harbour ferry hourly service	41	0	23	21
B	Announcement/Notices (No external speakers) Bay ferry hourly service	51	34	26	37
C(i)	Announcement/Pamphlet/Notice Overseas overnight voyage	99	75	84	86
C(ii)	Announcement/Pamphlet/Notice Overseas overnight voyage (return)	95	63	87	82
D	Full demonstration/Notice International multi-day voyage	100	91	75	90

Note: Media Utilisation Factors are Described in Section 5.1.7

Table 5.8	Experience of Passengers for Different Voyages			
Vessel Category	**Description**	**Same Vessel**	**Another Vessel**	**Same or Another**
A	Hourly Harbour Ferry (City To Major Suburb) Transport Only	81%	49%	92%
B	Hourly Bay Ferry (Tourist Town To Tourist Town) Tourist and Transport	51%	49%	76%
C(i)	Overnight Ferry (City to Tourist Town) Tourist and Transport	48%	56%	70%
C(ii)	Overnight Ferry (Tourist Town To City) Tourist and Transport	73%	56%	85%
D	Multi-day cruise (City to City) Tourist Only	6%	73%	76%

It should be noted that the information collected above is scenario specific and as such each proposed vessel should be assessed using surveys of existing vessels that run similar, if not the same service as that for the proposed vessel. It is important to assess the vessel for its worst-case scenario. As is noted from Table 5.8 the same vessel has very different passenger experience level depending on which leg the service is on.

If the designer has no basis for estimating the level of experience of the passengers then a conservative estimate would be 45%. This estimate is based on the lowest percentage of population that have travelled on a service other than the one that they were on at the time of the survey.

5.4 DATA INTERPRETATION

5.4.1 Key Relationship

The model for describing passenger selection of the assigned muster/assembly destination (S_m) based on safety information systems (I_s) can be described as follows:

	S_m	$= f(I_s)$	(5.02a)
Where,	S_m	= Percentage of the population that select the assigned muster/assembly area as the first destination in an evacuation.	
	I_s	$= f(m_s, e_x)$	(5.02b)
	m_s	= Media system	
	e_x	= Percentage of the population with passenger maritime experience	
	f	= Undefined function	
And where,			
	m_s	$= f(L_a, A_d, N_p)$	(5.02c)
	L_a	= Percentage of the population that examine the ship layout	
	A_d	= Percentage of the population that listen to announcement/drill	
	N_p	= Percentage of the population that examine notices/pamphlets	

To identify the best approximation of the percentage of passengers that select the ideal first destination choice, S_m, a number of alternative combinations of the parameters which make up the safety information systems, I_s, have been assessed.

To determine the best fit to the observed data the regression statistic, R^2, has been obtained. For the majority of combinations it is assumed that each parameter contributes equally for simplicity. By comparison, a multiple linear regression was also assessed (refer case 10). The results are shown in Table 5.9.

Table 5.9	Comparison of Alternative Information System Parameter Models	
Case	*Information System Parameter Alternatives* $\mathbf{I_s}$	**Regression Ratio R^2**
1	e_x	0.2745
2	A_d	0.9171
3	N_p	0.9621
4	L_a	0.9981
5	$^1/_2.(L_a + A_d)$	0.9762
6	$^1/_2.(L_a + N_p)$	0.9866
7	$^1/_2.(A_d + N_p)$	0.9960
8	$^1/_3.(L_a + A_d + N_p)$	0.9982
9	$^1/_4.(L_a + A_d + N_p + e_x)$	0.9975
10	$0.371.L_a + 0.213.A_d + 0.227.N_p + 0.105.e_x$	0.9996
Note:	A linear least squares fit was used to obtain the regression coefficients	

It is noted that the safety information system that has equal contributions from all four identified sub-parameters (case 9) has a comparable correlation to the multiple linear regression (case 10). Case 9 provides a more simplistic approximation. However it is based on a rational design approach (i.e. that all forms of media impact equally). Given that there are four dependant variables and only 5 observation data sets, it may be more sensible to adopt the simplistic model.

Hence for the purposes of the research herein the safety information system measure is calculated as follows:

$$I_s = {}^1/_4.(L_a + A_d + N_p + e_x) \tag{5.03}$$

If the passengers had no previous experience and had not utilised any of the available media mechanisms then none of them would correctly select the muster area for the first route destination or the perceived safest location. For this reason the relationship relating media and experience to correct destination selection was forced through zero at the y-axis intercept.

As yet the observations have been approximated by a linear fit only. To further improve the accuracy of the approximation approach other equations of best fit were assessed. These included a 2nd order polynomial and power fit. The best fit equation for each approach along with the regression statistic, R^2, are provided in Table 5.10 and are compared in Figure 5.3. These equations are compared against the multiple linear regression (case 10) approach as well as the linear regression of the approach that assumes that each of the media/experience components has the same influence (case 9).

Table 5.10 Comparison of Alternative Safety Knowledge Parameter Models			
	Form	**Coefficients**	**Correlation Ratio R^2**
Linear Fit (Equal distribution of m_i/e_x)	$y = A_1x + A_0$	$A_0 = 0$ $A_1 = 0.93$	0.9917
2nd Order Polynomial Fit	$y = A_2x^2 + A_1x + A_0$	$A_0 = 0$ $A_1 = 0.3$ $A_2 = 0.7$	0.9981
Power Fit	$y = A_1x^{A_0}$	$A_0 = {}^5/_4$ $A_1 = 1$	0.9983
Linear (Multiple regression on m_i/e_x)	$y = A_1x' + A_0$	$A_0 = 0$ $A_1 = 1$	0.9998

Note: x media and experience parameter $[{}^1/_4(L_a + A_d + N_p + e_x)]$

x' media and experience parameter $[0.371.L_a + 0.213.A_d + 0.227.N_p + 0.105.e_x]$

y safety knowledge (% to go to correct muster station)

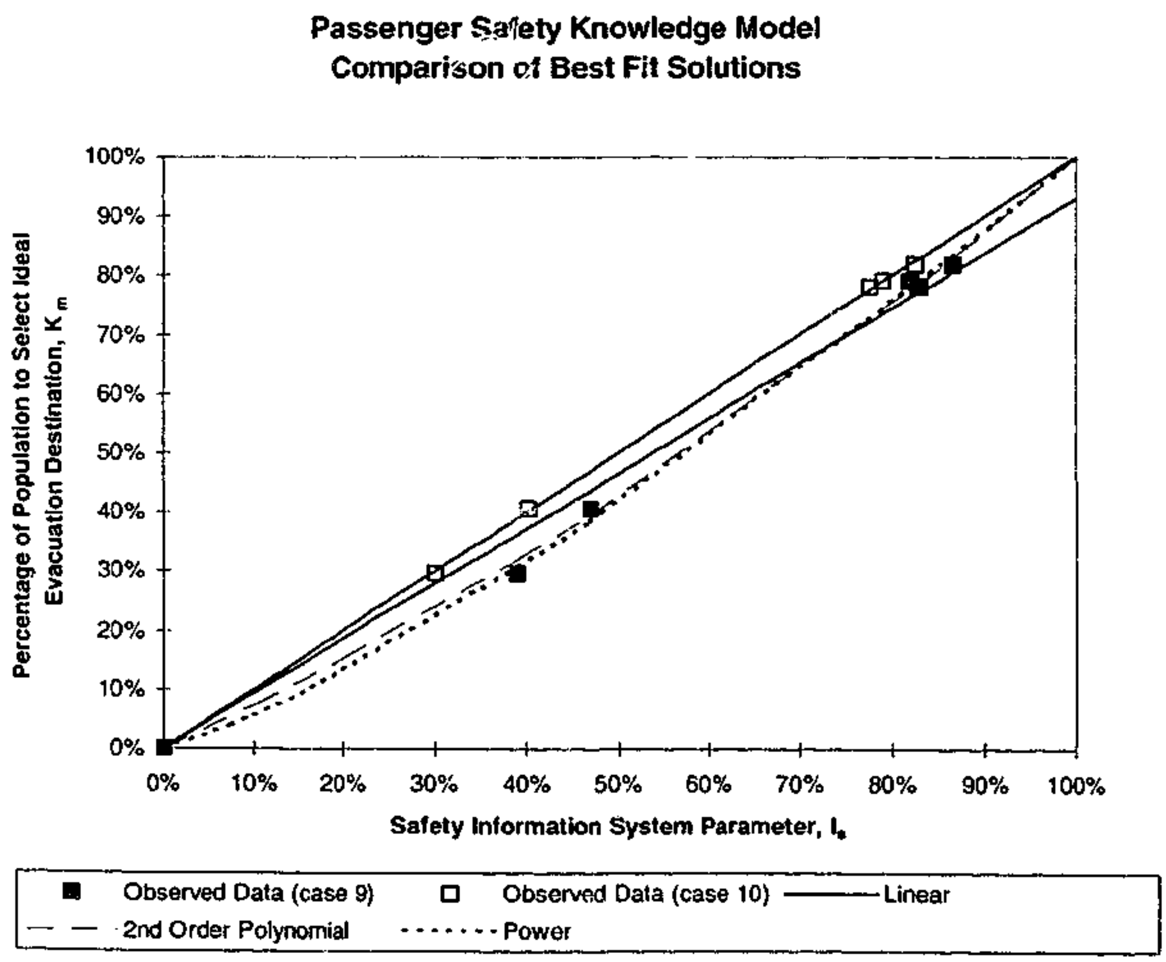


Figure 5.3 Comparison of Best Fit Solutions to Passenger Safety Knowledge Models

As can be appreciated from Figure 5.3 and Table 5.10 all approximation approaches provide excellent agreement with the observed data. For future calculations within this thesis submission the linear fit approximation of the Case 9 estimate of the safety information system will be adopted. That is:

$$S_m = 0.93.\ I_s \qquad (5.04)$$

Where, $I_s = {}^1/_4(L_a + A_d + N_p + e_x)$

Or, $$S_m = .2325\ (L_a + A_d + N_p + e_x) \qquad (5.05)$$

5.4.2 Alternative Destinations

With regard to alternative evacuation destinations the passengers responded with a wide variety of alternative destinations. The wide range in answers may be partly due to differences in terminology. For this reason it is important to group the answers in categories of intent. When assessing the responses three generic categories become evident as follows:

- *Muster/Assembly Area* - the assigned area that passengers are to receive further instruction and guidance from the crew (S_m);
- *External Area* - an area where passengers have ready access to water (S_e). This category may include the selection of explicit destinations:
    - Lifeboat/Embarkation Area (S_{e1})
    - Outside Decks, Exits, Doors (S_{e2})
    - Upper Decks (S_{e3})
    - Overboard (S_{e4})
- *Internal Area* - an area where there is no ready access to waters. However there may be access to further information, belongings or safety equipment such as life jackets (S_i). This category may include selection of explicit destinations such as the following:
    - Foyer/Reception (S_{i1})
    - Lower Decks/Car Decks (S_{i2})
    - Cabin/Seat (S_{i3})
    - Crew/Wait (S_{i4})
    - Don't Know (S_{i5})

The selection of muster/assembly area as first destination has already been assessed. However the selection of alternative destination selections has not yet been addressed. To identify the appropriate empirical relationships to adopt it is important to first identify what makes up the relationship. Firstly, it may be stated that all people will select a destination, S. That is

$$S = 100\% \tag{5.06}$$

Secondly, the people will select one of the generic destination categories identified above. That is

$$S = S_m + S_e + S_i \tag{5.07}$$

Finally, it assumed that the relative proportion of internal to external destination selection would not change with varying performance in the safety information system.

$$S_e/S_i = \text{constant, } c \tag{5.08}$$

Combining the above equations:

$S_i \quad = (1-S_m).\ 1/(1+c)$ (5.09)

$S_e \quad = (1-S_m).\ c/(1+c)$ (5.10)

To determine the constant, c, a least squares regression analysis was performed between S_i, S_e and S_m.

Figure 5.4 shows linear trends for the alternative destinations selection as a function of the muster destination selection.

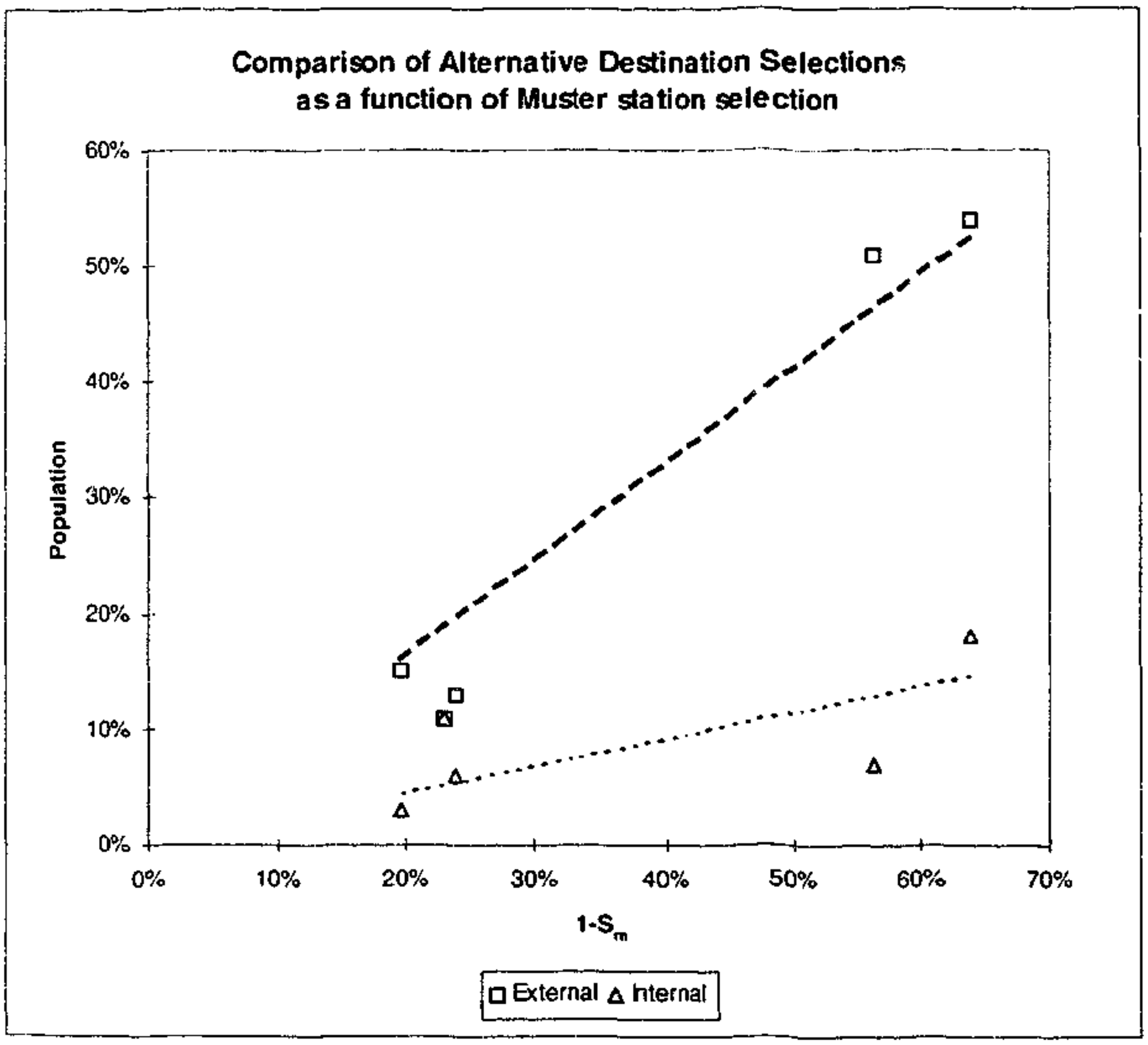


Figure 5.4. Comparison of Alternative Destination Selections

The average of the relative proportion of the external and internal destination selections was determined as:

$c \quad = 4$ (5.11)

Based on this value the equation for the external and internal destination selection are as follows:

$S_e \quad = {}^4/_5\,[1-S_m], \qquad R^2 = 0.977$ (5.12)

$$S_i = \frac{1}{5}\{1 - S_m\}, \qquad R^2 = 0.427 \qquad (5.13)$$

The regression statistic for the Internal Destination selection, S_i, is relatively low and accordingly it is likely that some factor, other than the information system parameter, S_m, is contributing significantly to the destination selection for the internal locations. When examining the layout of the various vessels it becomes clear that the vessel designs may contribute to the poor correlation between internal destination selection, S_i and the muster selection, S_m.

For example the following design factors may contribute to internal destination selection:

- No cabins on smaller vessels;
- No foyer on smaller vessels;
- Lower deck is open and at sea level on smaller vessels;
- Different lifejacket storage philosophies.

In addition many of the explicit destinations are selected by only a small proportion of the population for all vessels as such they may be subject to increased variability.

In particular each of the explicit internal destinations are selected by 5% of the population or less with the exception of the 12% destination selection of '*crew*' for the '*transit vessel*' trial. When examining this data more carefully we see that the categories of '*crew*' and '*wait*' have been combined where it has been assumed that '*wait*' implies wait for crew instruction. In addition, for the '*transit vessel,*' the lifejackets are located under passenger seats and also in the muster/assembly area. Where passengers have selected to get lifejackets that are under their seats they have been assigned to the '*wait*' destination selection because they will presumably don their lifejacket at their seat. This interpretation is subject to debate, as it could equally be said that the passengers are correctly carrying out their requirements as per safety instructions - i.e. they are moving to the correct location. In the absence of better data it is proposed to maintain the model developed for internal destination selection.

5.4.3 Detailed Breakdown of Destination Selections

There is considerable variability in the data gathered for the explicit destination selections for the internal destination selection. Due to the inconclusive nature of the breakdown of internal destination selection it is proposed that selection of each of the subcomponents that make up the internal destination be distributed evenly. This may be written as:

$$S_i/5 \quad = S_{i1} = S_{i2} = S_{i3} = S_{i4} = S_{i5} \qquad (5.14)$$

Where, S_{i1} = percentage that select Foyer

S_{i2} = percentage that to select Lower Deck

S_{i3} = percentage that to select Cabin/Seat

S_{i4} = percentage that to select Crew/Wait

S_{i5} = percentage that don't know

A large proportion of the population selected external destination, S_e, as the first destination and accordingly the regression statistics indicates a better fit to the data. In addition there is less opportunity for incorrect interpretation of response. It is worth noting that the regression statistic for the selection of lifeboats is very small. For this parameter a constant approximation of 4% selection for the lifeboat destination may be more appropriate across the range of vessels. However, to maintain a consistent basis for estimating the breakdown of destinations for evacuation analysis all explicit choices are described as a proportion of the total generic internal or external selection choices.

Table 5.11 Breakdown of Destination Selection Categories

Generic	Explicit	Equation	Coefficients	R^2
Internal, S_i		$y = A_1.x$	$A_1 = {}^1/_5$	0.427
	Foyer, Si1	$z_1 = B_1.y$	$B_1 = {}^1/_5$	0.048
	Lower Deck, S_{i2}	$z_2 = B_2.y$	$B_2 = {}^1/_5$	0.000
	Cabin/Seat, S_{i3}	$z_3 = B_3.y$	$B_3 = {}^1/_5$	0.002
	Crew/Wait, S_{i4}	$z_4 = B_4.y$	$B_2 = {}^1/_5$	0.798
	Don't Know, S_{i5}	$z_5 = B_5.y$	$B_3 = {}^1/_5$	0.940
External, S_e		$y = A_1.x$	$A_1 = {}^4/_5$	0.977
	Lifeboats, S_{e1}	$z_1 = B_1.y$	$B_1 = {}^1/_{10}$	0.147
	Outside Deck, S_{e2}	$z_2 = B_2.y$	$B_2 = {}^5/_{10}$	0.922
	Upper Deck, S_{e3}	$z_3 = B_3.y$	$B_3 = {}^3/_{10}$	0.861
	Over board, S_{e4}	$z_4 = B_4.y$	$B_4 = {}^1/_{10}$	0.874

Note: where x is $(1-S_m)$

It is noted that the approximations that are a poor fit to the data (Foyer, Lower Deck, Cabin/Seat, Lifeboats) represent less than 20% of the total distribution of destination selections not attributed to the muster station.

For the worst case of the vessels surveyed only 30% chose the muster station (or equivalent) as the first destination. Accordingly for the purposes of the application of the models presented herein at least 86% of the destination selections will be accurately modelled. The remaining 14% will be distributed amongst the less frequently selected locations such as the Foyer, Lower Deck, Cabin/Seat and Lifeboats.

5.4.4 Limitations

There are number of limitations placed on the application of the empirical design curves and coefficients derived herein. These may be summarised as follows:

- Only a single vessel per category was assessed for most vessel categories and minor differences between similar vessel in the same category have not been evaluated in full;
- All the vessels analysed sailed in Australian waters at the time of the survey. Accordingly issues such as language difficulties, cultural differences and racial differences were not assessed.
- The surveys were conducted prior to any disaster event occurring and do not represent the process of gathering knowledge during an evacuation. It is anticipated that passengers would have the ability to increase their knowledge base by listening to further announcements, re-reading muster bulletins and revisiting vessel layouts. Validation of a muster exercise in real conditions is currently being obtained through an ATSB accident investigation for one of the vessel surveyed previous to the incident. Unfortunately the results of the accident investigation are not available at time of publication of this thesis.

6. EVACUATION ANALYSIS

6.1 DESCRIPTION OF EVACUSHIP

As part of the thesis a software tool that incorporated many of the algorithms of standard evacuation analysis tools as well as the required maritime empirical models was developed. The software tool developed is known herein as 'EVACUSHIP.'

6.2 KEY FEATURES

EVACUSHIP uses a node-arc network layout infrastructure similar to that defined in Section 2.6.5. The EVACUSHIP key user features are described in terms of the major interface panels as follows:

- *Run* - Allows the alteration of general input factors;
- *Safety* - Allows the alteration of evacuation route choice based on safety media and experience;
- *Motions* - Allows the alteration of vessel motions;
- *Occupants* - Allows the alteration of vessel layout, and population distribution;

The *Run* user panel allows the input of the following factors:

- *How Many Runs?* - The number of runs per scenario;
- *Percentage Survival?* - The overall evacuation time is calculated on a set percentage of the entire population to successfully evacuate;
- *Maximum time?* - The program will consider all those that do no evacuate within the time limit to be fatalities;
- *Time interval?* - The simulation time interval at which each calculation step is completed;
- *Control Speed?* - The average walking speed of the population in ideal conditions;
- *Mean Height?* - Average height of the population;
- *Mean Weight?* - Average weight of the population;
- *Std. Dev.?* - The standard deviation about the associated mean (used for height, weight and control speed);
- *Start inclination?* - The inclination of the vessel deck when the evacuation is initiated;
- *Incline rate?* - The rate of capsize of the vessel (assumed linear);

The *Safety* panel includes the *Media*, *Experience*, *Analysis* and *Life Jacket Storage Policy* groups. The *Media* group defines the level of media system used to allow the level of safety knowledge of the passengers to be determined. The features of this group are as follows:

- *Regular/Repeated Training* - This represents ideal/optimum safety knowledge;
- *Practice Drill/Notices* - This represents very good safety knowledge;
- *Announcement/Pamphlets/Notices* - This represents good safety knowledge;

- *Announcement/Notices - Inside Only* - This represents moderate safety knowledge;
- *Notices* - This represents poor safety knowledge.

The *Experience* group defines the level of travel experience of each of the passengers on the vessel as follows:

- *Defence/Civilian Crew* - This represents optimum ideal experience levels;
- *Multi-Night Cruise* - This represents very little experience levels;
- *Overnight - To Tourist Location* - This represents moderate experience levels;
- *Overnight - From Tourist Location* - This represents good experience levels;
- *Hourly Tourist* - This represents good experience levels;
- *Hourly public transport* - This represents very good experience levels;
- *Unknown* - This represents very conservative experience levels;

The *Analysis Technique* group defines the type of empirical fit to the data required as follows

- *Best Fit to Data* - The program uses best fit polynomial to media experience data;
- *Upper Bound - 95% Confidence Limit* - The program provides an optimistic estimate;
- *Lower Bound - 95% Confidence Limit* - The program provides a conservative estimate.

The *Life Jacket Storage Policy* group allows the user to choose between life jackets located in cabins or at the muster station.

The *Motions* panel consists of the *Sea State, Vessel Type, Vessel Dimensions and Vessel Dynamic Motions* groups. The *Sea State* group allows the environmental design conditions to be identified including:

- *Significant Wave Height (m)*;
- *Spectral Peak Period (s)*.

The *Vessel Type* group defines which non-dimensionalised data should be used to determine vessel; response amplitude operators:

- *Large Monohull - Pinkster* - This calls data from vessels with a displacement greater than 150kDWT;
- *Small Monohull - API-RP-2SK* - This calls data from vessels with a displacement less than 150kDWT;
- *Catamaran* - This calls data from multihull vessels (inactive).

The *Vessel Dimensions* Group allows the key vessel dimensions defined to allow dimensionalisation of the vessel response amplitude operators. The dimensions are as follows:

- *Length bp (m)* - Length between perpendiculars;
- *Breadth (m)* - Breadth at midships;
- *Draft (m)* - Keel to waterline;
- *Tonnage (kDWT)* - Displacement of vessel;
- *VCG (m)* - Vertical centre of gravity pf the vessel.

The *Vessel Dynamic Motion* Group provides output of the anticipated linear and rotational motions at the vessel centre of gravity.

Occupant information includes the population Gender distribution (male: female ratio), Age (mean and standard deviation), and the distribution of the population on each floor.

Details of the EVACUSHIP General Arrangement Algorithm and Evacuation Simulation Algorithms are provided in Appendix 8. A sample layout of the EVACUSHIP user interface is also attached in Appendix 8.

6.3 TEST CASE CONDITIONS

The test case conditions considered for the parametric study are described in this section and include:

- Vessel start inclination;
- Vessel capsize rate;
- Vessel motions;
- Passenger motor ability;
- Passenger distribution;
- Life jacket storage;
- Global way finding based on media and experience.

It is noted that the parametric study conducted herein does not include consideration of the preparation phase or the embarkation stages. For the purposes of validating the hypothesis proposed within this thesis the exclusion of these stages provides an added conservatism. However, it is noted that for application to design, it is important these stages be included in their entirety.

6.3.1 Vessel Start Inclination

The vessel start inclination will be assigned for 5 start scenarios as follows 0, 10 and 20°.

Run Identifier	I0	Start Inclination = 0°
	I1	Start Inclination = 10°
	I2	Start Inclination = 20°

6.3.2 Vessel Capsize Rate

It is noted that vessel list rate may vary from complete capsize within few minutes or partial capsize over a number of hours. Given that the evacuation requirements by IMO (1999b) require complete evacuation within 60 minutes a reasonable estimate for vessel list rate is to consider capsize to 45° at 60 minutes. By comparison more rapid capsize rates up to 180°/hr are also assessed. Although vessel capsize often tends to occur in stages of rapid and gradual capsize the variability is dependant on the vessel, cause of failure and prevailing environmental conditions. For the purposes of the parametric study the vessel capsize rate is assumed to be linear.

Run Identifier	L0	List Rate = 0°/hr
	L1	List Rate = 45°/hr
	L2	List Rate = 90°/hr
	L3	List Rate= 180°/hr

6.3.3 Vessel Motions

For the purposes of this study it is assumed that the roll motions have an amplitude of 10° and a roll period of 10 seconds. It is also assumed that the passenger deck level will be at the level of the centre of gravity of the vessel.

Run Identifier $M0 = 0^{\circ}$, 10s

$M1 = 10^{\circ}$, 10s

6.3.4 Passenger Motor Ability

The normal walking speed will be randomly assigned using the standard normal distributions with a mean of 1.42m/sec and standard deviation of 0.2. In addition the following population distribution is assigned

Mean Height	= 1.73m
Age_m	= 45years
G	= 50%

For the purposes of investigating the influence of maritime factors on the evacuation of passenger ships the walking speed of each passenger is determined as follows:

$$V = \xi_{DC}.\ \xi_{Sci}.\ \xi_{age}.\ \xi_{gender}.\ \xi_{congestion}\ \xi_{infant}.\xi_{kinetosis}\ Vn$$

Where,

ξ_{DC}	$= 1\text{-}0.0017.A^{3.234}$		from (4.32)
ξ_{Sci}	$= 1$		
ξ_{age}	$= -0.000169\ Age^2 + 0.00661\ Age + 1.021$	$= 0.976$	from (4.36)
ξ_{gender}	$= (0.13G+1) / 1.078$	$= 0.988$	from (4.39)
$\xi_{congestion}$	$= 1.6e^{-.35\rho}/Vn$	$= 1.127\ e^{-.35\rho}$	from (4.42)
ξ_{infant}	$= 1$		
$\xi_{kinetosis}$	$= 1$		

The lateral acceleration, A, and the population congestion, ρ, are time varying parameters dependant on the list, roll and passenger distribution.

6.3.5 Vessel Description

The vessel considered for the parametric study was based on the floor plan of typical cruise ship operating in Australian waters. Only one deck of the vessel was considered in the analysis with approximately 130 cabins. The deck analysed primarily consists of a system of corridors connecting the cabins to 5 main stairwells. A minor stairwell at the aft of the vessel was ignored for the analysis, as it does not provide access to upper decks. The deck consists of one main communal gathering area, the foyer, which adjoins the communications centre and the Purser's office. Figure 6.1 presents the deck layout considered in the analysis. An overlay of the deck model is also provided in Figure 6.1. The following identification system has been adopted to depict the various areas of interest.

- Cabins, Large purple squares;
- Corridors, Thin green arrows;
- Junctions, Small blue squares;
- Foyer, Very large green circle;
- Muster/Assembly Stations, Large yellow circles;
- Embarkation Stations, Large red circles.

D DECK

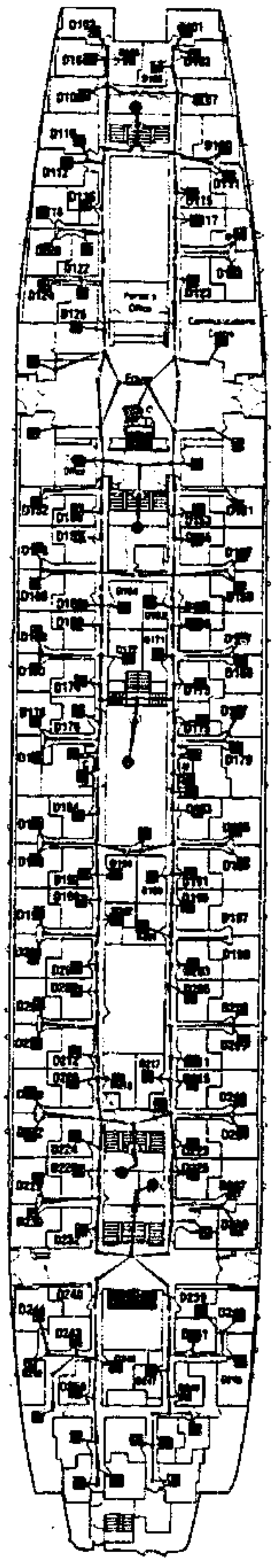


Figure 6.1 Standard Passenger Ship Deck

6.3.6 Passenger Distribution

The passenger distribution for the parametric study is as follows:

- 2 people per cabin, 260 in total;
- Passengers randomly distributed on the deck in question (not necessarily in the assigned cabin);
- Each person is a assigned a cabin and a muster station;
- As only one deck was considered no stairwells were assessed. Accordingly passenger muster stations and embarkation points were located at the designated stairwells of the vessel layout;
- The evacuation stops when the passenger has reached the assigned embark on station.

6.3.7 Safety Policy & Global Way finding

The vessel safety policy will influence the route that each passenger over the course of an evacuation. Two maritime specific factors with relation to the vessel safety policy are life jacket storage policy and safety media policy. The parametric study includes consideration of both factors. The life jacket storage policy separated into the following categorisations:

Run Identifier	S0	Life Jackets at Muster/Assembly Stations:
	S1	Life Jackets in Cabins.

Furthermore the destination selection of passengers will be dependant on the following media system parameters:

	S_m	$= 0.93I_s$	from (5.05)
Where,	I_s	$= {}^1/_4\,(L_a + A_d + N_p + e_x)$	
	S_c	$= {}^4/_5\,[1 - S_m]$	from (5.12)
	S_i	$= {}^1/_5\,[1 - S_m]$	from (5.13)
	S_{ij}	$= S_i/5$ where $j = 1,2..5$	from (5.14)
	S_{ck}	$= S_c/10$ where $k = 1,4$	from Table 5.11
	S_{c2}	$= 5.S_c/10$	
	S_{c3}	$= 3.S_c/10$	

The base case condition for the parametric study is based on media and experience parameters of the 'ideal' passenger compliment (i.e. defence or civilian crew with regular repeated training). It is assumed that the entire population of the base case condition have listened to a safety announcement (A_d =100%), looked at a layout of the ship (L_a=100%) and examined the safety notices supplied (N_p=100%). Furthermore the passengers are all assumed to have had previous experience on the ship (e_x=100%).

Accordingly the safety information system parameter, I_s is assumed to be equal to 100%. Based on the relationship in equation 5.05, 93% of the passenger compliment will be prompted to go directly to the muster/assembly station.

By comparison alternative information system parameter representing a more realistic passenger compliment will be based on the media and experience factors for an overnight tourist ferry described by category C(i). The parameters are as follows:

$La = 99\%$, $A_d = 75\%$, $N_p = 84\%$	from Table 5.7
$e_x = 70\%$	from Table 5.8

Finally, the worst-case scenario is based on the media system consists only of public notices (i.e. no drill or announcements). This scenario is coupled with the experience level of the overnight tourist ferry.

$La = 41\%$, $A_d = 0\%$, $N_p = 23\%$	from Table 5.7
$e_x = 70\%$	from Table 5.8

The three media system scenarios are categorised as a sub-component of the lifejacket storage philosophy as follows:

Run Identifier	SX/0	Base Case (Ideal Media/Experience)
	SX/1	Typical Case (Overnight Tourist Ferry)
	SX/2	Worst Case (Low experience/Low Media System)
Where,	X	Jacket Storage Policy Run Identifier

6.3.8 Run Details

For each condition the passengers were randomly distributed on the deck. The passenger base walking speed was randomly assigned using a normal distribution random number generator. Each analysis for a single condition was repeated 45 times with the static walking speed and passenger location distribution changed for each run. Each condition is assigned a run identifier as follows:

Run Identifier Ix-Lx-Mx-Sx/x

Where,
I = Start Inclination Run ID
L = List Rate Run ID
M = Roll Motion Run ID

S = Safety Policy Run ID with <Life Jacket Storage ID>/<Media ID>

The performance measure monitored to identify the influence of maritime specific parameters on the passenger evacuation is based on the overall evacuation time for 95% of the occupants to reach the muster station. In particular the performance measure indicates the percentage increase in evacuation time due to the maritime factor under investigation. This performance measure, denoted herein as T_R, is determined as follows:

$$T_R = T_q/T_p - 1$$

Where, T_R = Maritime Influence Performance Measure
T = Evacuation Time (s)
p = base case run identifier
q = maritime case run identifier

The influence of maritime factors is characterised using the descriptive influence rating system described in Table 6.1.

Table 6.1 Descriptive Influence Rating

Maritime Influence Performance Measure, T_R	Descriptive Influence Rating
0-4%	Negligible
5-9%	Minor
10-19%	Moderate
20-30%	Major
>30%	Extreme

6.4 FINDINGS

The evacuation times for each of the cases investigated in the parametric study are documented in Table 6.2. A comparison of the evacuation times for a variety of maritime altered scenarios against unaltered scenarios is documented in Table 6.3.

Table 6.2 Results of Parametric Evacuation Analysis

Run No.	Run ID	Vessel Start Incline (°)	List Rate (°/hr)	Roll Motion Amp (°)	Life Jacket Loc.	Media System	Evacuation Time (s)			
							Max	Avg	Min	Std
01	I0-L0-M0-S0/0	0	0	0	Muster	B	2:42	2:16	1:58	0:10
02	I0-L0-M1-S0/0	0	0	10	Muster	B	2:48	2:16	1:54	0:12
03	I0-L0-M1-S1/0	0	0	10	Cabin	B	2:48	2:30	2:08	0:10
04	I0-L0-M1-S1/1	0	0	10	Cabin	T	3:00	2:38	2:16	0:10
05	I0-L0-M1-S1/2	0	0	10	Cabin	W	3:18	2:56	2:38	0:10
06	I0-L1-M1-S0/0	0	45	10	Muster	B	2:38	2:16	1:54	0:10
07	I0-L0-M1-S0/0	10	0	10	Muster	B	2:44	2:24	2:04	0:10
08	I1-L1-M0-S0/0	10	45	0	Muster	B	2:40	2:16	1:54	0:10
09	I1-L1-M1-S0/0	10	45	10	Muster	B	3:04	2:24	2:02	0:12
10	I1-L2-M1-S0/0	10	90	10	Muster	B	2:58	2:24	1:58	0:14
11	I1-L3-M0-S0/0	10	180	0	Muster	B	2:30	2:14	1:58	0:08
12	I1-L3-M0-S1/0	10	180	0	Cabin	B	2:50	2:26	2:06	0:10
13	I1-L3-M1-S0/0	10	180	10	Muster	B	2:50	2:26	1:58	0:12
14	I2-L0-M0-S0/0	20	0	0	Muster	B	2:54	2:22	2:04	0:10
15	I2-L0-M1-S0/0	20	0	10	Muster	B	3:44	2:58	2:30	0:14
16	I2-L1-M1-S0/0	20	45	10	Muster	B	4:06	3:04	2:28	0:18
17	I2-L1-M1-S0/1	20	45	10	Muster	T	3:52	3:10	2:38	0:16
18	I2-L1-M1-S1/1	20	45	10	Cabin	T	4:10	3:40	3:10	0:14

Run Note: B = Base Case Media System (Refer Section 6.3.7)
T = Typical Case Media System (Refer Section 6.3.7)
W = Worst Case Media System (Refer Section 6.3.7)
Min = minimum; Avg = Average; Max = Maximum; Std = Standard Deviation.

Table 6.3	Comparison of Evacuation Times from Parametric Study									
	p vs. q	Vessel Start Incline (°)	List Rate (°/hr)	Roll Motion Amp (°)	Life Jacket Loc.	Media System	Evacuation Time (T_x), Standard Deviation (S_x). T_p	S_p	T_q	S_q
Start Incline a)	02 vs. 07	0 vs. 10	0	10	M	B	2:16	0:12	2:24	0:10
b)	02 vs. 15	0 vs. 20	0	10	M	B	2:16	0:12	2:58	0:14
c)	06 vs. 09	0 vs. 10	45	10	M	B	2:16	0:10	2:24	0:12
d)	06 vs. 16	0 vs. 20	45	10	M	B	2:16	0:10	3:04	0:18
List Rate a)	02 vs. 06	0	0 vs. 45	10	M	B	2:16	0:12	2:16	0:10
b)	07 vs. 09	10	0 vs. 45	10	M	B	2:24	0:10	2:24	0:12
c)	07 vs. 10	10	0 vs. 90	10	M	B	2:24	0:10	2:24	0:14
d)	07 vs. 13	10	0 vs. 180	10	M	B	2:24	0:10	2:26	0:12
e)	15 vs. 16	20	0 vs. 45	10	M	B	2:58	0:14	3:04	0:18
Motions a)	01 vs. 02	0	0	0 vs. 10	M	B	2:16	0:10	2:16	0:12
b)	08 vs. 09	10	45	0 vs. 10	M	B	2:16	0:10	2:24	0:12
c)	14 vs. 15	20	0	0 vs. 10	M	B	2:22	0:10	2:58	0:14
Jacket a)	02 vs. 03	0	0	10	M vs. C	B	2:16	0:12	2:30	0:10
b)	11 vs. 12	10	180	0	M vs. C	B	2:14	0:08	2:26	0:10
c)	17 vs. 18	20	45	10	M vs. C	T	3:10	0:16	3:40	0:14
Media a)	03 vs. 04	0	0	10	C	B vs. T	2:30	0:10	2:38	0:10
b)	03 vs. 05	0	0	10	C	B vs. W	2:30	0:10	2:56	0:10
c)	16 vs. 17	20	45	10	M	B vs. T	3:04	0:18	3:10	0:16
Combined Effects	01 vs. 18	0 vs. 20	0 vs. 45	0 vs. 10	M vs. C	B vs. T	2:16	0:10	3:40	0:14

Note:
B = Base Case Media System (Refer Section 6.3.7)
T = Typical Case Media System (Refer Section 6.3.7)
W = Worst Case Media System (Refer Section 6.3.7)
p, q = Run Numbers (Refer Table 6.2)

Table 6.4 Influence Rating of Maritime Factors on Evacuation Time
(Including Student T Test)

	p vs. q	Ratio (t_q/t_p)	DoF (ν)	Student T	$t_p \neq t_q$ $T > t_{\alpha/2}$ (α=5%)	Influence Performance Measure (T_R)	Influence Rating
Start Incline a)	2 vs. 7	1.06	85	3.44	✓	6%	Minor
b)	2 vs. 15	1.31	86	15.28	✓	31%	Extreme
c)	6 vs. 9	1.06	85	3.44	✓	6%	Minor
d)	6 vs. 16	1.35	69	15.64	✓	35%	Extreme
List Rate a)	2 vs. 6	1.00	85	0.00	×	0%	Negligible
b)	7 vs. 9	1.00	85	0.00	×	0%	Negligible
c)	7 vs. 10	1.00	80	0.00	×	0%	Negligible
d)	7 vs. 13	1.01	85	0.86	×	1%	Negligible
e)	15 vs. 16	1.03	83	1.77	×	3%	Negligible
Motions a)	1 vs. 2	1.00	85	0.00	×	0%	Negligible
b)	8 vs. 9	1.06	85	3.44	✓	6%	Minor
c)	14 vs. 15	1.25	80	14.04	✓	25%	Major
Jacket a)	2 vs. 3	1.10	85	6.01	✓	10%	Moderate
b)	11 vs. 12	1.09	84	6.29	✓	9%	Minor
c)	17 vs. 18	1.16	86	9.47	✓	16%	Moderate
Media a)	3 vs. 4	1.05	88	3.79	✓	5%	Minor
b)	3 vs. 5	1.17	88	12.33	✓	17%	Moderate
c)	16 vs. 17	1.03	87	1.67	×	3%	Negligible
Combined Effects	1 vs. 18	1.62	80	32.75	✓	62%	Extreme

Note:
p, q = Run Numbers (Refer Table 6.2)
DoF = Degrees of Freedom
$t_{\alpha/2}$ = 2.01 (Where, α = 0.05, n = 45)
n = number of runs

6.5 Discussion of Results of Evacuation Analysis

The results of the evacuation analysis are divided into the following categories:

- Start Incline – inclination about the longitudinal axis of the vessel at the start of the evacuation (refer Section 6.3.1)
- List Rate – rate of capsize about the longitudinal axis of the vessel (refer Section 6.3.2)
- Motions – wave induced dynamic vessel roll motions (refer Section 6.3.3)
- Jacket – the life jacket storage philosophy (refer Section 6.3.7)
- Media – media system employer and expected travel experience of the target passengers (refer Section 6.3.7)

The influence of the above factors on the total evacuation time of passenger vessels is discussed in Sections 6.5.1 to 6.5.5.

6.5.1 Start Incline

The influence of capsize at the commencement of an evacuation was minor (6%) for start inclinations of 10 degrees or less even with the capsize rate of 45°/hr and roll motions of 10° amplitude at a frequency of 0.1Hz. However when the capsize offset at the commencement of the evacuation is at 20° the influence on evacuation times becomes extreme (31-35%) even with a negligible capsize rate.

For a slowly capsizing vessel the implication of this finding is that evacuation of the vessel may commence at list of 10° with only a minor influence on the total evacuation time. However, it is noted that only one deck has been considered in this analysis and there has been no consideration in the parametric study of the influence of human factors on the delay of individuals to start an evacuation. Accordingly, short term rapid capsize rates in combination with more complex passenger vessel layouts (multi-deck) and human factors may lead evacuation of individuals to start at inclinations greater than 10° even where the Master orders the evacuation to commence at an initial capsize offset of less than 10°. Furthermore, interpolation between start inclinations of 10 and 20° indicates that even a start inclination of 15° will lead to moderate influence on evacuation time (15-17%).

6.5.2 List Rate

An assessment of the list/capsize rate indicates a negligible influence on the total evacuation times of the deck analysed. However, it is noted that the total evacuation time was less than five minutes for all cases considered. On larger (or multi-deck) vessels it is anticipated that the influence of capsize rate would have more influence on total evacuation times. This is supported by the influence of start capsize offset as described in Section 6.5.1.

6.5.3 Vessel Motions

The results of the parametric study indicate that vessel motions have a negligible impact on the total evacuation time for the level, static conditions. Where the vessel has a start inclination of 10° and a list/capsize rate of 45°/hr the vessel motions have a minor impact on total evacuation times (6%). However, where the vessel has a start inclination of 20° that is maintained throughout the evacuation the vessel motions have a major influence (25%) on total evacuation times. These findings indicate that vessel motions and vessel list should be considered together rather than separately. Furthermore it is noted that vessel motions are typically determined for the undamaged condition (i.e. no list and no intake of water). Where the vessel is damaged and capsizing the vessel motions may be different than for the intact condition due to water surface effects and the change in the mass distribution within the vessel due to the intake of water. Consideration of vessel motions in the damaged condition is required to confirm the final magnitude of the influence of vessel motions on evacuation times.

6.5.4 Jacket Storage

The jacket storage location has a minor to moderate influence on evacuation times (9-16%) for the evacuation of a single deck. It is noted that the extension of the jacket storage philosophy at the cabin on a multi-deck vessel will result in an increase in influence on maritime factors on the total evacuation time due to the potential requirement of passengers to traverse multiple decks to retrieve their lifejacket from their cabin. Accordingly the results obtained are conservative in the terms of the scope of this thesis. That is, the influence determined through the parametric study is less than the actual influence.

6.5.5 Media Systems

The typical media system had a negligible to minor influence on evacuation times (3-5%) when compared with the base case, ideal scenario. However a poor media system indicated a moderate influence on evacuation times (17%) when compared with the base case, ideal scenario. It is noted that, as with the jacket storage philosophy, a greater influence is anticipated on a multi-deck vessel where passengers have the potential to traverse multiple decks to get to intermediate goals. Accordingly the influence of maritime factors determined is conservative within the scope of this thesis.

6.5.6 Combined Influence

The factor that has the most significant impact on evacuation times is the start inclination. Other factors have negligible to moderate influence when considered separately. It is noted that vessel motions only have a major influence at a start inclination of 20°. However, the parametric study indicates that the cumulative influence of all the maritime factors considered is extreme. The comparison of the evacuation times for the base case scenario, which represents typical on land evacuation analysis techniques, and the maritime scenario indicates an increase of up to 62%.

6.6 LIMITATIONS

The parametric study conducted is subject to the following limitations:

- Influence of Fire/Smoke were not considered;
- Crew/passenger interaction was not considered;
- No delay time due to initial cues was considered;
- The influence of fatigue was not considered;
- Increased safety knowledge during the evacuation is not considered;
- The influence of egress up stairways was not considered;
- Operations to prepare life rafts and abandon the mother ship were not considered.

It is noted that the above parameters are necessary for the evacuation analysis of a passenger ship but in the context of this thesis the exclusion of the above factors provide an increased conservatism in the approach adopted to prove the hypothesis put forward

7. CONCLUSIONS

The literature review of Section 2 indicated that, at the commencement of this thesis, there existed no motor ability data suitable for application to evacuation analysis of passenger ships, nor was there any data reflecting the influence of media systems on destination selection. Furthermore, prior to the commencement of this thesis, the overall influence of maritime factors on evacuation analysis had never been quantified. Accordingly Section 3.1 presents the hypothesis defended in this thesis as:

'Maritime specific features have a significant influence on the evacuation analysis outcomes of passenger vessels: These features should be considered in the early stage of design.'

A special purpose facility was designed, built and commissioned to provide a means of obtaining the data required. 1000 people were tested in the facility for over 30 scenarios including varying list, roll, congestion and population distributions. Models describing the motor ability and in particular the walking speeds of passengers during the evacuation of a dynamic/capsizing environment was developed for the first time based on the data gathered in this thesis. The motor ability data was found to be consistent with the traditional models developed in the past describing the reduced performance of occupants in a dynamic environment for naval operations due to motion induced interruptions (failure events). However the empirical and theoretical data supporting the traditional models was found to be dramatically over conservative. Furthermore, the data in this thesis indicated that a single tipping threshold value was inconsistent with the performance of occupants on vessels. Accordingly a probabilistic distribution describing the number of failures and the duration of failures was found to describe the performance variance due intangible parameters not described by the traditional models such as motivation, skill and co-ordination. It was found that the traditional performance degradation models did not describe the influence of a dynamic/capsizing environment on walking speeds as well as a simple least squares regression power fit. Accordingly the empirical power fit model was adopted for subsequent evacuation analysis conducted in this thesis.

It was identified in this thesis that, walking speeds in a dynamic capsizing environment were also published by Bles, Nooy and Boer (2001) subsequent to Brumley and Koss (2000) publishing the findings of the research of this thesis. The data gathered by Bles, Nooy and Boer (2001) was re-analysed in this thesis in terms of the lateral accelerations acting on the centre of gravity of the evacuee in the dynamic environment and compared with the work of this thesis. A comparison of the data published externally with the work conducted in this thesis indicated that the two data sets were similar yet the work of Bles, Nooy and Boer (2001) indicated a greater influence of the capsize/dynamic environment on walking speeds than observed in the work of this thesis. The difference between the results was identified as being due to the differences in test set up and procedures. In particular, the facility of Bles, Nooy and Boer (2001) was shorter than the facility used to obtain the data for this thesis such that occupant acceleration and deceleration may play an important role. Furthermore, the work of this thesis included the differences in emotional states between the casual walking data gathered and the evacuation walking data. It was concluded that the motor ability data of this thesis is more suited to evacuation of larger vessels with long corridor sections while the work of Bles, Nooy and Boer (2001) is more representative of walking through confined complex spaces.

In addition to the work on motor ability, site surveys of over 640 passengers on four different vessels were conducted to determine the influence of a range of media systems on the destination selection of passengers. A strong relationship was observed between the use of information systems by passengers, past experience and the likely destination selection of passengers for an emergency evacuation. This relationship enables distribution of passengers on a vessel during an emergency evacuation to be determined based on the media systems employed. The empirical models to describe the influence of maritime specific variables are presented in Sections 4.4 and 5.4

An evacuation analysis tool, which includes the maritime specific factors, was developed as part of this thesis and is discussed in Sections 6.1 and 6.2. A typical deck of a cruise ship has been analysed for 18 conditions with 45 runs per condition described in Sections 6.3. The results have been compared against typical on land evacuation analysis techniques in Section 6.4 and a statistically significant difference has been observed between the cases. Furthermore a rational basis for evaluating the magnitude of influence that the maritime features have on the evacuation analysis has been developed and is presented in Table 6.1. The evacuation analysis indicates an influence of maritime factors ranging from negligible to extreme. However the combination of all maritime factors leads to a potential increase in total evacuation time of 62% for the muster stage of the evacuation alone when compared against on land techniques.

Accordingly, the world first data obtained, new models developed and evacuation analysis conducted provide evidence to support the first statement of the hypothesis that, '*Maritime specific features have a significant influence on the evacuation analysis outcomes of passenger vessels*'.

The basis for accepting the second phase of the hypothesis that these maritime specific features, '*should be considered in the early stage of design,*' is supported by the following:

1. High correlation coefficients were obtained for the empirical models developed, accordingly maritime features can be described in quantitative mathematical terms;
2. The maritime features can be readily incorporated into evacuation analysis models as evidenced by the EVACUSHIP model;
3. The maritime features do not constitute a significant capital expenditure for inclusion into conventional on land evacuation analysis tools as evidenced by the EVACUSHIP model;

4. The maritime features do not constitute a significant operating expenditure for the development of models for specific vessels as evidenced by the vessel layout developed within this thesis;
5. The combined influence of maritime factors have the potential to be extreme (i.e. as much as 62%)
6. IMO have a mandate to conduct evacuation analysis on new build passenger vessels in the early stage of design.

Accordingly it is concluded that the hypothesis argued in this thesis should be accepted in its entirety. That is:

'Maritime specific features have a significant influence on the evacuation analysis outcomes of passenger vessels: These features should be considered in the early stage of design.'

8. RECOMMENDATIONS

This section presents the recommendations for future research topics and practices.

8.1 FUTURE RESEARCH

The areas of future research can be categorised on the basis of the following objectives:

- Completing knowledge identified as lacking in the review of literature
- Validating the motor ability and destination selection models in environments that have not been tested, but for which there is a rational basis for extrapolation.
- Extending motor ability and destination selection models in so as to remove limitations

8.1.1 Completing Knowledge

It was identified in the literature review that the following areas require more information so that a comprehensive analysis of maritime vessels can be conducted:

- *Validate on land goal selection statistics for application to maritime vessels* - Validation can only be achieved through post accident investigations based on surveys of passengers. Evacuation trials have proven to be limited in the development of typical cognitive/way finding statistics because passengers are generally advised of the likely occurrence of the trial and also know that the trial is not a real emergency. Crew typically undergo more intense training prior to the trials to ensure the safety of participants and strategies are typically artificially imposed to assist in monitoring of staged evacuations. It is noted that ATSB have conducted surveys on the evacuation to muster station of a ferry in Australian waters due to a minor incident. Advice has been given to ATSB to ensure that the passenger surveys provide sufficient data to validate goal selection models. The results of this survey are in draft format and are not currently available to the public. However, when made available, it is recommended that a comparison with the results be made with the current on land data and considered for use in evacuation analyses.

- *Provide a unified theory for the operation and abandonment of survival craft* - It was identified in the literature review that data had been gathered on the risk of inflation failure, risk of injury, risk of capsize and the loading rates of survival craft in static and dynamic conditions. Further investigation into this area needs to be conducted to provide a unified theory that is compatible with evacuation analysis. It was noted in the literature review that a theory that relates risk of injury to loading rates has been developed. However no evidence is provided in the references to support the theory put forward.

- *Obtain statistical rather than deterministic failure rates, durations and overall task degradation due to dynamic and capsizing conditions for all maritime operational tasks* - It was identified in this thesis that operational performance degradation for maritime operations are typically based on deterministic tipping thresholds (either theoretically or empirically derived). It was observed from the trials conducted in this thesis that the statistical variation between people is so great that a probabilistic assignment of the tipping duration should be considered. This is particularly the case for mission critical naval operations that are already based on a probabilistic assignment of environmental conditions and consequently lateral accelerations.

8.1.2 Validating Extrapolations

It is noted that the motor ability data obtained in this thesis is limited to the predominant conditions of roll and list about the longitudinal axis of the vessel corridor. Bles, Nooy and Boer (2001) obtained data for pitch and roll motions in confined spaces and stairwells for less severe conditions as tested in this thesis. It is recommended that the data gathered in this thesis be used to provide a rational basis for extrapolating the work of Bles, Nooy and Boer (2001) to more severe conditions in degrees of freedom and path conditions not tested in this thesis. Accordingly it is recommended that these alternative degrees of freedom and paths be validated for more severe conditions in due course.

It is noted also that there is a minor disparity between the data obtained within this thesis and that obtained by Bles, Nooy and Boer (2001) due to differences in the trial set-up. It is recommended that a case study comparing the differences of the set-ups on a single site be conducted to validate the proposed basis for the disparity.

The data obtained for the destination selection in this thesis has not yet been validated through observations of passengers during a real ship evacuation. In addition to the goal selection data, the destination selection data can also be validated through surveys. ATSB have been advised on the appropriate means of conducting a survey to validate the data gathered in this thesis. Accordingly, it is recommended that the findings of the ATSB accident investigation be used to validate the data gathered in herein.

8.1.3 Extending Formulation

The motor ability data gathered has been conducted for short duration trials only. Accordingly the influence of motion sickness and fatigue has not been fully investigated. It is noted that theories are currently available which predict motion sickness incidence and fatigue of people on vessels. It is recommended that a correlation between these theories and task performance degradation be developed with a focus on walking speeds and a view to developing an all-encompassing unified theory for application to evacuation.

The way finding data and model is predominantly focussed on identifying the population that move to the muster station. While reasonable correlation was found for many other potential destinations it is recommended that the database be extended to increase confidence on these minor destinations.

APPENDIX 1: Co-ordinate System

RIGID BODY MOTION (after Branner and Sangberg 1997)

The rigid body motion of any point in a moving vessel can be written in vector form as:

$$\mathbf{s} = \eta_T + \eta_R \times \sigma \tag{A1.1}$$

Where, $\eta_T = (\underset{\text{surge}}{\eta_1}, \underset{\text{sway}}{\eta_2}, \underset{\text{heave}}{\eta_3})$

$\eta_R = (\underset{\text{roll}}{\eta_4}, \underset{\text{pitch}}{\eta_5}, \underset{\text{yaw}}{\eta_6})$

Where σ is the location vector measured from the centre of gravity of the vessel and 'x' denotes the vector product. See also definition in Figure A1.1. When these motions are calculated in a frequency domain formulation they get the form:

$$\eta_i = \sigma_i \cos(\omega t + \Theta_i) \tag{A1.2}$$

Where ω is the frequency of encounter and σ_i and Θ_i are the amplitude and phase respectively. The translation and rotation accelerations are then calculated by differentiating equation A1.2 twice with respect to time, thus:

$$\ddot{\eta}_i = \frac{\partial^2 \eta_i}{\partial t^2} = -\omega^2 \eta_i \tag{A1.3}$$

The acceleration of any point in the vessel can be written as:

$$\mathbf{a} = \mathbf{g} + \ddot{\eta}_T + \ddot{\eta}_R \times \sigma \tag{A1.4}$$

where g is the gravity vector as experienced in the coordinate system moving with the ship. Since the gravity vector is fixed to the earth and roll, pitch and yaw motions are defined in the coordinate system fixed to the ship, the coordinate transformation matrix is dependant on the order in which the three rotations are applied. Using the roll-pitch-yaw order of rotation the equation A1.4 becomes:

$$\mathbf{a} = -g\begin{bmatrix} \cos\eta_4 \sin\eta_5 \cos\eta_6 + \sin\eta_4 \sin\eta_6 \\ \cos\eta_4 \sin\eta_5 \sin\eta_6 - \sin\eta_4 \cos\eta_6 \\ \cos\eta_4 \cos\eta_5 \end{bmatrix} + \begin{bmatrix} \ddot{\eta}_1 + \ddot{\eta}_5 \bar{z} - \ddot{\eta}_6 \bar{y} \\ \ddot{\eta}_2 - \ddot{\eta}_4 \bar{z} + \ddot{\eta}_6 \bar{x} \\ \ddot{\eta}_3 + \ddot{\eta}_4 \bar{y} - \ddot{\eta}_5 \bar{x} \end{bmatrix} \tag{A1.5}$$

Where ($\bar{x}$, $\bar{y}$, $\bar{z}$) is the position of the considered point relative to the centre of gravity of the vessel.

CONSIDERATION OF CAPSIZING VESSEL

Where the vessel capsize angle is large about the roll axis the vessel equation A1.5 becomes:

$$\mathbf{a} = -g\begin{bmatrix} 0 \\ -\sin(\phi+\eta_4) \\ \cos(\phi+\eta_4) \end{bmatrix} + \begin{bmatrix} \ddot{\eta}_1 + \ddot{\eta}_5\bar{z} - \ddot{\eta}_6\bar{y} \\ \ddot{\eta}_2 - \ddot{\eta}_4\bar{z} + \ddot{\eta}_6\bar{x} \\ \ddot{\eta}_3 + \ddot{\eta}_4\bar{y} - \ddot{\eta}_5\bar{x} \end{bmatrix} \qquad \text{(A1.6)}$$

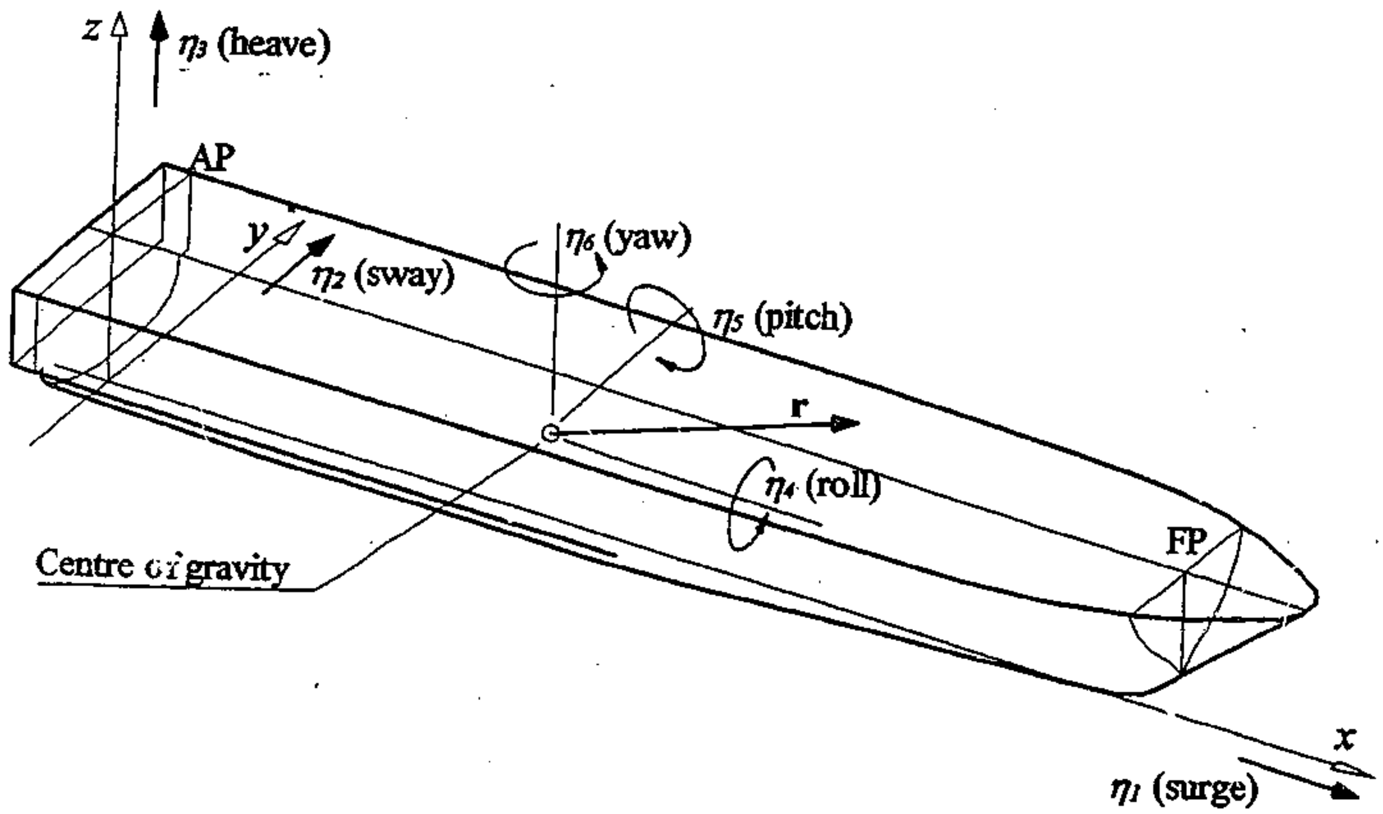


Figure A1.1 Global Axis System

Local Co-ordinate System

The local co-ordinate system represents the motions of the evacuee at the VCG of the evacuee. The co-ordinate system is adopted from the system for mechanical vibration influencing humans as defined in ISO 2631

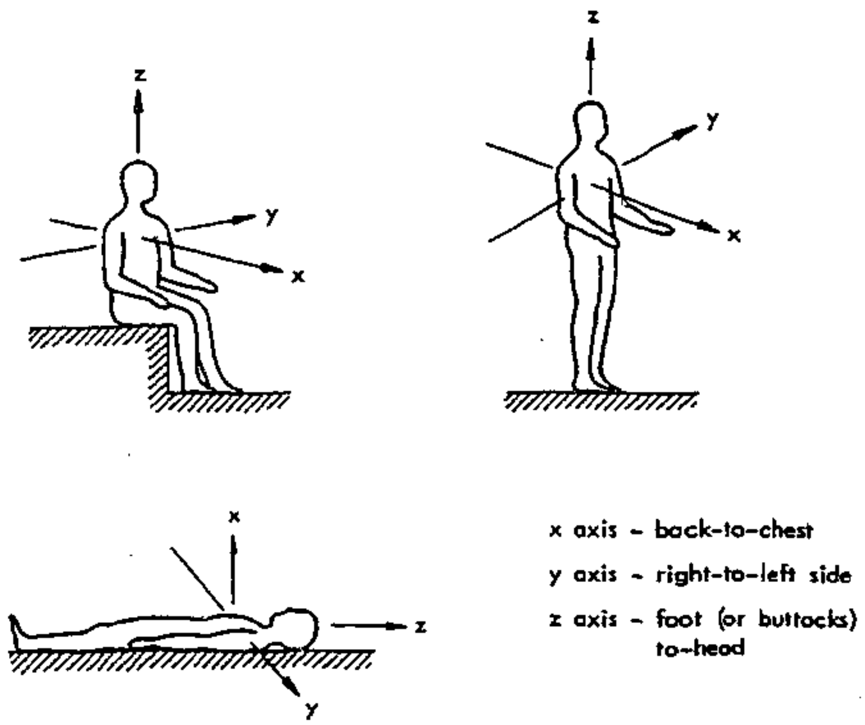


Figure A1.2 "Coordinate system for mechanical vibration influencing humans as defined in ISO 2631 (International Organization for Standardization, 1974, 1978, 1985)" x-axis: back to chest; y-axis: right to left side; z-axis: foot (or buttocks) to head.
Copied from Griffin (1990)

APPENDIX 2: Motor Ability Data Base

DESCRIPTION OF TERMS IN DATABASE

The following tables give the velocity ratio for the individual participants of conditions 5 –21. A units of the data in each of the columns are as follows:

Gender	Gender of participant where:	
	0	Female
	1	Male
Age	Age of participant in years	
Height	Height of participant in millimetres	
Velocity Ratio	Walking speed in dynamic capsizing environment divided by the walking speed in a static horizontal environment with dimensionless units	
SC_i	Sub-conditions i = 1 to 4 as described in Section 4 of this thesis.	
Failures	Number of times the participant required use of handrails when explicitly asked to avoid using the handrails.	

CONDITION 5								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	41	1651	1.01	0.91	0.91	0.73	2	x
1	18	1880	0.94	0.83	0.87	0.94	x	x
1	18	1575	0.84	0.90	0.92	0.86	1	1
1	20	1750	1.05	1.23	1.06	x	x	x
0	18	1778	0.85	0.88	0.97	0.95	1	1
0	35	1750	1.43	1.56	1.31	1.73	2	1
1	36	1750	0.74	0.76	0.98	0.86	1	x
1	20	1850	0.85	0.84	1.04	1.18	2	1
1	21	1800	1.07	1.05	1.06	1.01	1	1
0	20	1450	0.71	0.64	0.82	0.91	1	1
0	20	1550	0.39	0.53	0.55	0.58	3	1
0	38	1651	0.77	0.61	0.34	0.50	2	1
1	19	1880	1.09	1.10	1.13	1.36	x	x
1	28	1905	0.57	0.78	0.82	0.74	x	1
1	26	1778	0.86	0.84	0.90	0.92	x	x
0	38	1524	0.68	0.74	1.01	1.22	1	1
0	35	1549	1.00	0.97	0.86	0.91	2	2
0	37	1626	0.92	0.95	1.02	1.00	1	1
0	18	1730	0.42	0.34	0.74	0.72	x	x
0	19	1700	0.80	0.88	0.87	0.89	1	1
1	46	1676	0.80	0.87	0.96	1.03	x	1
0	23	1626	0.91	0.89	1.17	1.15	x	x
1	23	1803	0.91	1.07	1.19	1.00	1	1
1	40	1780	0.93	1.03	1.02	1.12	1	1
0	38	1750	0.78	0.79	1.05	0.90	2	1
0	40	1640	0.87	0.83	0.89	0.75	1	1
1	45	1780	0.86	0.82	1.01	0.98	x	x
0	24	1600	0.66	0.66	0.48	0.50	1	2
1	26	1820	0.74	0.78	0.79	0.88	x	x
1	19	1775	0.65	0.76	0.82	0.82	4	1
1	21	1720	0.72	0.91	0.84	0.92	x	x
1	22	1702	0.82	0.87	0.93	0.87	1	4
1	38	1800	1.12	1.42	x	x	x	x
0	34	1702	0.93	1.02	0.86	1.05	2	3

CONDITION 6								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	23	1730	1.21	1.34	1.33	1.31	x	x
0	30	1700	0.51	0.73	0.63	0.65	x	x
1	46	1778	0.95	1.02	1.17	1.30	x	x
1	31	1720	0.77	1.04	0.92	1.27	x	x
1	38	1700	0.83	0.71	0.84	0.78	3	3
0	0	1651	0.53	0.53	0.58	0.63	x	x
1	46	1829	0.52	0.44	0.57	0.56	x	x
1	25	1854	0.38	0.60	0.68	0.71	x	x
0	20	1700	0.71	0.59	0.81	0.72	x	1
1	42	1778	0.99	1.01	1.00	1.05	2	x
1	41	1829	0.96	1.00	1.12	1.09	x	x
0	28	1760	0.62	0.72	0.51	0.58	2	x
0	25	1575	0.77	0.81	0.86	0.83	x	x
1	27	1803	0.85	0.99	1.03	1.17	x	x
1	41	1780	0.84	0.90	0.90	0.92	x	x
1	35	1780	1.03	1.07	1.06	1.17	3	3
0	35		0.77	0.71	x	x	x	x
1	34	1829	0.85	0.94	0.88	0.90	x	x
0	41	1780	0.86	0.86	0.87	0.87	x	x
0	18	1650	0.56	0.60	0.43	0.61	3	3
1	45	1850	0.64	0.61	0.57	0.62	x	x
0	18	1702	0.58	0.45	0.28	0.28	6	6
0	25	1740	0.84	0.89	1.31	1.15	x	x
1	27	1803	0.97	0.97	0.71	1.05	x	x
0	38	1626	0.78	0.76	0.79	0.77	x	x
1	24	1830	0.90	0.93	1.05	1.01	1	x
0	43	1778	0.64	0.55	0.42	0.46	2	3
0	35	1778	0.93	0.97	0.93	0.97	x	1
1	24	1580	0.95	1.18	1.18	1.21	x	x
1	21	1890	x	x	1.03	1.19	x	x
0	25	1600	0.80	0.87	0.69	0.76	x	x
1	23	1780	1.08	1.30	x	x	x	x
1	24	1880	0.66	0.87	0.92	0.87	2	1
0	47	1780	1.06	1.16	1.13	1.35	2	2
1	37	1867	0.71	0.72	0.70	0.82	x	x
0	33	1549	0.91	0.94	0.79	0.96	x	x
1	43	1727	0.49	0.50	0.33	0.34	x	x
1	28	1740	0.86	1.09	0.95	1.05	2	2
0	21	1702	0.51	0.58	0.77	0.75	x	x
1	22	1854	0.60	0.55	0.66	0.76	x	x
1	25	1905	1.01	1.01	0.89	0.93	x	x
1	22	1727	0.61	0.59	0.71	0.77	x	x
1	36	1753	1.00	1.04	1.05	1.05	1	1
1	39	1753	0.86	0.98	0.75	0.92	3	4
1	26	1727	0.71	0.82	0.79	0.83	x	x

CONDITION 7								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	41	1600	0.77	0.86	0.86	0.90	1	1
1	25	1750	0.68	0.70	0.73	0.70	1	1
1	26	1750	0.76	0.68	0.85	1.08	x	1
1	31	1950	0.78	0.75	1.13	1.04	1	1
0	42	1676	1.28	1.28	0.98	1.18	x	x
1	42	1800	0.39	0.32	0.55	0.61	2	1
1	24	1800	0.73	0.71	0.87	0.98	1	x
0	26	1550	0.65	0.57	0.61	0.57	2	2
1	23	1880	0.76	0.76	0.92	1.06	1	x
1	30	1720	0.55	0.48	0.56	0.69	2	1
0	28	1626	0.62	0.60	0.56	0.64	2	2
1	33	1850	0.91	0.87	0.85	0.99	1	x
0	42	1524	0.53	0.53	0.57	0.43	6	6
1	31	1860	0.98	1.39	1.21	1.39	2	2
1	18	1800	0.90	0.88	0.91	0.75	2	1
1	23	1800	1.35	1.27	1.09	1.26	1	1
1	40	1760	x	1.26	1.19	1.21	1	1
1	19	1830	0.95	0.90	0.99	0.99	x	x
1	19	1830	0.83	0.89	0.91	0.85	x	1
0	43	1600	0.91	0.60	0.62	0.74	1	2
1	47	1830	0.95	1.15	x	x		
1	39	1860	0.73	0.69	0.70	0.68	2	1
0	29	1524	0.63	0.65	0.53	0.52	2	2
1	23	1524	0.68	0.92	0.89	0.89	x	x
1	23	1839	0.68	0.67	0.86	0.86	x	x
1	50	1700	0.75	0.60	0.81	0.84	2	1
1	41	1700	0.78	0.75	0.86	0.96	1	1
1	18	1700	0.75	0.69	0.80	0.96	x	x
0	47	1562	0.86	0.86	0.72	0.97	3	2
1	46	1651	0.49	0.51	0.24	0.55	3	1
1	34	1524	1.45	1.55	x	x	x	x
1	23	1829	0.61	0.63	0.67	0.63	1	x
1	41	1772	0.62	0.70	0.63	0.65	1	1
0	28	1560	0.69	0.61	0.86	0.77	x	x
1	66	1700	0.76	0.72	0.93	1.10	x	x
1	22	1850	0.22	0.41	x	x	x	x
1	43	1775	0.75	0.84	0.95	1.10	x	x
1	45	1854	0.61	0.61	0.87	0.75	1	1
1	21	1850	0.48	0.48	0.68	0.75	5	4
1	20	1830	0.52	0.45	0.54	0.46	3	2
1	34	1750	0.71	0.80	0.79	0.92	2	1

CONDITION 8								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	63	1803	0.76	0.80	1.04	1.00	1	3
1	69	1803	0.67	0.74	x	x	x	x
0	41	1550	0.79	0.84	0.78	0.80	2	2
1	39	1800	0.72	0.84	0.83	1.01	x	x
0	47	1630	0.75	0.69	0.40	0.74	3	1
1	33	1930	0.73	0.74	0.75	0.94	3	2
0	22	1540	0.40	0.37	0.35	0.50	5	3
0	37	1650	0.38	0.81	0.63	0.69	x	1
1	19	1760	0.87	1.06	0.88	0.77	2	x
1	19	1800	1.00	1.04	1.00	1.07	1	x
1	19	1780	0.86	0.90	1.04	1.01	x	x
1	20	1740	0.97	0.98	x	x	x	x
1	20	1780	0.76	0.70	0.80	0.81	x	x
1	20	1920	0.95	1.02	1.08	0.58	2	x
1	20	1910	0.99	x	1.04	1.06	2	1
1	27	1750	0.91	0.94	0.88	0.93	x	1
1	37	1829	0.51	0.44	0.41	0.55	x	x
1	19	1750	0.56	0.56	0.89	0.85	x	x
0	33	1676	0.95	0.81	0.59	0.63	2	1
0	35	1524	0.28	0.34	0.49	0.49	2	2
1	41	1905	0.98	0.76	0.80	0.89	1	1
0	46	1626	0.62	0.64	0.48	0.72	2	1
0	20	1680	0.86	0.91	0.94	1.03	x	x
1	30	1720	1.04	0.96	0.92	1.05	1	x
1	46	1778	0.86	0.85	0.68	0.84	x	x
0	44	1870	0.57	0.52	0.87	0.98	x	x
1	63	1911	0.59	0.65	0.58	0.65	2	1
0	27	1740	0.72	0.77	0.77	0.74	2	2
0	28	1626	0.95	0.85	0.75	0.84	x	x
0	59	1651	0.62	0.64	0.80	0.73	3	3
1	18	1680	0.41	0.54	0.51	0.53	4	x
1	18	1780	0.65	0.71	0.90	0.88	3	4
0	40	1549	0.76	0.81	0.71	0.99	3	4
1	20	1651	0.81	0.93	x	x	1	1
0	69	1473	0.72	0.74	0.48	0.45	x	x
1	18	1800	0.58	0.65	0.68	0.72	x	x
1	18	1800	0.84	0.82	0.87	1.03	x	x
1	53	1700	0.49	0.48	0.96	0.87	1	x
1	54	1753	1.05	0.86	0.78	0.68	2	2
0	48	1600	0.30	0.32	0.28	0.30	5	6
0	19	1676	1.04	1.18	1.17	1.24	1	1

CONDITION 9								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	37	1830	0.67	0.66	0.81	0.51	2	2
1	44	1870	0.62	0.75	0.51	0.71	2	x
1	37	1829	0.65	0.75	0.61	0.67	2	2
1	40	1778	0.58	0.66	0.67	0.73	x	x
0	52	1676	0.59	0.58	0.54	0.51	1	1
1	40	1778	0.53	0.69	0.66	0.72	x	x
1	41	2108	0.91	0.87	0.74	0.69	1	3
1	39	1803	0.99	1.22	1.24	1.30	x	x
1	39	1800	0.83	0.78	0.86	0.86	4	4
1	56	1730	0.77	0.81	0.78	0.78	x	x
1	32	1702	0.66	0.68	0.55	0.50	1	1
0	44	1774	0.66	0.75	0.51	0.59	x	x
1	62	1778	1.16	1.12	1.03	0.93	3	5
1	44	1803	1.10	1.01	0.90	0.93	x	x
1	41	1854	0.40	0.41	0.43	0.55	[illegible]	1
1	25	1867	0.35	0.35	0.37	0.47	1	2
1	44	1727	0.93	0.91	0.83	1.03	2	3
1	44	1524	0.41	0.55	0.49	0.60	3	2
0	46	1727	0.78	0.72	0.71	0.67	x	1
0	21	1727	0.88	0.87	0.71	0.98	2	1
0	23	1800	0.79	1.01	1.02	0.98	1	3
1	22	1829	1.47	1.57	1.78	1.19	x	x
1	46	1727	1.08	1.07	0.83	1.00	1	1
1	24	1880	1.12	1.43	1.20	1.19	1	1
1	40	1720	1.04	1.04	0.95	0.93	1	1
1	43	1803	0.70	0.73	0.72	0.73	1	x
1	40	1727	0.95	1.04	0.87	1.00	2	2
1	26	1803	1.03	1.15	1.11	1.34	2	1
1	41	1690	0.90	0.95	0.82	1.10	2	2
1	21	1700	1.09	1.09	0.95	0.95	2	x
1	22	1702	0.51	0.58	0.73	0.70	x	x
1	20	1700	0.67	0.88	1.07	0.95	x	x
1	22	1727	0.79	0.69	0.78	0.74	x	x
0	22	1549	0.81	0.89	0.78	0.74	x	x
1	27	1800	0.65	0.68	0.81	0.59	x	x

1	45	1778	0.81	0.86	0.86	0.87	x	x
1	30	1800	0.96	0.83	0.80	0.70	x	x
1	36	1730	0.61	0.66	0.61	0.70	x	x
1	45	1880	0.86	0.79	0.64	0.65	1	1
0	39	1620	1.20	1.11	1.18	1.10	x	x
1	18	1670	1.02	0.86	0.68	0.55	x	x
1	16	1600	0.70	1.04	0.83	0.88	2	2
1	37	1700	0.52	0.47	0.65	0.58	1	3
1	31	1778	0.64	0.65	0.93	0.88	x	x
0	23	1549	0.92	1.22	0.90	0.73	x	x
0	24	1620	0.78	0.63	0.79	0.84	x	x
1	31	1750	1.09	1.18	1.20	1.14	x	1
1	28	1700	0.69	0.79	1.13	1.12	x	x
1	18	1829	0.97	1.02	1.12	0.98	x	x
1	19	1800	0.93	1.08	1.20	1.15	x	2
0	18	1727	0.70	0.78	0.68	0.72	x	x
0	19	1780	0.47	0.46	0.44	0.33	1	1
1	55	1816	1.05	0.92	0.75	0.62	2	1
1	37	1780	0.77	0.79	0.79	0.97	2	1
1	39	1820	0.71	x	0.68	0.64	x	x
1	26	1790	1.10	0.91	0.79	0.71	x	x
1	24	1800	0.62	0.68	0.59	0.61	1	2
1	22	1730	0.57	0.62	0.54	0.56	1	2
1	23	1920	0.54	0.56	0.49	0.51	4	4
1	32	1854	0.98	1.05	1.00	1.08	2	3
0	23	1753	0.96	0.93	0.95	1.16	4	3

CONDITION 10										
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	28	1854	1.11	1.16	0.67	0.90	4	4
1	40	1780	1.10	1.22	0.94	0.86	x	x
1	41	1830	0.71	0.85	0.68	0.76	x	x
0	39	1680	0.92	0.84	0.76	0.53	2	x
1	21	1829	0.87	0.79	0.57	0.65	x	x
1	20	1780	0.80	0.83	0.83	0.96	x	x
1	43	1803	0.98	0.97	0.80	0.90	x	x
1	27	1750	1.24	1.23	0.66	0.82	2	x
1	21	1860	0.67	0.63	0.55	0.56	x	x
0	28	1753	0.86	1.06	0.37	0.44	1	4
0	40	1680	x	1.15	0.53	0.52	6	7
0	30	1727	0.76	0.71	0.71	0.65	x	4
0	48	1600	0.97	0.68	0.74	0.73	2	2
1	46	1727	0.95	0.98	1.06	1.08	1	x
0	36	1780	1.31	x	1.32	1.22	1	x
0	21	1580	1.46	1.20	1.44	1.36	x	x
1	22	1760	0.76	0.71	0.64	0.60	x	1
1	45	1765	0.66	0.54	0.37	0.45	x	x
1	29	1800	1.06	1.07	1.18	1.28	x	x
1	27	1803	1.06	1.28	1.17	x	x	x
1	24	1820	0.93	0.89	0.87	0.94	x	x
0	19	1680	1.12	1.06	1.03	1.03	2	x
0	25	1630	0.89	0.83	0.85	1.18	x	x
0	30	1626	0.71	0.66	x	x	x	x
1	40	1778	0.80	0.81	0.67	0.68	x	x
1	53	1691	0.83	0.96	0.50	0.76	4	x
1	31	1829	1.27	1.13	1.32	1.49	[illegible]	x
1	20	1810	1.41	1.42	1.40	1.42	x	x
0	69	1755	0.91	1.06	1.08	1.12	x	x
1	16	1730	0.57	0.58	0.35	0.36	x	x

CONDITION 11								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	35	1651	0.66	0.70	0.62	0.62	4	4
1	38	1905	1.42	1.57	1.52	1.42	x	x
0	33	1702	0.72	0.89	0.79	0.69	3	4
1	39	1800	1.31	1.44	0.99	0.99	x	x
1	42	1715	0.57	0.71	0.66	0.71	3	5
0	31	1778	0.81	0.87	0.66	1.08	2	3
0	21	1575	1.08	0.93	x	x	x	x
0	20	1575	1.00	0.85	0.81	1.01	2	4
1	53	1753	0.66	0.72	0.48	0.60	5	4
1	43	1816	1.11	0.99	0.92	0.94	x	x
1	35	1778	0.96	1.09	1.08	0.96	x	x
1	37	1702	1.00	0.98	1.15	0.89	5	5
1	36	1638	1.02	0.81	0.59	0.55	4	2
1	29	1850	1.01	1.03	0.65	0.71	1	2
0	24	1613	0.85	0.87	0.55	0.60	1	1
1	52	1778	0.51	0.49	0.44	0.45	5	5
1	26	1854	0.95	0.97	1.13	1.24	x	x
0	27	1702	0.68	0.67	0.85	0.61	x	1
1	27	1778	0.85	0.92	0.71	0.98	x	1
0	42	1549	0.55	0.49	0.50	0.46	1	2
1	24	1829	0.84	1.02	1.12	1.09	x	2
0	23	1700	1.14	1.42	1.16	0.86	2	3
0	16	1720	0.91	1.54	0.93	1.01	4	4
0	13	1676	0.69	0.55	0.59	0.58	7	7
1	39	1778	0.71	0.79	0.79	0.86	2	2
0	70	1540	0.86	0.71	0.63	0.61	2	3
0	38	1689	0.97	1.05	0.65	0.78	2	2
0	35	1549	0.73	0.90	0.72	0.87	2	2
0	36	1600	0.62	0.63	0.59	0.54	2	1
1	43	1803	0.80	0.75	0.75	0.64	2	2
0	37	1727	1.17	1.03	0.85	0.89	x	x
1	16	1803	0.57	0.65	x	x	x	x
0	32		1.16	1.10	1.02	1.07	x	x
0	43		0.52	x	0.45	0.46	2	3
0	26	1626	0.77	0.86	0.86	1.02	x	x
0	36	1549	0.96	0.96	0.90	0.78	2	2
1	32	1900	1.03	0.75	1.11	0.87	x	x
0	33	1626	0.92	0.83	0.76	0.67	1	x
1	45	1829	0.92	0.96	0.73	0.82	1	x
1	23	1880	0.67	0.83	0.65	0.66	x	x
0	24	1727	1.14	1.16	0.68	1.20	1	2
1	49	1715	0.94	0.96	0.56	0.99	1	1
1	28	1829	0.71	0.91	0.77	0.87	1	1
1	26	1981	0.87	0.94	1.07	1.27	x	x
1	40	1778	1.23	1.15	0.90	1.10	1	x
1	42	1829	0.60	0.84	0.78	1.12	1	x

CONDITION 12								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	35	1600	0.71	0.63	0.67	0.63	2	2
1	35	1780	1.06	1.23	0.82	1.38	2	1
0	18	1540	0.77	0.83	0.72	0.92	3	2
0	45	1670	0.63	0.71	0.67	0.84	1	x
0	20	1549	0.83	0.72	0.77	0.85	x	x
1	22	1880	0.81	0.98	0.82	1.02	2	2
0	26	1626	0.90	0.83	0.59	0.63	x	x
1	54	1778	0.86	0.86	0.93	0.93	6	6
0	41	1676	0.60	0.90	0.71	0.48	2	1
0	39	1676	0.80	0.71	0.52	0.49	2	2
0	46	1676	1.01	1.40	1.02	1.30	x	x
0	24	1660	0.49	0.69	x	x	x	x
1	42	1800	0.65	0.61	0.51	0.65	2	1
1	37	1750	0.87	0.89	0.92	0.87	x	x
0	24	1680	0.72	0.73	0.66	0.69	6	3
0	39	1575	0.77	0.86	0.84	0.49	3	1
0	19	1700	0.76	0.72	0.66	0.33	6	4
0	29	1575	0.64	0.60	0.49	0.53	2	1
0	32	1600	0.62	0.57	0.36	0.34	2	6
0	37	1575	0.63	0.62	0.57	0.53	3	3
1	20	1860	0.76	0.78	0.59	0.77	1	x
1	37	1840	0.97	0.89	0.81	0.88	x	1
1	40	1780	1.02	0.83	0.53	0.58	5	3
1	40	1820	0.99	1.08	0.87	0.78	2	1
0	43	1600	1.37	1.04	1.35	1.35	x	x
0	19	1670	0.46	x	0.37	0.49	6	6
0	37	1700	0.72	0.70	0.75	0.62	2	3
1	19	1803	0.88	0.88	0.89	0.90	x	x
0	39	1753	0.77	0.65	0.62	0.69	x	1
0	41	1626	1.11	0.97	0.46	0.63	3	4
1	42	1740	0.94	0.88	1.01	x	1	x
1	46	1840	0.83	0.84	0.75	0.83	3	x
0	44	1500	0.86	0.92	0.33	0.40	6	5
0	18	1680	0.75	0.67	0.68	0.69	2	1
0	29	1689	0.93	0.78	0.45	0.39	3	2
1	32	1860	1.15	1.29	x	x	x	x
1	41	1829	0.62	0.62	x	x	x	x
0	22	1650	0.77	1.03	0.75	0.55	x	x
1	43	1800	0.87	0.82	0.33	0.31	x	4
0	26	1626	0.88	0.96	0.73	0.88	1	1
1	29	1803	0.89	0.89	0.87	0.85	1	x
1	39	1626	0.88	0.77	0.79	0.96	5	2
0	46	1630	0.63	0.52	x	x	x	x
1	16	1900	0.87	0.94	1.04	1.05	1	x
1	16	1900	0.74	0.74	0.71	0.75	3	3
1	48	1760	1.09	1.25	0.81	0.91	x	1
1	28	1613	0.75	0.78	0.93	1.21	x	1
0	35	1600	0.59	0.50	0.42	0.43	4	4
1	51	1830	0.69	0.86	0.67	0.79	2	3
1	36	1740	0.79	0.71	0.93	1.12	x	x
1	45	1778	0.89	0.89	0.81	0.87	4	4
1	54	1676	0.82	0.80	0.74	0.94	4	3

0	34	1650	0.92	0.81	0.64	0.64	4	4
1	28	1630	0.84	0.99	0.89	0.89	1	2
0	25	1765	0.80	0.72	0.60	0.65	2	2
0	21	1700	0.87	0.73	x	x	x	x
0	22	1640	0.52	0.47	x	x	x	x
1	26	1651	0.85	0.91	1.22	1.22	1	1
1	24	1800	1.23	x	1.03	1.10	4	4
1	24	1830	0.88	0.91	0.51	0.40	2	2
1	21	1760	1.15	1.12	0.77	0.63	2	1
1	23	1803	1.03	1.03	0.67	0.36	2	4
0	23	1750	0.96	0.92	0.52	0.61	x	x
1	21	1800	0.90	1.19	0.82	1.05	x	x
1	36	1753	1.25	1.26	0.78	0.92	x	x
1	24	1829	0.93	0.83	1.09	1.00	x	x

CONDITION 13								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	19	1800	0.79	0.72	0.46	0.42	x	x
1	20	1800	0.81	0.78	0.95	0.85	x	x
0	20	1651	0.67	0.56	x	x	x	x
0	24	1549	0.39	0.39	x	x	x	x
1	33	1830	0.87	0.86	x	x	x	x
1	19	1930	0.75	0.85	0.53	0.66	x	x
1	46	1778	1.02	1.01	1.06	1.05	x	x
0	33	1626	0.63	0.92	0.48	0.49	x	3
1	44	1753	0.75	0.68	0.52	0.85	2	x
1	36	1930	0.86	0.88	0.95	0.87	x	x
0	36	1664	1.26	1.07	0.94	1.27	2	x
1	39	1800	0.89	0.97	1.05	1.08	x	x
1	41	1750	0.80	0.91	x	x	x	x
1	46	1800	1.19	0.96	0.88	1.03	x	x
1	45	1770	0.91	0.85	0.68	0.84	3	3
1	19	1630	0.85	1.06	1.09	1.26	x	x
1	29	1854	0.61	0.71	0.84	0.76	x	1
0	18	1720	1.10	1.16	1.24	1.08	x	x
0	54	1650	0.66	0.65	0.60	0.83	x	2
0	41	1600	0.68	0.70	0.59	0.70	x	x
1	33	1803	1.05	1.04	1.36	1.33	x	x
1	47	1850	0.78	0.81	0.60	0.77	1	x
1	52	1740	0.71	0.81	0.68	0.92	2	2
0	23	1650	0.81	0.93	0.86	0.61	1	2
1	34	1780	0.65	0.74	x	x	x	x
0	32	1650	0.86	0.87	x	x	x	x
1	39	1800	1.16	1.17	0.89	1.09	1	x
0	34	1626	0.48	0.54	0.68	0.73	1	2
0	36	1626	0.50	0.49	0.71	0.55	2	4
0	20	1626	0.65	0.52	x	x	x	x
1	31	1750	0.73	0.28	x	x	x	x
1	32	1778	0.77	0.75	x	x	x	x
1	27	1680	x	x	1.05	x	x	x
0	24	1670	0.91	0.75	0.86	0.90	2	1
0	23	1750	0.53	0.60	x	x	2	2
1	20	1870	1.03	1.02	1.05	1.19	1	1
0	18	1570	0.38	0.38	x	x	x	
0	19	1750	0.70	0.78	0.51	0.69		1
0	18	1650	0.68	0.59	x	x	x	x
1	39	1750	0.77	0.94	1.00	x	1	1
0	33	1650	0.64	0.65	x	x		
1	39	1670	1.02	1.25	1.34	x	x	x
1	39	1727	0.75	0.75	0.96	1.02	x	1
1	32	1750	0.81	x	0.77	0.89	x	x
0	27	1600	0.65	0.68	x	x	x	
0	35	1651	0.63	0.55	0.56	0.69	5	5
1	19	1780	0.75	0.70	0.66	0.58	1	2
0	32	1650	0.58	0.54	x	x		x
1	15	1750	0.68	0.86	0.89	0.84	4	1

CONDITION 14								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	36	1753	0.93	0.92	0.95	0.84	1	1
0	39	1651	1.03	0.84	0.83	0.82	1	1
1	47	1753	0.43	0.58	0.62	0.95	4	x
1	18	1829	0.68	0.77	0.80	0.61	x	x
1	19	1820	1.12	0.97	1.18	1.06	1	1
1	18	1790	0.90	0.87	0.65	0.96	2	1
0	28	1676	0.53	0.53	0.60	0.62	2	2
0	28	1702	0.86	0.81	0.93	0.93	1	x
1	27	1956	1.26	0.99	0.99	1.02	3	3
0	19	1549	1.13	1.42	0.79	0.73	1	1
0	37	1702	x	1.05	0.92	0.92	x	x
0	34	1770	1.31	1.53	1.31	1.53	x	x
1	44	1900	0.80	0.80	0.92	0.89	3	2
1	45	1830	0.53	0.53	0.66	0.66	x	x
1	21		0.57	0.59	0.71	0.73	1	3
1	19		0.60	0.48	0.55	0.54	1	1
1	18	1803	0.60	0.71	0.87	0.74	x	1
1	51	1740	0.48	0.62	0.57	0.58	1	1
0	48	1575	0.51	0.40	0.85	0.68	1	1
0	21	1700	0.81	0.78	1.19	1.00	1	x
0	21	1750	0.71	0.96	0.61	0.53	1	2
0	33	1626	0.82	0.82	0.70	0.73	1	2
1	42	1830	1.04	1.19	0.82	0.85	1	1
0	25		0.47	0.48	0.56	0.67	2	2
1	38	1680	0.78	0.66	0.93	1.18	x	x
1	37	1753	0.47	0.35	0.46	0.37	2	2
0	28	1549	0.41	0.40	0.42	0.44	1	1
1	24	1930	0.66	0.69	0.74	0.73	x	1
0	34	1680	0.92	1.06	0.76	0.84	2	2
1	26	1829	0.87	0.95	0.63	0.83	2	1
0	35	1575	0.78	0.71	0.56	0.73	2	1
1	26	1575	0.93	0.93	0.82	0.80	x	x
1	32	1930	0.67	0.65	0.65	0.70	x	x
1	44	1676	0.74	0.93	0.75	0.89	2	2
0	18	1676	0.51	0.47	0.62	0.60	1	3
0	18	1740	0.63	0.63	0.86	0.75	1	x
0	22	1600	0.85	0.63	0.62	x	2	x
1	41	1676	0.67	0.65	0.85	0.93	x	x
0	29	1676	0.88	0.89	0.64	0.73	1	2
0	21	1710	0.75	0.72	0.88	0.83	1	2
0	21	1680	0.86	0.72	0.39	0.46	4	4
1	24	1820	1.10	1.09	1.10	1.09	x	x
1	17	1600	0.77	0.84	0.79	0.88	x	x
0	24	1600	0.94	0.88	0.45	0.78	4	2
0	24	1651	0.47	0.47	0.32	0.61	2	3
0	27	1803	0.61	0.44	0.36	0.32	1	1
1	42	2000	0.90	0.84	0.88	0.84	2	1
1	35		0.58	0.66	0.49	0.42	2	2
1	33	1956	0.53	0.46	x	x	x	x
1	22	1700	0.64	0.72	0.91	1.01	x	x

CONDITION 15								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	39	1650	0.37	0.52	0.57	0.44	1	3
1	42	1626	0.76	0.73	0.67	0.76	2	3
1	34	1850	0.98	0.90	0.79	0.89	x	x
0	47	1689	0.41	0.40	0.41	0.40	x	x
0	18	1650	0.51	0.61	1.15	0.93	1	3
0	48	1600	0.72	0.64	0.60	0.74	2	2
1	51	1700	1.14	1.08	0.74	0.76	2	2
1	37	1700	1.23	1.36	1.23	0.84	1	1
0	20	1640	0.78	0.66	0.76	0.85	1	1
0	24	1700	0.72	0.70	0.56	0.63	x	x
0	25	1727	0.69	0.57	0.71	0.67	1	1
0	26	1562	0.71	0.63	0.81	0.81	1	2
1	36	1727	0.79	0.87	0.81	0.89	3	1
1	54	1829	0.40	0.44	0.51	0.62	2	3
1	33	1800	0.52	0.52	0.53	0.56	1	x
1	32	1829	0.75	0.74	0.82	0.94	1	x
1	31	1820	0.68	0.67	0.84	0.70	3	2
1	39	1750	0.38	0.39	0.40	0.41	3	4
0	39	1650	0.95	0.80	0.82	0.78	1	1
1	36	1753	0.91	0.97	0.63	0.82	2	1
1	19	1860	0.54	0.54	0.68	0.58	3	2
0	18	1670	0.82	0.72	0.89	0.84	2	2
1	44	1829	1.19	1.03	0.86	0.94	1	2
0	20	1575	0.51	0.64	0.59	0.53	2	2
1	22	1676	0.56	0.61	0.76	0.76	x	1
1	43	1650	0.87	0.67	0.81	0.75	1	1
0	39	1600	1.07	0.80	1.00	0.88	1	2
1	43	1829	1.07	0.91	0.86	0.85	2	2
0	22	1753	0.84	0.99	0.65	0.54	1	2
0	24	1630	0.62	0.54	0.69	0.78	3	2
1	33	1829	0.92	0.97	0.90	1.05	x	x
1	42	1800	0.51	0.46	0.33	0.37	3	3
1	25	1626	0.85	0.92	0.96	0.82	x	1
1	24	1970	0.96	0.97	0.83	0.83	1	1
0	42	1720	0.99	1.32	0.99	1.15	2	3
1	42	1727	0.66	0.94	0.62	0.50	3	2

CONDITION 16								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
0	38	1550	0.94	1.25	1.22	1.91	4	2
1	33	1702	1.23	1.21	1.25	1.01	2	x
1	33	1676	1.23	1.23	0.97	0.99	2	x
0	34	1778	0.54	0.51	0.40	0.59	3	1
1	35	1854	0.87	1.02	0.65	0.78	1	x
1	33	1854	0.99	0.95	1.19	1.25	x	1
1	44	1870	0.97	0.93	0.69	0.73	4	1
1	33	1750	0.58	0.62	0.52	0.56	3	2
0	27	1750	0.83	0.90	x	x	x	x
1	42	1840	0.95	0.85	0.55	0.58	2	2
1	46	1780	0.53	0.54	0.56	0.51	4	4
1	44	1778	0.96	0.80	0.53	0.61	2	6
1	36	1778	1.14	1.16	1.00	1.16	x	x
1	36	1803	0.83	0.81	0.51	0.53	2	2
0	23	1600	0.82	0.74	x	x	x	x
1	20	1740	0.74	0.82	0.62	0.50	3	1
1	25	1561	0.74	0.78	0.52	0.54	1	2
1	36	1829	0.58	0.61	0.59	0.74	2	1
1	37	1790	0.97	1.02	0.98	1.10	x	x
1	23	1720	1.17	0.97	0.63	0.96	3	4
1	34	1920	0.96	1.17	0.56	0.94	5	2
0	24	1655	0.74	0.64	0.42	0.43	4	4
1	22	1890	0.90	0.66	0.48	0.55	6	6
0	21	1690	0.59	0.68	0.87	0.97	2	2
1	21	1650	0 63	0.61	0.74	0.88	x	x
1	40	1727	1.10	1.07	0.80	1.10	2	3
1	42	1750	0.81	0.96	0.87	0.93	1	1
1	18	1750	0.66	0.62	0.72	0.69	x	x
0		1650	0.93	0.89	0.90	0.87	1	3
0	22	1550	0.69	0.66	0.69	0.67	3	3
1	35	1753	0.91	0.88	0.89	0.86	1	3
1	35	1880	0.90	0.86	0.90	0.87	3	3
1	34	1854	0.86	0.87	0.83	0.89	1	x
1	18	1727	0.95	0.97	1.05	0.97	1	1
0	32	1670	0.96	0.89	1.00	0.92	x	x
1	48	1727	1.25	1.20	0.97	1.29	x	x
1	31	1829	1.18	0.88	1.13	0.73	x	1
0	36	1651	x	x	1.22	1.23	1	2
0	26	1626	0.79	0.77	0.83	0.84	2	3
0	39	1600	0.88	0.92	0.89	1.05	1	x
1	53	1854	0.75	0.75	0.68	0.76	x	x
1	34	1854	0.98	0.92	1.01	1.05	x	x
1	26	1727	1.00	0.96	0.89	1.04	x	x
1	27	1778	0.87	0.81	0.77	0.78	x	x
1	46	1830	0.64	0.68	0.74	0.65	x	x
			0.82	0.80	0.77	0.92	x	x
			0.74	0.83	0.87	0.89	x	x
0	27	1550	0.75	0.66	0.77	0.74	4	6

CONDITION 17								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	32		0.59	0.54	0.57	0.41	x	x
0	40		0.27	0.28	x	x	x	x
0	19	1720	0.85	0.71	0.36	0.36	3	4
0	31		0.48	0.42	0.27	0.29	6	6
1	33	1830	0.52	0.60	0.52	0.57	4	3
0	18	1650	0.69	0.69	x	x	x	x
1	30		0.82	0.87	0.66	0.64	5	3
1	36	1800	0.53	0.47	x	x	x	x
1	23	1870	0.65	0.63	0.53	0.94	4	1
0	30		0.64	0.61	0.41	0.41	x	x
0	25	1650	0.59	0.69	x	x	x	x
1	29	1770	0.93	0.83	0.79	0.93	x	x
0	42		0.78	0.80	0.54	0.55	5	5
1	30	1780	0.78	0.79	0.42	0.47	x	x
0	36	1727	0.52	0.58	0.46	0.36		2
0	37	1753	0.35	0.46	x	x	x	x
1	29	1880	0.89	0.99	0.90	0.91	x	1
0	38	1720	0.62	0.83	x	x	x	x
1	33	1676	0.74	0.92	0.75	0.88	1	x
1	38	1830	0.47	0.48	x	x	x	x
0	34	1626	0.61	0.71	x	x	x	x
0	19	1600	0.67	0.67	x	x		x
0	38	1600	0.84	0.72	0.71	0.81		1
0	31	1575	0.20	0.26	x	x		
0	35	1600	0.54	0.71	0.57	0.68	3	2
1	22	1800	0.96	0.99	0.64	1.25	1	1
1	20	1800	0.97	0.86	0.75	x	x	x
1	18	1830	0.78	0.78	0.59	0.52	5	3
1	43	1803	0.66	0.83	0.81	0.84	3	1
0	42	1700	0.36	0.44	0.83	0.92	x	x
1	44	1778	1.03	1.07	x	x	x	x
0	36	1651	0.59	0.61	x	x	x	
1	26	1800	0.94	0.92	0.79	0.77	x	x
1	44	1905	0.93	0.93	0.62	0.66	4	4
1	34	1778	0.66	0.71	x	x		
0	28	1778	0.47	0.48	x	x		
1	65	1830	0.63	0.64	x	x		x
0	25	1600	0.75	0.86	1.04	0.89	x	x
1	23	1750	0.41	0.37	0.41	0.39	x	x
1	26	1780	0.71	0.62	0.66	0.67	3	3
1	25	1800	0.56	0.71	0.60	0.61	3	3
1	42	1830	0.80	0.82	0.55	x	3	3
1	36	1750	1.05	1.05	0.79	1.05	2	2

CONDITION 18								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	49	1626	0.76	0.86	0.59	0.61	x	x
0	48	1549	0.51	0.62	x	x	x	x
1	22	1700	1.11	1.16	1.14	x	x	x
1	21	1900	0.68	0.61	0.75	0.69	x	x
1	38	1727	0.39	0.34	0.35	x	x	x
1	64	1791	0.27	0.29	x	x	x	x
0	18	1690	0.59	0.68	0.66	0.68	x	x
0	42	1600	0.34	0.32	x	x	x	x
0	41	1664	0.72	0.65	0.51	x	x	x
1	43	1830	0.87	0.75	0.56	0.57	x	x
0	45	1630	0.43	0.43	x	x	x	x
0	46	1575	0.60	0.72	x	x	x	x
1	36	1800	0.89	0.97	x	x	x	x
0	45	1530	1.08	0.98	0.74	x	x	x
1	46	1702	0.60	0.69	0.41	0.44	x	x
1	19	1930	x	1.16	0.94	1.18	x	x
1	19	1780	0.95	0.85	0.82	0.86	x	x
1	46	1830	0.83	0.77	0.66	0.77	x	2
0	46	1750	0.69	0.57	0.42	x	x	x
1	18	1880	0.94	0.93	0.50	0.61	x	x
1	56	1854	0.87	1.11	0.49	0.57	5	x
1	41	1778	0.78	0.83	0.70	0.82	2	x
1	28	1960	0.99	1.00	0.59	0.61	x	x
1	51	1790	0.87	0.53	0.44	0.52	x	x
1	48	1727	0.79	0.84	0.35	0.35	x	x
0	43	1650	0.61	0.56	0.30	0.30	6	6
0	23	1680	0.66	0.71	0.60	0.60	x	x
0	55	1676	0.41	0.32	x	x	x	x
1	35	1760	0.84	1.02	0.85	0.91	x	x
1	25	1880	0.66	0.61	x	x	x	x
1	35	1800	0.72	0.66	0.60	0.52	x	x
0	22	1720	0.57	0.56	0.44	0.61	1	x
1	22	1829	0.98	x	0.68	0.67	1	x
0	23	1570	0.53	0.53	0.62	0.65	6	6
0	43	1600	0.55	0.55	x	x	x	x
0	39	1727	0.43	0.43	x	x	x	x
1	28	1750	0.64	0.75	0.32	0.33	x	x
0	39	1626	0.72	0.77	0.40	0.57	x	x
1	49	1676	0.64	0.74	0.35	0.50	5	2
1	26	1676	1.01	1.06	1.05	1.07	3	x
1	23	1880	0.81	0.87	0.83	0.81	x	x
0	22	1700	x	1.12	0.89	1.00	x	x
1	22	1854	0.84	0.98	0.74	0.83	4	4
1	34	1803	0.73	0.73	0.59	0.63	2	x
1	44	1791	1.03	1.11	1.04	1.10	x	x
1	41	1710	1.27	1.24	1.10	1.18	x	x
1	26	1727	1.29	1.25	1.08	1.10	x	x
0	24	1727	0.97	0.76	0.61	0.65	4	6
1	49	1740	0.93	0.99	0.59	0.40	x	2
1	43	1727	0.97	0.87	0.87	0.95	x	x
1	42	1727	1.00	0.90	0.65	0.79	x	x
1	54	1800	1.13	x	x	x	x	x

CONDITION 19								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	39	1702	0.51	0.66	0.55	0.55	x	x
1	28	1791	0.81	1.02	0.94	0.93	x	x
1	50	1650	0.81	0.79	0.49	0.48	x	x
1	28	1702	0.78	0.86	0.77	0.86	x	x
1	25	1676	0.56	0.73	0.46	0.63	x	x
0	21	1570	0.35	0.35	x	x	x	x
1	19	1778	0.80	0.76	0.47	0.64	x	x
1	19	1800	0.79	0.61	0.81	0.51	x	x
1	22	1905	0.62	0.59	0.47	0.42	x	x
0	23	1680	1.12	0.96	x	x	x	x
1	34	1820	0.70	0.73	0.51	0.52	x	x
1	39	1702	0.86	0.90	0.84	0.93	x	x
1	35	1670	0.62	0.62	0.37	0.45	x	x
1	18	1790	0.65	0.84	0.63	0.74	x	x
1	39	1770	0.70	0.87	0.54	0.64	x	x
1	48	1753	0.69	0.96	0.81	0.86	x	x
1	40	1778	0.77	0.84	0.85	0.56	x	x
0	38	1575	0.58	0.55	x	x	x	x
0	19	1600	0.58	0.58	0.43	0.58	x	x
0	19	1600	0.59	0.68	0.33	0.41	x	x
0	20	1700	0.47	0.60	0.50	0.57	x	x
0	20	1680	0.55	0.51	0.60	0.57	x	x
1	23	1830	0.78	0.93	0.73	0.82	x	x
0	22	1702	0.76	0.95	0.76	0.71	x	x
1	53	1830	0.66	0.86	x	x	x	x
1	29	1900	0.68	0.81	0.66	1.09	x	x
0	47	1626	0.82	0.67	0.65	0.60	x	x
1	44	1790	0.52	0.69	0.47	0.48	x	x
1	37	1702	1.13	1.20	0.91	0.86	x	x
1	30	1830	0.53	0.56	0.57	0.61	x	x
1	41	1778	0.94	1.22	0.86	0.88	x	x
1	30	1820	1.32	1.35	1.15	1.32	x	x
1	26	1850	0.90	1.22	1.11	1.11	x	x
1	44	1850	0.70	0.96	0.55	0.40	x	x
0	22	1676	0.77	0.72	0.32	0.21	x	x
1	34	1800	0.92	0.88	0.92	1.03	x	x
1	23	1810	1.20	1.06	1.05	1.03	x	x
1	31	1715	0.74	0.84	0.34	0.46	x	x
0	31	1727	1.09	1.04	0.78	0.70	x	x
1	31	1803	x	1.12	0.62	0.68	x	x
1	22	1850	0.83	0.96	0.51	0.32	x	x
0	20	1626	0.52	0.51	0.43	0.36	x	x
0	25	1753	0.42	0.28	0.37	0.33	x	x
0	22	1710	0.55	0.62	0.73	0.76	x	x
1	24	1880	0.60	0.69	0.81	0.84	x	x
1	25	1753	0.38	0.37	0.27	0.28	x	x
0	19	1580	0.43	0.45	0.45	0.49	x	x
1	37	1830	0.86	x	0.95	x	x	x
0	26	1630	0.73	0.66	0.62	0.63	x	x
1	30	1830	1.01	1.15	0.87	0.85	x	x
1	27	1702	0.47	0.54	0.44	0.44	x	x
1	68	1727	0.57	0.76	0.37	0.50	x	x

1	19	1800	0.74	0.78	0.54	0.92	x	x
1	24	1800	0.61	0.84	0.46	0.78	x	x
1	49	1750	1.00	1.06	0.66	0.87	x	x
1	28	1780	0.71	0.84	0.85	x	x	x
0	23	1680	0.80	0.69	0.66	0.72	x	x

CONDITION 20								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
			0.87	0.88	0.56	0.56	x	x
1	23	1960	0.80	0.95	0.72	0.62	x	x
1	23	1790	0.86	0.87	0.57	0.48	2	8
1	22	1770	0.93	0.67	0.34	0.36	x	x
0	27	1626	0.55	0.51	x	x	x	x
1	22	1829	0.63	0.62	x	x	x	x
1	22	1780	1.04	0.70	0.53	0.65	7	8
1	23	1650	0.82	0.75	0.83	0.82	4	4
1	22	1780	0.94	0.79	0.57	0.64	6	5
0	26	1626	0.67	0.58	x	x	x	x
1	23	1829	0.88	0.96	0.63	0.39	4	6
1	26	1830	0.89	0.82	0.58	0.66	5	3
1	22	1830	1.22	1.13	0.44	0.49	5	5
1	22	1750	0.96	0.90	0.41	0.37	5	5
1	24	1650	0.74	0.69	0.50	0.59	6	x
1	24	1880	1.13	1.02	0.58	0.67	3	2
0	23	1590	0.91	0.87	x	x	x	x
0	22	1630	0.74	0.80	x	x	x	x
1	22	1750	0.96	0.79	0.55	0.78	3	2
1	28	1778	1.19	1.13	0.58	0.53	x	x
1	23	1900	0.87	0.76	0.44	0.51	x	x
1	23	1830	1.27	1.42	0.78	0.65	x	x
1	22	1830	0.87	0.85	0.42	0.43	5	8
1	23	1640	0.80	0.80	0.40	0.45	5	5
1	24	1780	0.91	0.96	0.50	0.48	6	6
1	22	1880	0.83	0.80	0.55	0.50	7	7
1	22	1575	0.58	0.52	0.44	0.54	7	6
1	23	1778	0.97	0.91	0.95	0.83	2	1
1	23	1780	0.79	0.90	0.59	0.56	x	1
1	22	1780	0.59	0.48	x	x	x	x
1	24	1930	1.15	1.14	0.60	0.46	x	x
1	25	1720	1.22	0.90	x	x	x	x
1	22	1810	0.74	0.49	x	x	x	x
1	22	1829	1.05	0.87	0.37	0.63	4	8
1	22	1803	0.61	0.57	0.35	0.42	4	6
1	21	1803	0.37	0.40	x	x	x	x
0	22	1575	0.31	0.33	x	x	x	x
1	23	1720	0.66	0.55	0.57	0.58	6	7
1	23	1630	0.47	0.26	x	x	x	x
1	28	1780	0.55	0.48	0.24	0.29	x	x
0	22	1750	0.62	0.38	x	x	x	x
1	22	1700	0.61	0.40	0.41	0.40	8	8
1	22	1750	0.21	0.63	x	x	x	x
1	25	1800	0.79	0.83	0.59	0.58	6	6
1	24	1650	1.01	0.85	0.43	0.79	3	6
1	21	1790	0.67	0.59	0.41	0.43	6	6
1	24	1750	0.84	0.88	0.55	0.48	2	4
			0.72	0.65	0.48	0.49	6	x
0	24	1520	0.43	0.39	x	x	x	x
1	22	1829	0.58	0.54	x	x	x	x
1	23	1670	0.60	0.67	x	x	x	x
1	22	1720	0.52	0.51	x	x	x	x

1	22	1702	0.63	0.66	x	x	x	x
1	23	1720	0.69	0.88	x	x	x	x
0	22	1550	0.62	0.65	x	x	x	x
0	22	1750	0.60	1.10	x	x	x	x
1	22	1700	0.90	0.84	x	x	x	x
1	24	1730	0.98	1.26	x	x	x	x
0	24	1670	0.86	0.52	x	x	x	x
1	24	1905	0.89	0.90	0.34	0.48	2	5
1	22	1870	0.95	0.90	0.40	0.40	4	4
1	24	1900	1.01	0.78	0.51	0.43	6	7

CONDITION 21								
GENERIC DATA			VELOCITY RATIO				FAILURES	
GENDER	AGE	HEIGHT	SC1	SC2	SC3	SC4	SC3	SC4
1	33	1702	0.81	0.81	x	x	0	0
1	33	1753	0.70	0.83	x	x	0	0
0	30	1640	0.65	0.71	x	x	0	0
1	39	1676	0.88	0.84	x	x	0	0
0	35	1676	0.90	0.78	x	x	0	0
1	22	1700	1.00	1.01	x	x	0	0
0	21	1500	1.08	0.94	x	x	0	0
1	21	1690	0.94	1.03	x	x	0	0
0	19	1680	0.90	0.93	x	x	0	0
1	21	1650	0.63	0.61	0.74	0.88	x	x
1	40	1727	1.10	1.07	0.80	1.10	2	3
1	42	1750	0.81	0.96	0.87	0.93	1	1
1	18	1750	0.66	0.62	0.72	0.69	x	x
0	0	1650	0.93	0.89	0.90	0.87	1	3
0	22	1550	0.69	0.66	0.69	0.67	3	3
1	35	1753	0.91	0.88	0.89	0.86	1	3
1	35	1880	0.90	0.86	0.90	0.87	3	3
1	34	1854	0.86	0.87	0.83	0.89	1	x
1	18	1727	0.95	0.97	1.05	0.97	1	1
0	32	1670	0.96	0.89	1.00	0.92	x	x
1	48	1727	1.25	1.20	0.97	1.29	x	x
1	31	1829	1.18	0.88	1.13	0.73	x	1
0	36	1651	x	x	1.22	1.23	1	2
0	26	1626	0.79	0.77	0.83	0.84	2	3
0	39	1600	0.88	0.92	0.89	1.05	1	x
1	53	1854	0.75	0.75	0.68	0.76	x	x
1	34	1854	0.98	0.92	1.01	1.05	x	x
1	26	1727	1.00	0.96	0.89	1.04	x	x
1	27	1778	0.87	0.81	0.77	0.78	x	x
1	46	1830	0.64	0.68	0.74	0.65	x	x
			0.82	0.80	0.77	0.92	x	x
			0.74	0.83	0.87	0.89	x	x
0	27	1550	0.75	0.66	0.77	0.74	4	6
1	20	1778	1.07	x	x	x	x	x
0	38	1550	0.94	1.25	1.22	1.91	4	2
1	33	1702	1.23	1.21	1.25	1.01	2	x
1	33	1676	1.23	1.23	0.97	0.99	2	x
0	34	1778	0.54	0.51	0.40	0.59	3	1
1	35	1854	0.87	1.02	0.65	0.78	1	x
1	33	1854	0.99	0.95	1.19	1.25	x	1
1	44	1870	0.97	0.93	0.69	0.73	4	1
1	33	1750	0.58	0.62	0.52	0.56	3	2
0	27	1750	0.83	0.90	x	x	x	x
1	42	1840	0.95	0.85	0.55	0.58	2	2
1	46	1780	0.53	0.54	0.56	0.51	4	4
1	44	1778	0.96	0.80	0.53	0.61	2	6
1	36	1778	1.14	1.16	1.00	1.16	x	x
1	36	1803	0.83	0.81	0.51	0.53	2	2
0	23	1600	0.82	0.74	x	x	x	x
1	20	1740	0.74	0.82	0.62	0.50	3	1
1	25	1561	0.74	0.78	0.52	0.54	1	2
1	36	1829	0.58	0.61	0.59	0.74	2	1

1	37	1790	0.97	1.02	0.98	1.10	x	x
1	23	1720	1.17	0.97	0.63	0.96	3	4
1	34	1920	0.96	1.17	0.56	0.94	5	2
0	24	1655	0.74	0.64	0.42	0.43	4	4
1	22	1890	0.90	0.66	0.48	0.55	6	6
0	21	1690	0.59	0.68	0.87	0.97	2	2

APPENDIX 3: Dimensional Analysis

To correlate experimental data more easily it is convenient, in a physical system with two or more quantities that are interrelated, to set up dimensionless quantities that are in turn interrelated. There are a number of different scenarios and factors that may affect the walking speed of an individual in a capsizing ship environment. Using the Force/Length/Time (FLT) system of dimensions the factors and scenarios, for the single degree of system, can be refined to the following:

1. Mean list angle	(ϕ)	(none)
2. Roll amplitude	(σ)	(none)
3. Roll frequency	(ω)	($1/T$)
4. Congestion	(ρ_c)	($1/L^2$)
5. Reverse flow	(ρ_r)	($1/L^2$)
6. Passenger vertical centre of gravity	(VCG)	(L)
7. Passenger mass	(m)	(FT^2/L)
8. Overturning resistance	(F_{or})	(F)
9. Normal walking speed	(V_n)	(L/T)
10. Dynamic walking speed	(V_d)	(L/T)
11. Gravity	(g)	(L/T^2)

In the case under investigation there are n=11 quantities involved and m=3 fundamental dimensions. The dynamic walking speed (V_d) may be written as:

$L/T = f(\text{none, none}, 1/T, 1/L^2, 1/L^2, L, L, FT^2/L, F)$

The π theorem states there will be n-m (i.e. 8) independent dimensionless groups in the dimensional analysis.

The independent groups will be designated as $\pi_1, \pi_2, \dots, \pi_{n-m}$ and the repeating variable method for determining π groups will be employed herein.

The following repeating variables have been chosen for this analysis:

Gravity	(g)	(L/T^2)
Mass	(m)	(FT^2/L)
Normal Walking Speed	(V_n)	(L/T)

The independent groups may be defined as follows.

π_1, contains g, m, V_n and V_d

$= (g)^x (m)^y (V_n)^z V_d = (L/T^2)^x (FT^2/L)^y (L/T)^z (L/T) = (L)^{x-y+z+1}(F)^y(T)^{-2x+2y-z-1}$

$= \mathbf{V_d / V_n}$

π_2, contains g, m, V_n and ϕ

$= (g)^x (m)^y (V_n)^z \phi = (L/T^2)^x (FT^2/L)^y (L/T)^z = (L)^{x-y+z}(F)^y(T)^{-2x+2y-z}$

$= \boldsymbol{\phi}$

π_3, contains g, m, V_n and σ

$= (g)^x (m)^y (V_n)^z \sigma = (L/T^2)^x (FT^2/L)^y (L/T)^z = (L)^{x-y+z}(F)^y(T)^{-2x+2y-z}$

$= \boldsymbol{\sigma}$

π_4, contains g, m, V_n and ρ_c

$= (g)^x (m)^y (V_n)^z \rho_c = (L/T^2)^x (FT^2/L)^y (L/T)^z (1/L^2) = (L)^{x-y+z-2}(F)^y(T)^{-2x+2y-z}$

$= \boldsymbol{\rho_c.(g/V_n^2)^2}$

π_5, contains g, m, V_n and ρ_r

$= (g)^x (m)^y (V_n)^z \rho_r = (L/T^2)^x (FT^2/L)^y (L/T)^z (1/L^2) = (L)^{x-y+z-2}(F)^y(T)^{2x+2y-z}$

$= \boldsymbol{\rho_c.(g/V_n^2)^2}$

π_6, contains g, m, V_n and VCG

$= (g)^x (m)^y (V_n)^z h = (L/T^2)^x (FT^2/L)^y (L/T)^z (L) = (L)^{x-y+z+1}(F)^y(T)^{-2x+2y-z}$

$= \mathbf{VCG/(g/V_n^2)}$

π_7, contains g, m, V_n and F_{or}

$= (g)^x (m)^y (V_n)^z F_{or} = (L/T^2)^x (FT^2/L)^y (L/T)^z (F) = (L)^{x-y+z}(F)^{y+1}(T)^{-2x+2y-z}$

$= \mathbf{F_{or}/m.g}$

π_8, contains g, m, V_n and ω

$= (g)^x (m)^y (V_n)^z \omega = (L/T^2)^x (FT^2/L)^y (L/T)^z (1/T) = (L)^{x-y+z}(F)^y(T)^{-2x+2y-z-1}$

$= \mathbf{V_n.\,\omega / g}$

Hence, $\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8)$ or

$$\boxed{\mathbf{V_d/V_n = f\,(\phi, \sigma, \rho_c.(g/V_n^2)^2, \rho_r.(g/V_n^2)^2, VCG/(g/V_n^2), F_{or}/m.g, \omega.V_n/g)}}$$

The vertical centre of gravity, angle of inclination, roll amplitude and roll frequency can be reduced to a single variable, namely, the applied overturning acceleration, A.

Where, A $= f(g, \phi, VCG, \omega, \sigma)$

Or in the non-dimensionalised form,

$\pi_9 = f(\pi_2, \pi_7, \pi_8, \pi_3)$

Where, π_9 contains g, m, V_n and A

$$= (g)^x (m)^y (V_n)^z A = (L/T^2)^x (FT^2/L)^y (L/T)^z (L/T^2)$$

$$= (L)^{x-y+z+1} (F)^y (T)^{-2x+2y-z-2}$$

$$= A/g$$

Hence, $\pi_1 = f(\pi_4, \pi_5, \pi_7, \pi_9)$ or

$$\boxed{\mathbf{V_d/V_n = f\,(\rho_c \cdot (g/V_n^2)^2, \rho_r \cdot (g/V_n^2)^2, F_{or}/m.g, A/g)}}$$

Assuming gravity remains constant we may further simplify the system by converting the repeating variables to:

Overturning Acceleration	(A)	(L/T^2)
Mass	(m)	(FT^2/L)
Normal Walking Speed	(V_n)	(L/T)

As the overturning acceleration, A, and acceleration due to gravity, g, have identical dimensions we may modify the relationship to:

$$\boxed{\mathbf{V_d/V_n = f\,(\rho_c \cdot (A/V_n^2)^2, \rho_r \cdot (A/V_n^2)^2, F_{or}/m.A)}}$$

Ignoring congestion and counter flow in the interim we may infer that

$$\mathbf{V_d/V_n = f\,(F_{or}/m.A)}$$

To validate the influence of maritime specific factors the influence of overturning accelerations as well as congestion and counter flow must be assessed. However, the bulk of the assessment on motor ability is focussed on the influence on walking speeds due to overturning accelerations. A smaller component is devoted to the influence of congestion and counter flow.

For the purposes of simplicity the non-dimensional parameters identified are referred to as follows:

Velocity Ratio	Vr	$= V_d/V_n$
Environmental Force Factor	Er	$= F_{or}/m.A$

APPENDIX 4: Explanatory Statement

[DATE]

Human Behaviour During the Evacuation of Ships

My name is Adam Brumley, and I am studying for a PhD at Monash University. A research project is an important component of my course and I am undertaking my research under the supervision of Dr Len Koss an Associate Professor in the Department of Mechanical Engineering.

The aim of this research project is to quantify the effect of sinking ships motions on the walking speed of passengers during evacuation. Recent safety guidelines now require an evacuation analysis to be completed in the early stages of design for large passenger transport ships. However relatively little information is available on the effects a sinking ship on the evacuation process. The findings of this research will provide that data.

I am seeking adults in good health who are prepared to participate in an experiment in a simulator that will provide the expected motions of a ship. The occupants will be required to walk the length of the simulator (approximately 10m) a number of times under varying light conditions. Unfortunately if you are under 18 or have a medical condition that may be exacerbated by such experiments you will be unable to participate. The procedure should only take about 5 minutes of your time and will be undertaken at Luna Park at your convenience.

No findings that could identify any individual participant will be published. The anonymity of your participation is assured by our procedure in which you will not be required to submit your name. Access to data will be restricted to my supervisor and me. Coded data will be stored for five years, as prescribed by University regulations.

Participation in this research is entirely voluntary, and if you agree to participate, you may withdraw at any time by simply requesting your exclusion. You may also decline to participate in any part of the experimental procedure by the same method. If you have any queries or would like to be informed of the research findings, please contact telephone (03) 9905 3551 fax (03) 9905 3558

Thank you,

Adam Brumley
(03) 9905 3551

Should you have any complaint concerning the manner in which this research is conducted, please do not hesitate to contact the Standing Committee on Ethics in Research on Humans at the following address:

The Secretary
The Standing Committee on Ethics in Research on Humans
Monash University
Wellington Road
Clayton Victoria 3168
Telephone (03) 9905 2052 Fax (03) 9905 1420

Informed Consent Form

Human Behaviour During the Evacuation of Ships

I agree to take part in the above Monash University research project. I have had the project explained to me, and I have read and understood the explanatory statement, which I retain for my records.

I understand that any information I provide is confidential, and that no information that could lead to the identification of any individual will be disclosed in any reports on the project, or to any other party.

I understand that my participation is voluntary, that I can chose not to participate, and that I can withdraw my participation at any stage of the project.

Name:..(please print)

Signature:...Date:.........................

APPENDIX 5: 1st MATE Facility

The following detail drawings have been completed by Deer Park Engineering Pty Ltd (the structural fabricators) to meet the 1st MATE design specifications. The general arrangement is shown in Figure A5.1.

- M46-01 '1st MATE' Test Rig, General Arrangement,
- M46-02 '1st MATE' Test Rig, Base Frame Details,
- M46-03 '1st MATE' Test Rig, Platform Frame Details,
- M46-04 '1st MATE' Test Rig, Mechanical Details,
- M46-05 '1st MATE' Test Rig, Access Stair Details,
- M46-06 '1st MATE' Test Rig, Test Rig Motion Limits,
- M46-07 '1st MATE' Test Rig, Power Pack Base Frame,
- M46-08 '1st MATE' Test Rig, Linear Transducer Pivot Assembly
- M46-09 '1st MATE' Test Rig, Name Plate Details.

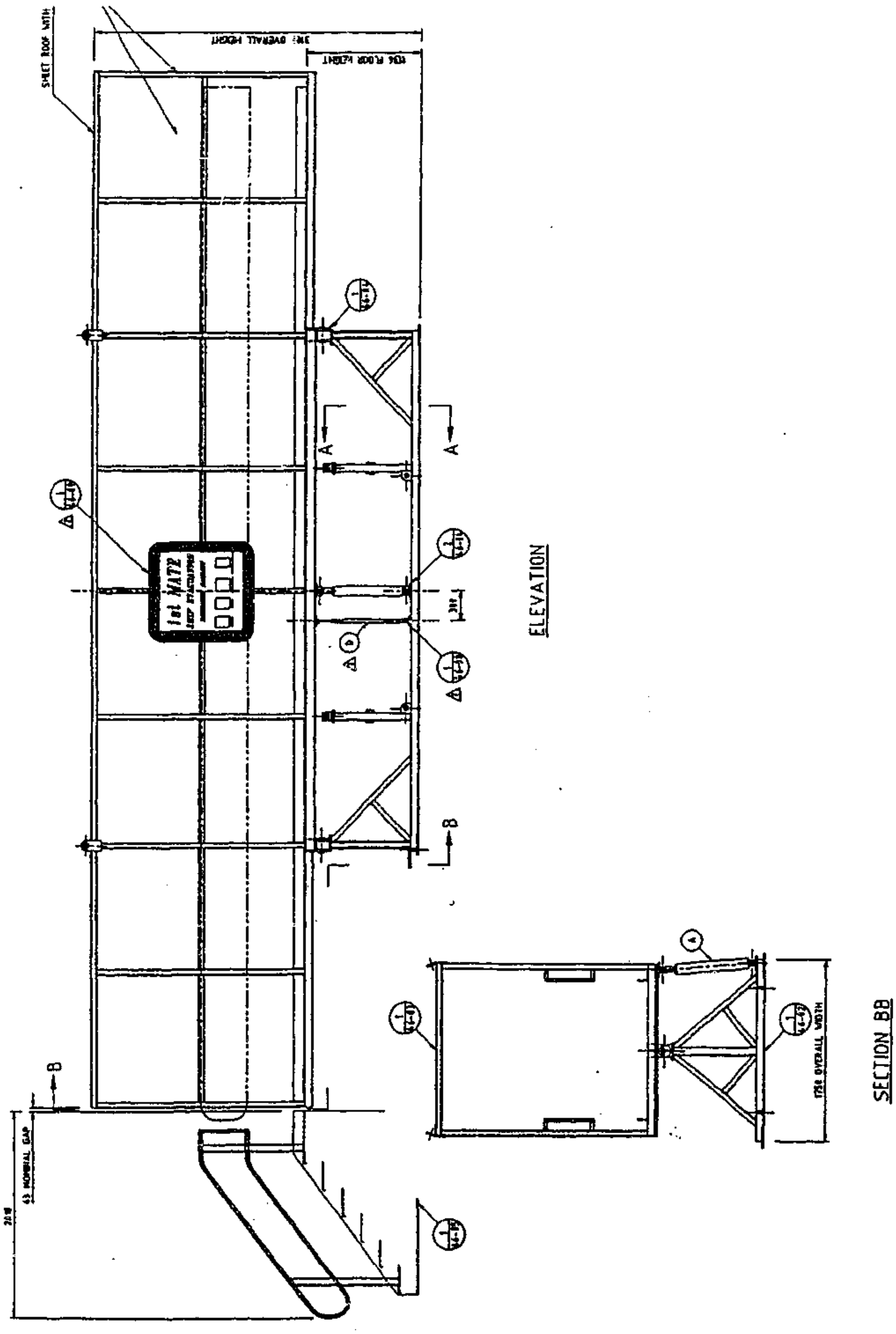


Figure A5.1 **1st MATE General Arrangement**

APPENDIX 6: Motor Ability Detailed Test Methodology

Generic Test Methodology

1. Explain the purpose of the facility to potential participants and invite them to assist;
2. Provide participant with explanatory statement;
3. Provide participant with consent form and file signed copy;
4. Check footwear of participant;
5. Gather Generic Demographic Information - including height, weight, moment resistance, age, and gender;
6. Explain test procedure to volunteers;
7. Fit Volunteer with protective gear (lifejacket and helmet);
8. Distribute identification tags to volunteers;
9. Escort Volunteers to starting bay;
10. Conduct preliminary (land based) trials and questionnaire;
11. Start Video;
12. Escort Volunteers onto Facility;
13. Request occupant to commence facility based trial;
14. Conduct tests according to specific instructions of test (see below);
15. Fill out egress times and identification numbers;
16. Stop Video;
17. Escort Volunteers out of Facility;
18. Gather Physiological and Psychological Information
19. Retrieve safety equipment (helmet and lifejacket)
20. Repeat from Item 1. until end of day

Single Flow

Single flow trials were conducted to investigate the walking speed characteristics of a single evacuee in the absence of obstructions including other people. The test methodology

1. The subject is instructed to proceed in the following manner:

   "Please walk as though a crew member requested that you evacuate in a safe and orderly manner. Interpret how you would evacuate given the moving conditions that you are experiencing. Walk to the very end of the corridor and stop. Return when I call you back. Please use the handrails at all times."

2. The subject starts walking to the closed end of the facility,
3. When the subject crosses start marker the operator starts stopwatch.
4. The subject continues to walk in an orderly fashion.
5. When the subject crosses stop marker the operator stops stopwatch
6. The operator calls the subject back.
7. When subject crosses start marker the operator starts stopwatch
8. The subject continues to walk in an orderly fashion
9. When subject crosses stop marker the operator stops stopwatch
10. The subject is instructed to repeat the test in the following manner.
11. *"Please repeat the test. However this time avoid using the handrails and kick rails as much as possible. Only use the rails as a last attempt to avoid falling."*
12. The operator counts the number of times the handrails/kick rails are used and records the time taken between markers as explained above.
13. The subject is requested to inform the operator of the subjects assigned ID number.

Group Flow

As above for single flow. However volunteers position side by side in rows of two and walk together.

Counter Flow

As for single flow. However trial is completed firstly using upper rail (the rail raised due to the list inclination of the corridor) then using the lower rail only. This is to simulate the case of passengers only having access to one set of rails at any time (i.e. large open plan areas or multiple columns of evacuees).

APPENDIX 7: Sample Way Finding Survey

<table>
<tr><td></td><td>Australian Maritime Engineering CRC Ltd
ACN 060 208 577

Melbourne Research Core
Monash University
Building 70
Wellington Road Clayton Victoria 3168 Australia
Tel +61 (0)3 9905 1854 Fax +61 (0)3 9905 1878</td></tr>
<tr><td>SURVEY 1 of 2</td><td>[VESSEL NAME]</td></tr>
</table>

IT IS ESSENTIAL FOR THE SUCCESS OF THIS SURVEY THAT YOU DO NOT READ OR COMPLETE THIS SURVEY UNTIL 8.00 P.M.

DO NOT READ PAGE TWO UNTIL YOU HAVE COMPLETED THIS PAGE

THIS SURVEY IS A MEMORY BASED SURVEY - PLEASE DO NOT REFER TO SAFETY NOTICES OR WITH YOUR COMPANIONS UNTIL YOU HAVE COMPLETED THIS SURVEY.

1. AGE ________ 2. GENDER ________

3. What is your first language? ________

4. Have you travelled on the [VESSEL NAME] before? ________

If yes, approximately how many times? ________

5. Have you travelled on any other passenger ship? ________

If yes, was there a safety announcement? ________

6. How many people are you travelling with (do not include yourself)? ________

7. Do you remember hearing the safety announcement? ________(if no, go to 9)

8. Did you listen to the safety announcement?

a. yes, very carefully b. yes, most of it

c. yes, some of it d. no

9. Did you understand the safety announcement?

a. yes, it seemed straight forward b. yes, but could have been explained better

c. yes, but some things were confusing d. no, I was confused

10. Have you looked at a layout of the ship?

a. yes, in detail b. yes, briefly

c. no, but I know where one is d. no, where are they?

11. Where do you think the safest place is on a ship during an emergency? ________

12. Where is the first place you would go in the event of an emergency? ________

	Australian Maritime Engineering CRC Ltd ACN 060 208 577
SURVEY 2 of 2	***[VESSEL NAME]***

IT IS ESSENTIAL FOR THE SUCCESS OF THIS SURVEY THAT YOU DO NOT READ OR COMPLETE THIS SURVEY UNTIL 8.00 P.M.

DO NOT READ THIS PAGE UNTIL YOU HAVE COMPLETED PAGE ONE.

13. Do you get confused about your location on the ship?

a. yes, very often b. yes, sometimes

c. no, never

14. Where is your life jacket stored? ____________________

15. How well do you think your travelling companions know the safety procedures?

a. better than me, b. the same as me,

c. worse than me.

16. How well do you think your travelling companions know the ship?

a. better than me, b. the same as me.

c. worse than me.

17. Do you know your muster station number? ________

if no, do you think your travelling companion does? ________

if yes, what is it? ________

18. Did you notice any emergency exit signs on the way to your cabin? ________

19. How many alcoholic drinks do you intend to have during your journey? ________

20. Have you read the safety notice on the back of your door?

a. yes, in detail b. yes, briefly

c. no. if no, why not?____________________

21. Have you read the safety pamphlet given to you on boarding?

a. yes, in detail b. yes, briefly

c. no. if no, why not?____________________

21. Did prior knowledge of this survey influence your answers to any of the questions?________ Which questions?____________

22. Comments? ____________________

APPENDIX 8: EVACUSHIP Key Algorithms

Figure A8.1 EVACUSHIP General Arrangement Algorithm

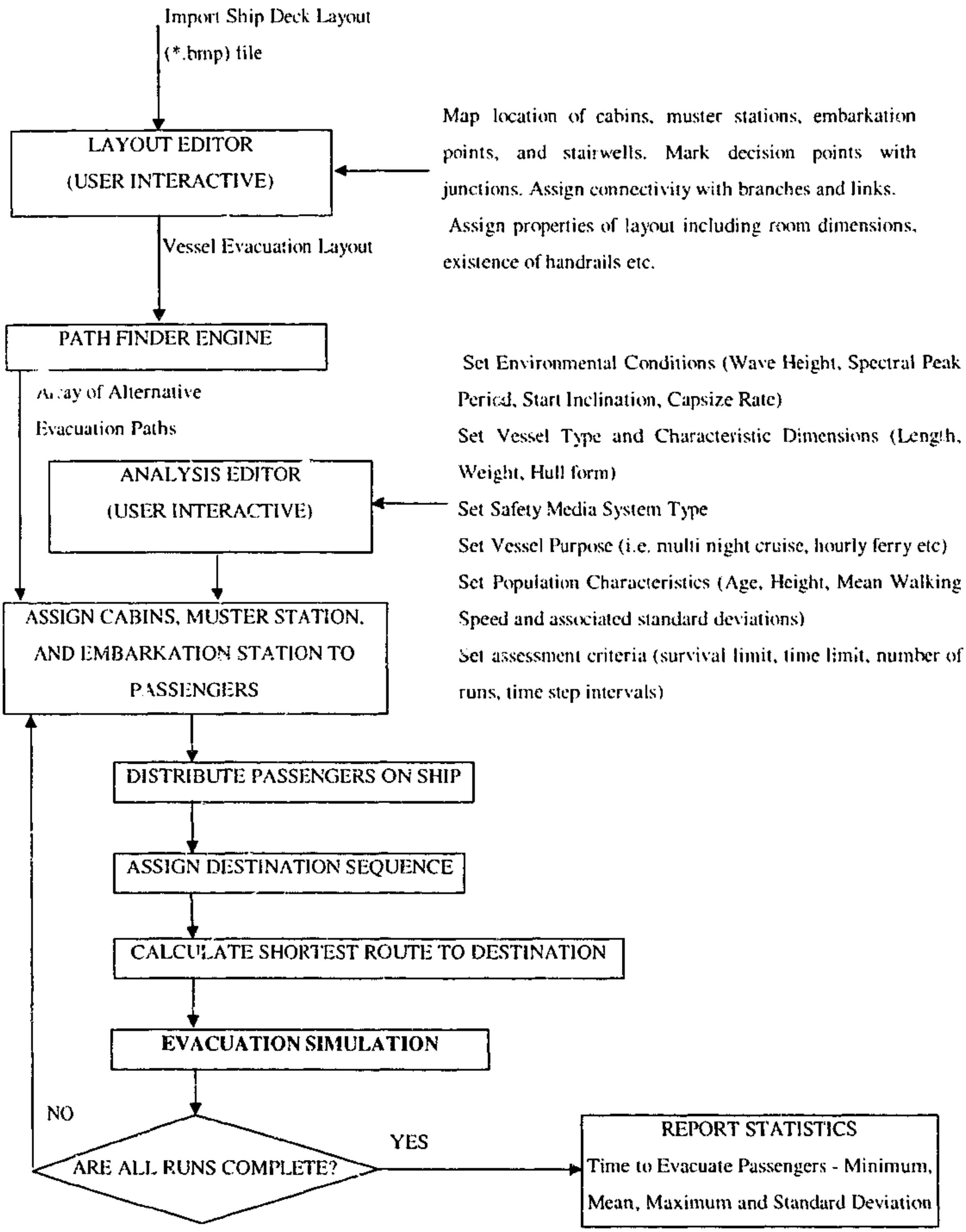


Figure A8.2 EVACUSHIP Evacuation Simulation Algorithm, Page 1 of 2

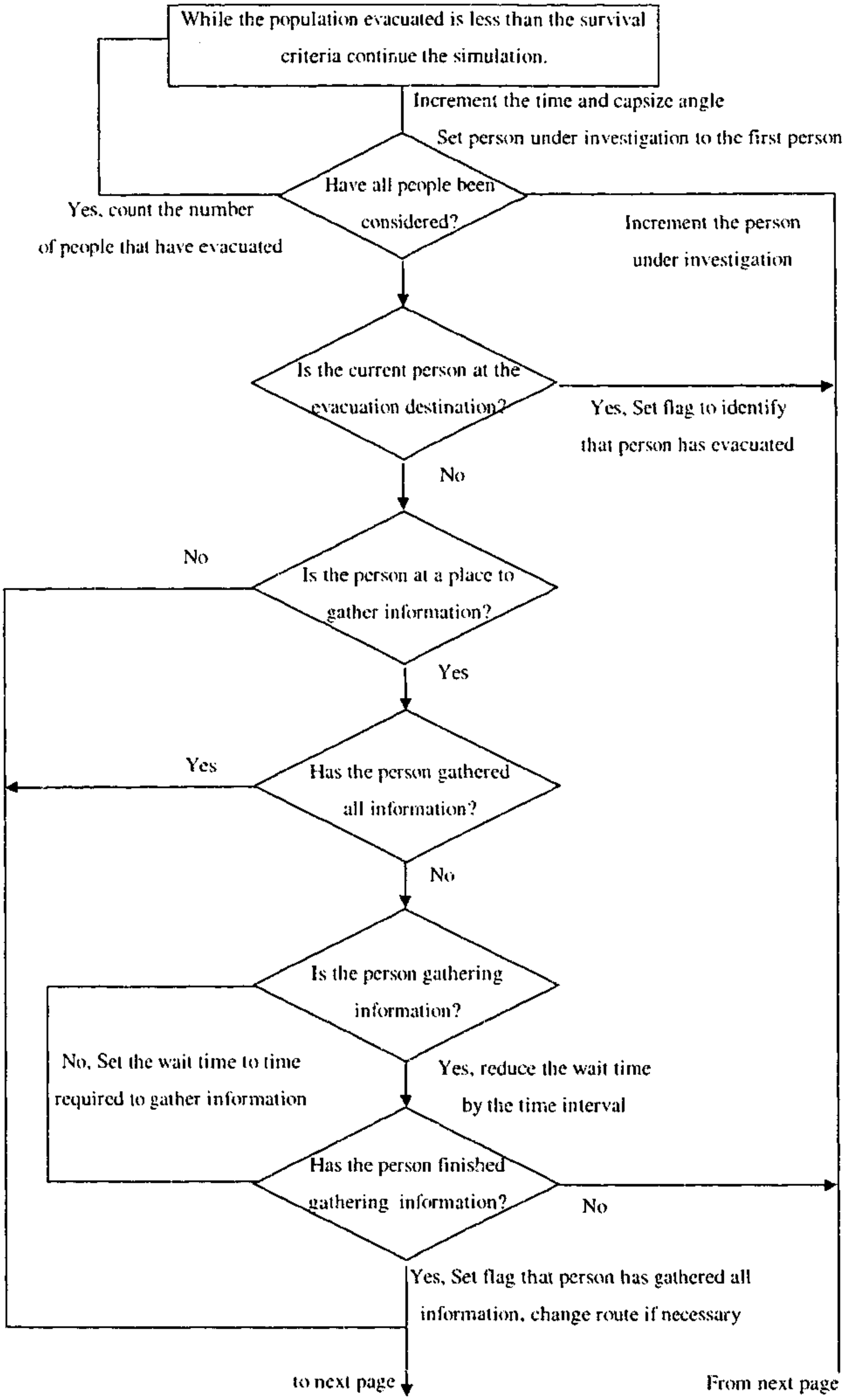


Figure A8.3 EVACUSHIP Evacuation Simulation Algorithm, Page 2 of 2

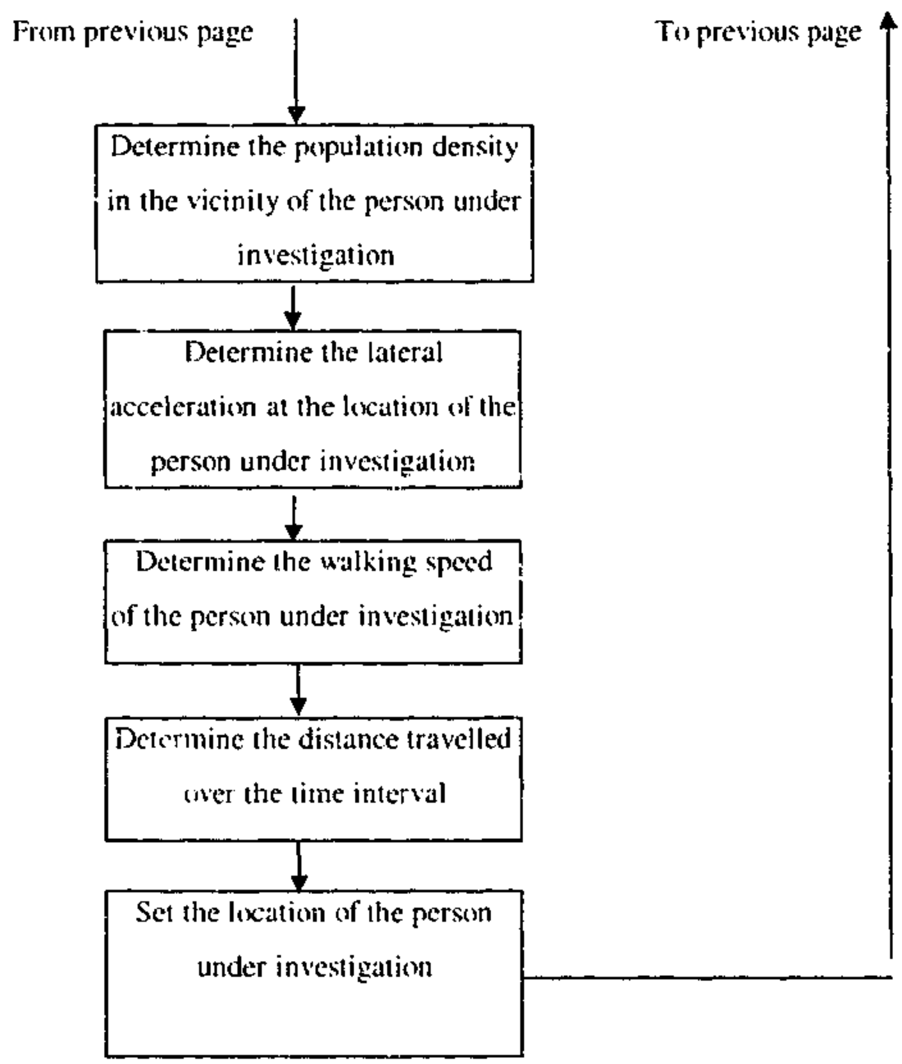
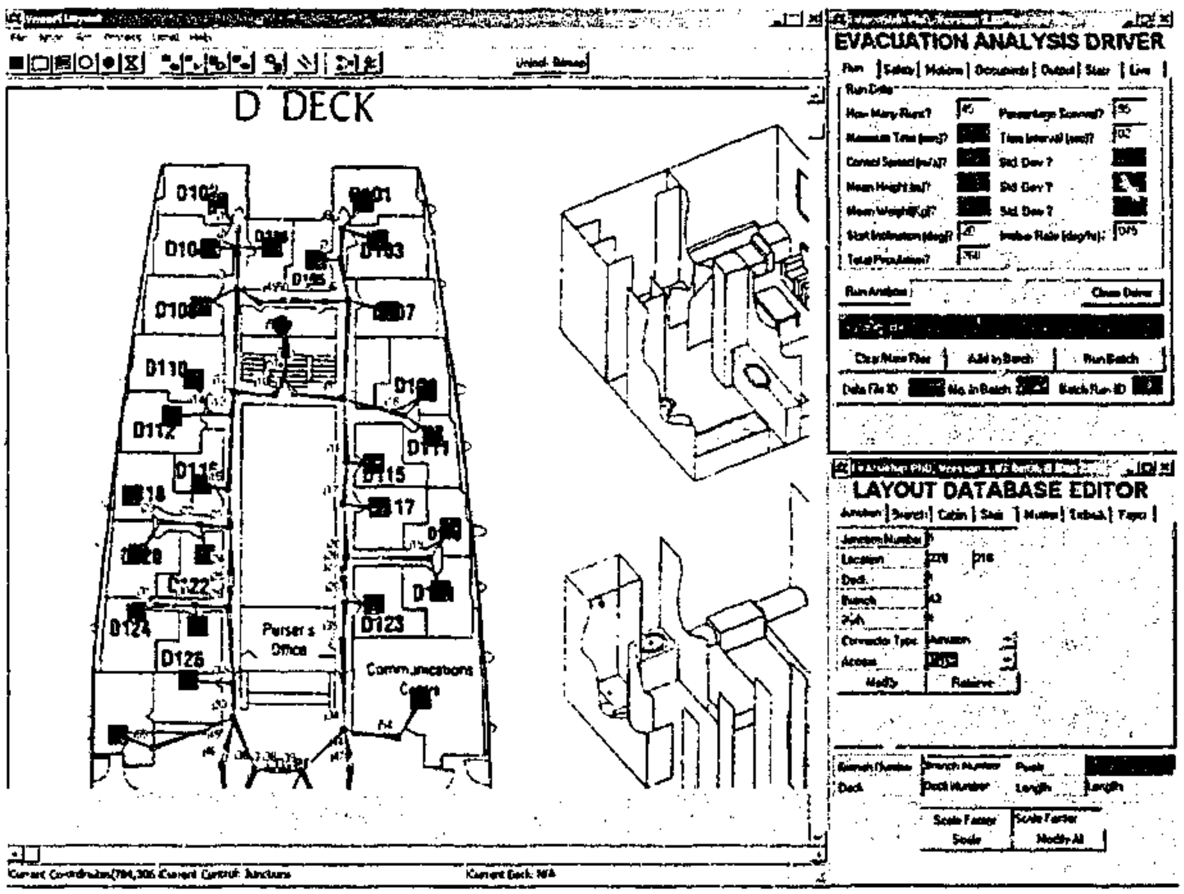


Figure A8.4 EVACUSHIP Example Settings (Run and Safety)



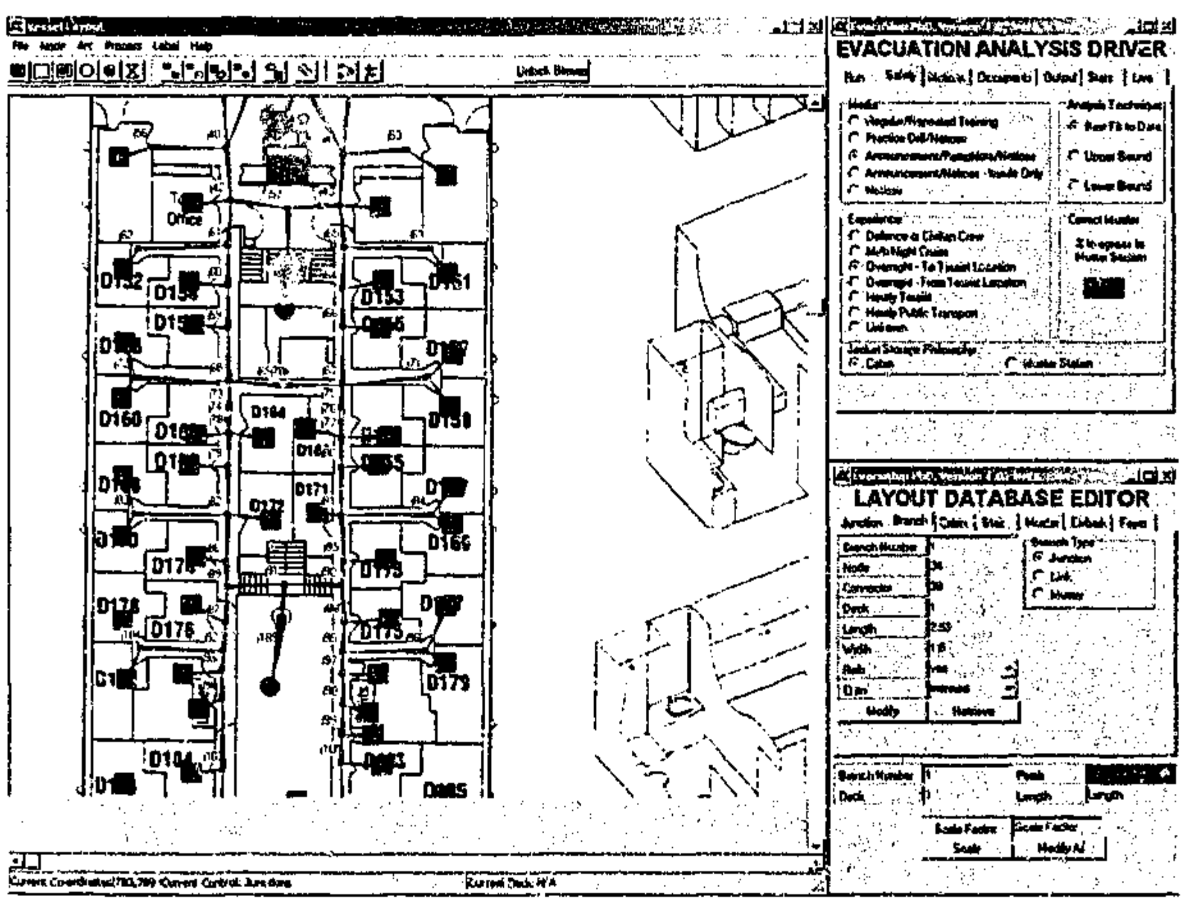
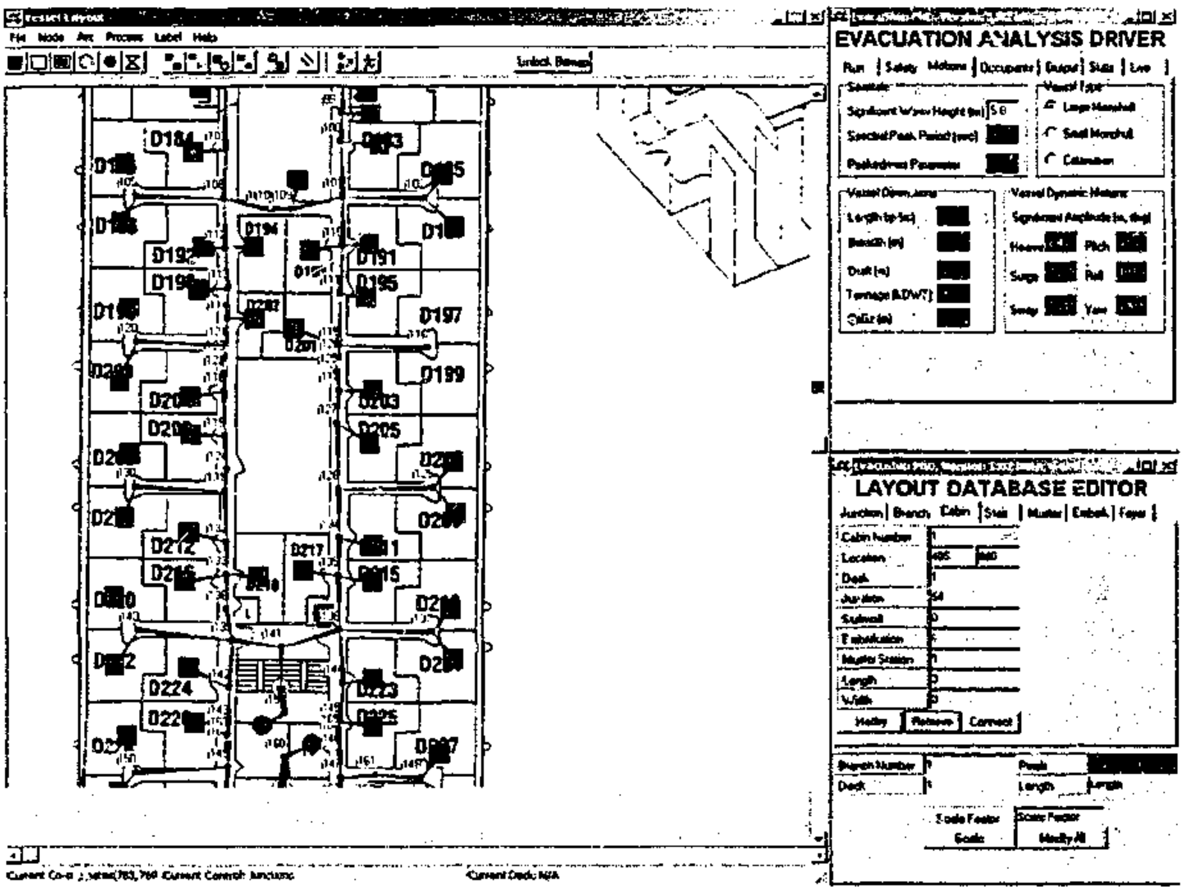
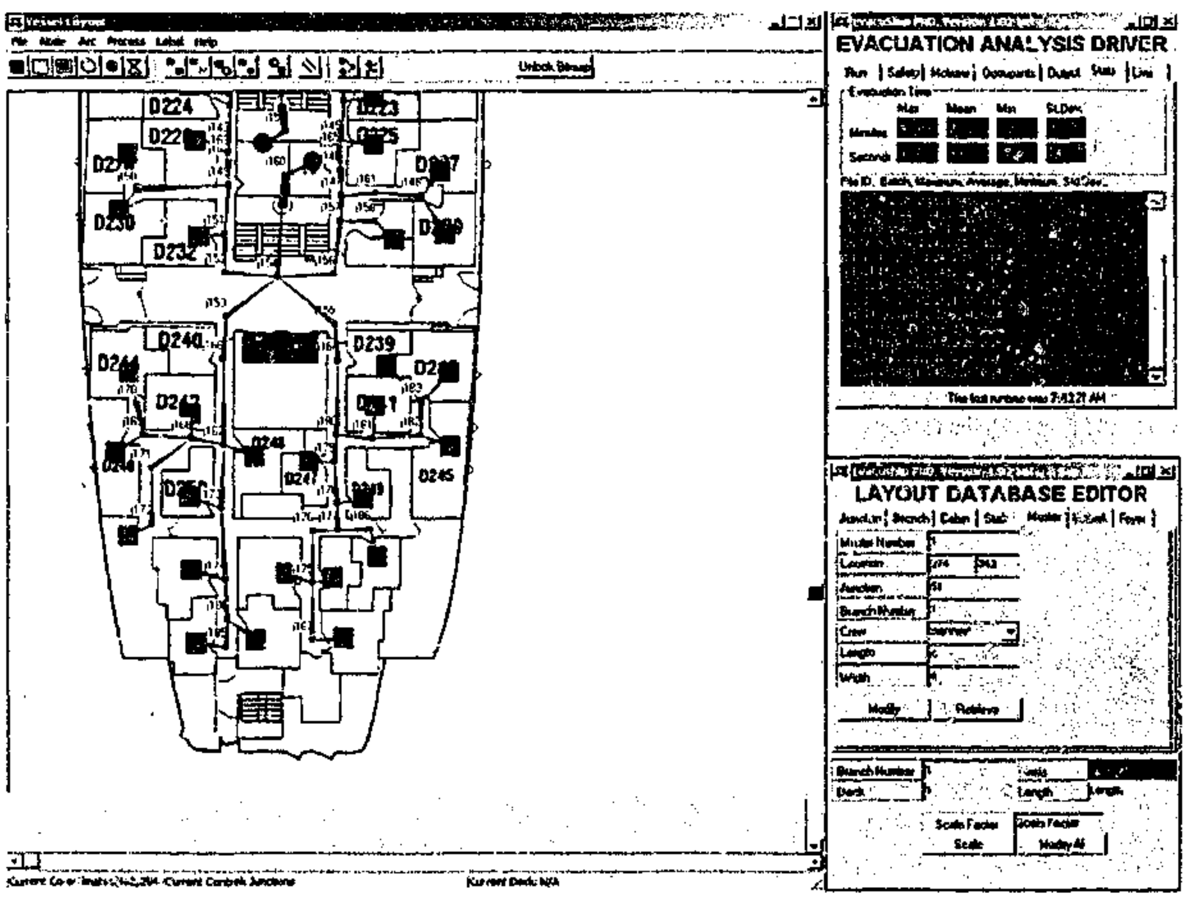


Figure A8.5 EVACUSHIP Example Settings (Motions and Stats)





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