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Voluntary Speed Loss of Ships

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MASTER THESIS IN MARINE TECHNOLOGY

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FOR

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Voluntary speed loss of ships

The speed of ships tends to decrease when they travel in heavy seas. The speed will be reduced due to increased wind resistance and added wave resistance, as well as increased resistance due to steering and reduced propulsive efficiency. This is called involuntary speed loss. Voluntary speed loss means that the shipmaster is reducing the speed because some operational criterion is exceeded. These operational criteria are usually not formalized or documented, and is therefore varying from person to person. Still, it is often of interest to include voluntary speed loss when the attainable speed of ships in a seaway is computed.

The objectives of the master thesis are:

- To explain the concept of voluntary speed loss
- To give an overview of what is known (published) about the criteria used by shipmasters in voluntary speed reduction.
- To discuss the extent and relevance of a voluntary speed loss.
- To discuss when and under which conditions a voluntary speed loss occur.
- To give examples of how criteria can be used to predict attainable ship speed in a seaway
- To discuss how one can calculate attainable speed of ships in a seaway when voluntary speed loss is included.

In the thesis the candidate shall present his personal contribution to the resolution of problem within the scope of the thesis work.

Theories and conclusions shall be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The thesis work shall be based on the current state of knowledge in the field of study. The current state of knowledge shall be established through a thorough literature study, the results of this study shall be written into the thesis. The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis shall be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

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The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The plan shall include a budget for the use of laboratory or other resources that will be charged to the department. Overruns shall be reported to the supervisor.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The thesis shall be submitted electronically (pdf) in DAIM:

- Signed by the candidate
- The text defining the scope (this text) (signed by the supervisor) included
- Computer code, input files, videos and other electronic appendages can be uploaded in a zip-file in DAIM. Any electronic appendages shall be listed in the main thesis.

The candidate will receive a printed copy of the thesis.

Supervisor : Professor Sverre Steen
Start : 12.01.2017
Deadline : 11.06.2017

Trondheim, 12.01.2017

Sverre Steen
Supervisor

Preface

This thesis is written by Sigbjørn Wiik as a part of a Master's degree at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim. It was written during the spring semester of 2017. The topic was brought up by my supervisor Sverre Steen as a field with little documented study with a potential and need for more information.

During the fall semester of 2016, I worked on a project thesis to evaluate feasibility of calculating voluntary speed loss, where the primary focus was to understand why a voluntary speed loss occurred, and whether there were any general trends.

In this thesis, a big part is understanding voluntary speed loss and factors that influence it. Individual studies were done to look at trends and bring verification to results found in literature.

The thesis has in general been difficult to carry out at times, due to the strong human influence on the subject where literature is little specified. The questionnaire proved to be a more time consuming (the last answer was received May 28.). This made the last couple of weeks quite hectic on the cost of amount and accuracy in numerical calculations.

The thesis has given me a great opportunity of learning in a field that previously was new to me, and I have enjoyed doing research on it. The strong influence of subjectivity made it more difficult, but also more interesting as it gave a chance to work with and interview officers.

Readers will benefit from having basic ship knowledge, but strictly speaking this should not be needed in this thesis.

Norges Teknisk Naturvitenskapelige Universitet, September 12, 2017

Sigbjørn Wiik

Summary

When a ship is caught in heavy seas, speed loss follows. This thesis focuses on the subjective part of speed loss; voluntary speed reductions to maintain the safety of the ship, the cargo and the people. The objective is to establish reasonable operability limits to objectionable motions that jeopardize the safety. Although the ideas presented in this thesis are intended to be generalized for any ship, only single-hull surface displacement vessels operating in typical port-to-port missions are considered.

Factors that degrade the ship performance, and thus the operability, can be governed by prescribing operability criteria that are set to an acceptable and an unacceptable level. These operability criteria and their influencing factors as well as their significance will be investigated in this thesis.

A literature research was conducted to find current operability criteria of a ship. Individual studies were then conducted to verify or find new operability limits. This was done in three ways: First, a questionnaire to look at the subjectivity involved as well as verifying that operability criteria from literature are valid for the type of ship investigated. Second, through ship service investigation to look at actual trends for sea-going vessels, the likelihood of a voluntary speed loss for a given sea state, the amount of speed loss, and whether it was possible to generalize results. Lastly, the operability criteria found in literature and the questionnaire were implemented in numerical analyses to validate the limiting operability criteria.

From the questionnaire, it was found that voluntary speed loss would become prominent for significant wave height around 5.5 meters in a loaded and ballasted condition for head and beam seas. In following sea, voluntary speed losses become prominent at higher wave heights; around 10 meters. The questionnaire also highlighted a larger tolerance for root mean square roll angle, water on deck and slamming and lateral acceleration. However, with very varying results it was impossible to set operability criteria from the questionnaire. Human comfort was not indicated as a limiting factor in the questionnaire, yet from numerical calculations it was found that motion sickness incidences (MSI) was the operability criteria that dictates safe speed in both head and beam seas. In following seas, numerical results showed that propeller racing was the single most important factor inducing a voluntary speed loss.

As no responses were recorded in the ship service data, it was impossible to set operability criteria from it. However, the ship service data gave valuable information about inception and occurrence of voluntary speed loss. It showed that a voluntary speed loss is likely to occur for significant wave height around 5.5 meters, although ship differences occur, varying from wave height of 4-10 meters.

Both the questionnaire and service data encompass approximately similar ship type and size. 24 of 26 answers from the questionnaire were received on general cargo vessels, and the ship service data only contains general cargo vessels. The general dimension varies in length from 180-230 meters, width of 29-32 meters and depth/draft of 10-35 meters.

The ship service data and questionnaire data show good correlation, yet it must be emphasized that general operability criteria were found to be highly dependent on ship size, type, heading, area of operation and type of mission.

From service data it was found that vessels sailing in significant wave height larger than 3 meters consists approximately of 11% of the time. For significant wave height around 5.5 meters, the time is only 4.6%.

Numerical calculations showed a higher importance of MSI in head and beam seas, and propeller racing in following seas. More calculations should be done though, as the questionnaire and service data was prioritized in this thesis.

With the high subjectivity involved, one of the most important factors found was that everything on board must feel safe (for the master), regardless of the actual situation. As the master holds the most responsibility, the action of lowering the ship-speed is dependent on a master's experience, preference, perception of the situation and willingness to expose the ship to hazardous situations.

It is also important to emphasize that there is no guarantee that a speed loss will occur when exceeding the operability criteria. The service data showed that although sailing in conditions that normally yield voluntary speed loss, it is highly dependent on vessel. This thesis shows however that a voluntary speed loss is likely to occur for a significant wave height around 5.5m for a general cargo ship with dimensions as previously stated. The average voluntary speed loss is around 5 knots. This limit is however very questionable as there are large differences in answers received from the questionnaire and ship service data.

Considering the relatively few responses from the survey, one should be careful in transferring results, especially to other ship types.

More research should be done on specific ship types, as well as getting an increased trend of more ship service monitoring where responses are recorded. This will make it possible to find feasible operability criteria from ship service data.

Sammendrag

Når et skip er fanget i dårlig vær er en vanlig konsekvens et hastighetstap. Denne avhandlingen fokuserer på den subjektive delen av hastighetstapet; Frivillige hastighetsreduksjoner for å opprettholde sikkerheten til skipet, lasten og menneskene ombord. Målet med avhandlingen er å etablere rimelige operasjonsgrenser til ubehagelige bevegelser som setter sikkerheten i fare. Selv om ideene som presenteres i avhandlingen er ment å være generalisert for alle typer skip, er det hovedsaklig alminnelige lasteskip med typisk havn-til-havn-oppdrag som blir vurdert.

Faktorer som forringer skipets ytelse, og dermed skipets operabilitet, kan dette kontrolleres ved å foreskrive operasjonelle kriterier som er satt til et akseptabelt og uakseptabelt nivå. Disse operasjonelle kriterene, dems påvirkningsfaktorer og dems betydning vil bli undersøkt i denne avhandlingen.

En litteraturstudie ble utført for å finne dagens operasjonelle kriterier for et skip. Individuelle studier ble deretter utført for å verifisere og finne nye funksjonsgrenser. Dette ble gjort på tre måter: Først ved et spørreundersøkelse for å se på subjektiviteten som er involvert, samt å verifisere operasjonelle kriterier fra litteraturen er gyldig for den undersøkte typen fartøy. Deretter ble data fra skip i sjøgang gjennomgått for å se på faktiske trender. Her ble det undersøkt sannsynligheten for et frivillig fartstap for en bestemt sjøtilstand, mengden hastighetsfall og om det var mulig å generalisere resultatene. Til slutt ble operasjonelle kriterier fra litteraturen og spørreundersøkelsen implementert i numeriske analyser for å validere de begrensende operasjonelle kriteriene.

Fra spørreundersøkelsen ble det funnet ut at frivillig hastighetstap blir fremtredende for signifikant bølgehøyde rundt 5,5 meter i både lastet og ballast tilstand for head- og beam sjø. I følgende sjø blir frivillig fartstap fremtredende ved høyere bølgehøyder; Rundt 10 meter. spørreundersøkelsen fremhevet også en større toleranse for rullevinkel, vann på dekk, slamming og lateral akselerasjon. På grunn av svært varierende resultater var det umulig å sette operasjonelle kriterier fra spørreundersøkelsen. Menneskelig komfort ble ikke indikert som en begrensende faktor i spørreundersøkelsen, men fra numeriske beregning ble det funnet at sjøsyke var det operasjonelle kriteriet som induserer en hastighetsreduksjon i head og beam-sjø. I følgende sjø viste numeriske beregninger at propellventilasjon var den viktigste faktor som induserte et frivillig fartstap.

Siden det ikke var logget skipsresponser i de innsamlede driftsdataene var det umulig å angi operasjonelle kriterier fra dem. Imidlertid ga driftsdataene verdifull informasjon om oppstart og forekomst av frivillig fartstap. Driftsdataene viste at frivillig hastighetstap oppstår for signifikant bølgehøyde rundt 5,5 meter, selv om skipsforskjeller forekommer. Avhengig av skip undersøkt, varierte den significante bølgehøyden for et frivillig fartstap mellom 4 og 10 meter.

Både spørreundersøkelsen og driftsdataene omfatter omtrent samme skipstype og -størrelse. 24 av totalt 26 svar ble mottatt for lasteskip, og driftsdataene inneholder kun data fra lasteskip. Den generelle størrelsen på skipene varierer i lengde fra 180-230 meter, bredde på 29-32 meter og dybde/høyde på 10-35 meter.

Skipsdriftsdata og spørreundersøkelsen viste god korrelasjon, men det må understrekes at de operasjonelle kriterier som ble funnet er svært avhengig av skipsstørrelse, type, retning sjøen kommer fra, operasjonsområde og oppdragstype.

Fra servicedata ble det funnet ut at skipene i snitt seilte 11% av tiden i signifikant bølgehøyde større enn 3 meter. For signifikant bølgehøyde over 5,5 meter er tiden kun 4,6%.

Numeriske beregninger viste en høyere betydning av sjøsyke i head og beam-sjø, og hurtig propellrotasjonsøkning i følgende hav. Flere beregninger bør imidlertid gjøres, fordi spørreskjemaet og tjenestedataene ble prioritert i denne oppgaven.

Med den høye subjektiviteten som er involvert, en av de viktigste faktorene som ble funnet var at alt om bord må føles trygt (for kapteinen), uavhengig av den faktiske situasjonen. Siden kapteinen har mest ansvar, er handlingen av å senke skipshastigheten avhengig av en kapteins erfaring, preferanse, situasjonsoppfatning og villighet til å utsette skipet for farlige situasjoner.

Det er også viktig å understreke at det ikke er noen garanti for at et hastighetstap vil oppstå når man overgår de operasjonelle kriteriene. Driftsdataene viste at selv om seiling under forhold som normalt gir frivillig hastighetstap, er det avhengig av det enklete fartøyet. Denne oppgaven viser imidlertid at et frivillig fartstap er sannsynlig for en signifikant bølgehøyde på 5,5m for et generelt lasteskip med dimensjoner som tidligere nevnt. Det gjennomsnittlige hastighetstapet var rundt 5 knop. Denne grensen er imidlertid svært tvilsom, da det er store forskjeller i svar mottatt fra spørreskjemaet og tjenestedata.

Med betrakting i de relativt få svarene fra spørreundersøkelsen, bør man være forsiktig med å overføre resultater, spesielt til andre skipstyper.

Mer forskning bør gjøres på spesifikke skipstyper, samt å få en økt trend for mer tjenestedata der skipsrespons registreres. Dette vil gjøre det mulig å finne mulige operasjonelle kriterier fra tjenestedata.

Acknowledgment

I would like to express my gratitude to Professor Sverre Steen at the Department of Marine Technology for valuable guidance in the field of hydrodynamics, and with putting me in contact with SFI SmartMaritime where ship service data was provided.

I would like to thank Sverre, Jasna Prpić-Oršić and shipmasters from the Hurtigruta-fleet for valuable input in the questionnaire. The questionnaire has only very minor changes from the original questionnaire provided to me by Jasna Prpić-Oršić. An additional gratitude goes to Agathe Rialland at SINTEF for help in distributing and following up the questionnaire to ship-owners. I would also like to thank all people involved with the questionnaire. The answers received have been invaluable, and this thesis would not be the same without them. In the end, the questionnaire was both rewarding and interesting to work with and gave a particular sense of achievement and meaning to the work conducted.

I would also like to thank my family for much patience and support throughout the semester - it has proved to be one of the more challenging ones, yet highly rewarding. I would like to thank my office mates for keeping me sane and always wanting to work at school.

Lastly, thanks go to my friend Charles for proofreading, clarifying and finishing touches with the thesis.

S.W

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Abbreviations and symbols

NTNU	Norges Teknisk Naturvitenskapelige Universitet
RMS	Root Mean Square
MSI	Motion Sickness Incidences
MII	Motion Interrupted Incidences
MIF	Motion Induced Fatigue
ULCS	Ultra Large Container Ship
LNG	Liquefied Natural Gas
FP	Fore Perpendicular
C_B	Bloack coefficient
$H_{1/3}$	Significant wave height
T_m	Modal period

1 Introduction

1.1 Background

Performance of a ship is important in today's global economy that stimulates and expands the shipbuilding and shipping industry. For designers, there is hard competition that drives for precise shipbuilding and evaluation. Owners drive to find the most profitable and economical route with the set of conditions and restrictions given. Safety of the ship is particularly important for the users, be it crew or passengers. Seakeeping of a ship is the sum of all factors that differentiate one ship from another, and good seakeeping is the ability to successfully operate under various conditions without lack of performance (Andrew and A.R.J.M Lloyd 1980). Generally, an indicator of good seakeeping is the ability of the ship to remain at high speeds even in heavy seas, because ship performance in real seas will degrade. The degradation arises from equipment operability, ship survivability, habitability considerations or a combination of these (Smith and Thomas 1989). With the degradation, there is an increased risk of malfunctioning, which in turn jeopardize the ship's safety (Lewis 1989). If the risk is found intolerable, speed reduction, course change or both are the most recognized actions to restore some of the safety (Guedes Soares 1990).

A speed loss in the magnitude of a few knots (2-3 knots) can result in substantial financial losses for a merchant ship (A.R.J.M. Lloyd 1998). Thus, it will be in the interest of all partners to get accurate speed calculations. To be able to predict the behavior of a ship in any environment of wind, current and waves for given loading, orientation, course and speed will help in this calculation. If a delay can be anticipated so port authorities can be informed in time for a new arrival schedule, it will help decreasing waiting time and traffic congestion for the port of interest (Prpić-Oršić, Parunov, et al. 2014).

1.2 Objective

The purpose of this thesis is to formulate a concept that includes voluntary speed loss in ship-speed calculation. To this end, it is necessary to introduce certain definitions, to set forth criteria for assessing the operability and to outline a logic for the evaluation. Specifically, an endeavor will be made to answer the following questions:

1. What is voluntary speed loss?
2. How is it measured?
3. By what operability criteria is voluntary speed loss assessed?

4. How is the speed reduced?

The answer to these questions will permit further inquire along the following lines:

1. How does one predict safe attainable ship-speed in moderate and severe sea states?
2. What is the relative importance of the several criteria of assessment?
3. How do these operability criteria affect design, operation and/or mission?
4. How can performance relative to the environment be included in optimizing the system?

The last set of questions has only been partially answered, and is listed to indicate eventual goals to be attained.

The operability of a ship is a function of the ship-speed, the geographical area and season the ship is sailing in. The performance of a ship is predicted by the Response Amplitude Operator (RAO), the sea state, the ship-speed, the heading and the operability criteria (Dallinga et al. 2002). Factors that degrade the ship performance and thus the operability can be governed by prescribing operability criteria that are set to an acceptable and unacceptable level. Ideally, this limit would be an abrupt discontinuity between motions and performance, but such an abrupt discontinuity does not, of course, exist. Rather, it is changing based on factors that will be investigated in this thesis, with an objective to obtain criteria limits to responses and motions that degrade the operability of the ship (Comstock 1980).

In this thesis, limiting operability criteria are responses that result in a voluntary speed loss due to safety. As the action of a voluntary speed reduction is highly subjective, a questionnaire will be conducted to look at trends and bring further validations to the final operability criteria limits. To bring validations to the operability criteria, limits are based from limits from literature. The operability limits will also be checked with operational ship data, if possible. At last, an effort is made in implementing the operability criteria in numerical analysis to find performance limitations of a ship.

1.3 Scope and limitations

The scope of this thesis covers single-hull surface displacement ships operating in typical port-to-port missions. Although the ideas presented are intended to be general; catamarans, trimarans, hydrofoil craft, air-cushioned craft, SES, SWATH and submarines are not considered as they present a somewhat special problem requiring extra care to be resolved. Surface vessels such as merchant, navy, pleasure, research and fishing vessels will be discussed. Omitted from consideration are icebreakers and other vessels intended for operation in ice. They also represent somewhat special problems that are, perhaps, best discussed after a general perspective has been achieved. The focus will therefore be on a ship for which mobility is the prime nautical quality (i.e. voluntary speed reductions are of particular importance), which is the case for port-to-port vessels (Lewis 1989).

The intention is to inquire into factors by which one can judge how fast (or slow) a ship sails in the weather and the seaways it is expected to encounter during a mission. Mission can universally be a single voyage or integrated to include a lifetime of service. Mission is in this thesis used mainly to describe single voyage trips and how well the ship can maintain its speed under increasing environmental influence.

Another important assumption is that a course change or a speed lowering will reduce the objectionable motions. This is certainly not always true, as will be discussed in Section 4.1. On a general basis, it is assumed true for large single-hull displacement vessels, which is the primary ship type in focus for this thesis.

It is assumed that the ship is always seaworthy. This implies that the seaworthiness is ensured at all times and that the environment is never so severe that the survivability of the ship is threatened, thus that the ship:

1. Can be manned with safety
2. Is always responsive to directional control

One implication of this is that available power is always adequate and attainable speed dependent on direct and indirect effects of motions. In other words, it is meant that there is enough fuel available so that the engine can be run at the intended speed without considering fuel costs, CO_2-emissions or other subsystems.

Involuntary speed loss will be considered, but not given emphasis in this thesis (see Section 2.2.1).

Operability criteria listed in this thesis have been found to commonly limit ship operations. The criteria are still tentative and revisions should be made once more information is commonly available. They are biased to the literature found and will as such present a source of error.

By use of current technology, better weather predictions are more readily available. This access and advanced notification system allows for possible avoidance of heavy seas if permissible. For that reason, vessels going through heavy seas will remain the exception. From a probabilistic point of view, occurrence will be minimalistic however important
(Guedes Soares 1990).

Finding operability criteria to set common standards for seakeeping performance of all types of vessels and operations might not be possible at all (Dubrovskiy 2000), but methods to calculate voluntary speed loss for some vessels and operations are certainly within the scope of present technology. If there are descriptions of the expected mission, environment, and a set of tolerable operability criteria of the ship responses, quantitative assessments of performance can be made in terms of comfort, workability and reliability (Marin 2016). This will enable prediction of possible voluntary speed loss, given operability criteria that are not to be exceeded.

1.4 Principles of assessing criteria

Speed lowering can be a result of traffic in port or canal of entry, moon-tide water levels, fuel economy, ship-to-ship operations or any other various reasons not further mentioned here. In this thesis, it is assumed that a speed reduction is enforced temporarily to maintain the safety.

Before proceeding to discuss quantitative measures of the seakeeping performance of a ship it is well to note that the single word ship is used throughout this thesis. When referring to a ship or ship system, it is the general term that comprises in all cases the minimum of the following four elements (Lewis 1989):

1. Global safety i.e. the hull (type, geometry and structure).
2. The systems needed to operate the hull. i.e. the power plant, steering system, motion control systems, etc.
3. The systems needed to perform the mission or missions assigned to the ship.
4. The people (in number, kind and training) necessary to operate the ship. This includes the habitability, comfort and safety for the people.

Assuming that the environment is the only factor affecting the performance of a ship, the performance of the ship will be directly related to the weather, the sea state and expected route of operation. The expected performance will define the degree of mission performance expected in the long run from the degradation imposed by the environment. Elements taken into consideration in assessment of the ship performance are:

1. The cumulative distribution of expected weather over routes of operation. Both short and long term.
2. The environmental (sea and weather) behavior characteristics of the system.

The environmental operability of a ship is not only determined by the hydrodynamic aspects of seakeeping, but are of a multi-disciplinary character, which requires accurate description of the ship hydrodynamics, the climate and description of seamanship to evaluate the actions made in particular scenarios (Dallinga et al. 2002).

1.5 Outline of Master Thesis

Section 2 presents the seakeeping theory needed for this thesis.

Section 3 is a more specific literature review with findings and information regarding voluntary speed loss to date. An effort has been made to use recent research, although there is no guarantee that everything has been included as well as much of the theory are references to old literature.

Section 4 is a presentation of the individual studies with corresponding results.

Section 5 is a discussion of the results. An effort was made to check if results from questionnaire, service data and numerical analysis correspond.

Section 6 presents the conclusion of this thesis with operability criteria for the ship in investigation in individual studies.

Section 7 discuss possible further work to be made in the topic of voluntary speed loss.

2 Seakeeping theory

In this section, theory needed for this thesis is presented. Objectionable motions are discussed in Section 3.

2.1 Seakeeping performance

Seakeeping performance of a ship can be broken into (Lewis 1989):

- Mission
- Environment
- Ship responses
- Operability criteria

2.1.1 Mission

The mission of a ship is the task it is set to do. It can be regarded as the fraction of the time a ship can perform a specified mission in a given environment and season. Generally, the mission can be broken down into three categories; port-to-port, military and commercial missions at sea (Lewis 1989).

As mentioned, the focus will be on port-to-port missions. Although safety is paramount for all mission types, information, validation as well as verification of results are more easily obtainable for port-to-port vessels.

2.1.2 Environment

The world meteorological organization (WMO) produced in 1970 a standard for categorization of the sea, known as the WMO sea state code (given in Table 1). It was done to simplify and give a more uniform description of different sea states. The prime parameter in the standard is the significant wave-height, $H_{1/3}$, where $H_{1/3}$ is the mean value from the highest third waves from many peak-through waves (Carlton 2012).

To describe a sea state numerically, a modal period T_m and wave spectrum $S(\omega, \Theta)$ (which combines the wave height spectrum $S(\omega)$ and wave direction spectrum $f(\Theta)$) are needed in addition to $H_{1/3}$. With these parameters, a description of the short term statistics for irregular

Table 1: WMO sea state code (WMO 1970)

WMO Sea State Code	Significant wave height	Characteristics
0	0 meters	Calm (glassy)
1	0 - 0.1 meters	Calm (rippled)
2	0.1 - 0.5 meters	Smooth (wavelets)
3	0.5 - 1.25 meters	Slight
4	1.25 - 2.5 meters	Moderate
5	2.5 - 4 meters	Rough
6	4 - 6 meters	Very rough
7	6 - 9 meters	High
8	9 - 14 meters	Very high
9	Over 14 meters	Phenomenal

sea can be made. Short-term refers here to a time-period where there is no significant change in wave period or wave height.

By combining many short-term sea state statistics, long term sea state statistics can be produced. This long-term sea state statistics gives information about changes over months or even years, and are usually given as a joint frequency table of significant wave height and mean wave period.

A third category can be made, namely deterministic situations through where special types of waves are described (i.e. breaking waves, etc.) (Faltinsen 1990). This is important because it means that the parameters of a sea state changes over not only specific location but has seasonal changes that needs to be accounted for.

However, in this thesis the main parameter in describing the sea state, $H_{1/3}$ will be used. $H_{1/3}$ is recognized as the most important factor imposing a voluntary speed loss. In defining heavy seas, only the significant wave height needs to be used.

Heavy seas is an ambiguous term and will depend on the ship dimensions, type and mission. For Ultra Large Container Ships (ULCS), heavy seas constitutes to $H_{1/3}$ of around 6-8m. (Prpić-Oršić, Parunov, et al. 2014). This limit will be explored in regards to the ship dimensions.

2.1.3 Ship responses

Ship responses are important both in absolute and relative values, and will depend on the sea state, the ship-speed and the ship-wave heading. During heavy seas, the ship will be exposed to strong environmental conditions with one consequence being additional dynamical effects that influences the ship-speed (Greco 2011).

Important seakeeping and wave load problems for a ship are illustrated in Figure 1 and the responses and other objectionable motions will be discussed in Section 3.

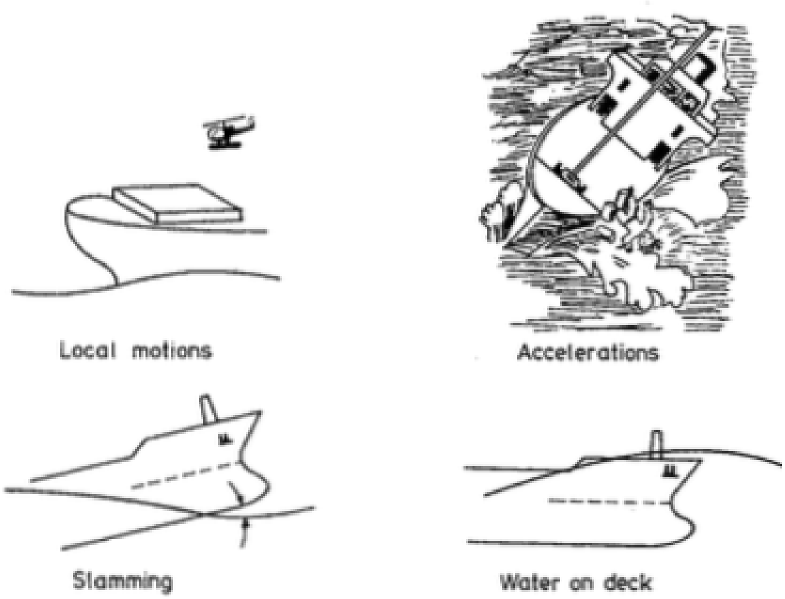

Figure 1: Seakeeping and wave problems that can impose voluntary speed loss (Faltinsen 1990)

2.1.4 Operability criteria

Setting operability criteria is essential in developing a methodology for assessing the seaway performance of a ship. With certain prescribed limiting values one can check whether a voluntary speed loss will occur or not.

The dependency on ship size is important to note. As a general remark, a large, full low-powered ship is usually slowed down sufficiently by involuntary speed loss in heavy seas to avoid problems of severe motions. For moderate to high-speed vessels however, motions are more important in determining voluntary speed loss (Lewis 1989).

2.2 Speed loss

Environmental degradation (i.e. degradation of operability due to wind, waves, current, visibility conditions etc.), is essential in validating voluntary speed loss (Denis 1976). The service speed is realized under stipulated, or idealized conditions such as no wind, no waves, no current, deep water, smooth hull and other surfaces for a ship at contract drought. These stipulated conditions, known as calm water conditions cannot be expected during actual seaways because of ship fouling, increased steering resistance, reduction of propulsive efficiency, etc. The result is an increased power demand compared to original prediction, and causes a speed loss in real seas (STA-JIP 2006).

The usual way to compensate for this speed loss in seaway is by adding a sea margin to the power prediction with a typical increased value of 15-20%. This margin is set according to tradition and some practical experience, however it is usually not based on the actual ship at hand, its condition and its operational profile (Eide 2015).

The performance of the ship will be the degree of attainment of the idealized conditions compared to the actual performance of the ship. The environmental operability relates the performance of the ship to the sea state and the weather (Denis 1976). A principal relation of this is shown in Figure 2.

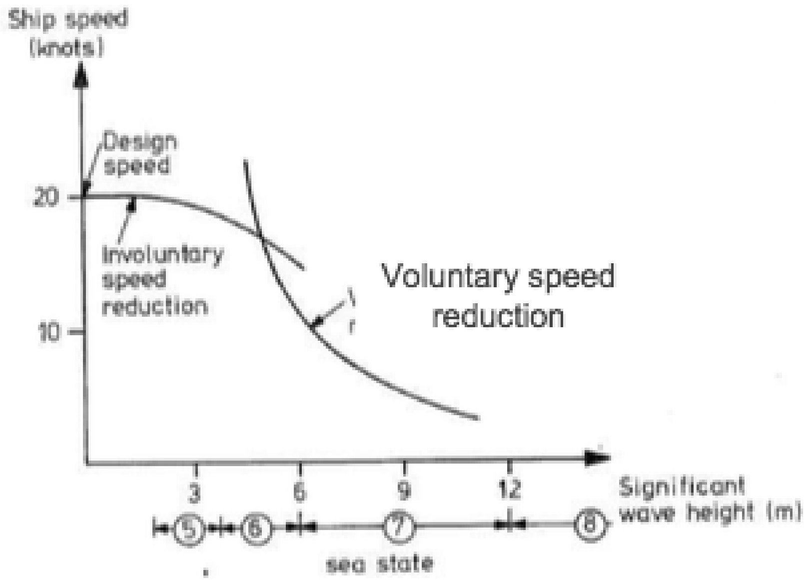

Figure 2: Speed loss of a ship in seaway (Greco 2011)

The speed loss, with a consequent increase in transit time, is divided into two principal categories (Faltinsen 1990):

1. Involuntary speed loss
2. Voluntary speed loss

2.2.1 Involuntary speed loss

Involuntary speed loss is a result of non-idealized conditions that influence the ship already at small ship-speeds and low significant wave heights, with increasingly larger speed loss for higher sea states, as illustrated in Figure 2 (Greco 2011).

There are two reasons for this speed loss. One reason is a reduction in power output due to change in wake field, off-regime propeller loadings and overloading of the main engine causing loss of thrust. The other reason is an increase of required power due to added drag caused by added resistance from wind, waves, change of draft and change of submerged parts in a seaway. Both reasons are important for involuntary speed loss considerations, and are specific for every ship. (Lewis 1989).

As involuntary speed loss occurs whether the ship captain wants it to or not, further investigations will not be made into this topic. Extensive research on involuntary speed loss can be found with corresponding papers and readers are encouraged consider associated and analogous papers.

2.2.2 Voluntary speed loss

A voluntary speed loss occurs when an active decision is made to lower the ship. The reason for lowering the ship-speed will be discussed in Section 3. This makes the influence of human action in deciding a voluntary speed loss (or change in ship-wave heading direction) quite subjective. This implies that although human reasoning might not always be easily understood it will be strongly associated to a voluntary speed loss, so that a quantitative assessment of medicine and psychology is needed (Andrew and A.R.J.M Lloyd 1980).

With progress being made in analytic methods and experimental techniques, more accurate determination of ship responses is available. This helps not only in determining the added resistance, of which much of the involuntary speed loss is based on, but also the responses which lead to voluntary speed loss based on a ship masters' judgment (Prpić-Oršić, Vettor, et al. 2016). This judgment in heavy seas can be divided into the following two parts (Prpić-Oršić, Parunov, et al. 2014):

- Route changes to avoid heavy seas
- Ship master's actions when in heavy seas

Weather forecasting gives relevant information for safe navigation where avoidance of heavy seas is often preferred. Based on questionnaires done by Prpić-Oršić, Parunov, et al. 2014, ship masters who have experienced the destructive power of a storm have a higher tendency of re-routing to avoid heavy seas. The effect being either a route modification to avoid heavy seas or a period of waiting in safe harbors until the conditions are more favorable. When a ship is caught in heavy seas with ensuing objectionable motions, the motions can become so violent that the safety of the ship is jeopardized. Weather avoidance in these situations might be difficult or impossible because of few places to seek shelter (such as crossings of the Atlantic (Moan et al. 2006)). In these cases, there are usually two possible actions (Guedes Soares 1990):

- Course change
- Reduction of speed

Either action is called voluntary because they are brought about by a decision of the master or person in charge.

A course change is faster than a speed reduction, as it is quicker to change thrust direction compared to throttling of the main engine RPM, especially for large diesel engines, whereas a course change can be regarded as a result of wanting to avoid capsizing or excessive ship rolling amplitudes that inhibits the normal working activities on board (Guedes Soares 1990).

The action of changing the course was found to be most prominent for vessels under 200 meters, which in some cases would bring the vessel in a heading that caused higher wave-induced bending moments (up to 25% higher). For a longer vessel (L > 200m), course changes were not found to be as prominent. One possible explanation being that the captain of such vessels felt safer and thus accepted larger amplitudes. In addition, longer vessels were found to be almost insensitive to increased changes of wave-induced bending moments due to a course change (Guedes Soares 1990).

Results from a course change alone might not lower the objectionable motions sufficiently, which will enforce a speed loss. The relation between a course change and speed reduction depends on initial speed and heading. A combination usually occurs for beam or bow sea, and in head sea a speed reduction (Guedes Soares 1990). A speed reduction can be seen in operational ship service data as a drop in RPM, given that the sampling frequency is sufficient to catch the temporary speed reduction. Illustration of this is shown in Figure 3.

Throttling of the main engine is a subjective action, related to whether the objectionable motions are tolerable or not (A.R.J.M. Lloyd 1998). As the ship masters ultimately hold the most responsibility for the ship, it will also be highly dependent on a ship master's experience and willingness to expose the ship to objectionable and violent motions (Prpić-Oršić, Vettor, et al. 2016).

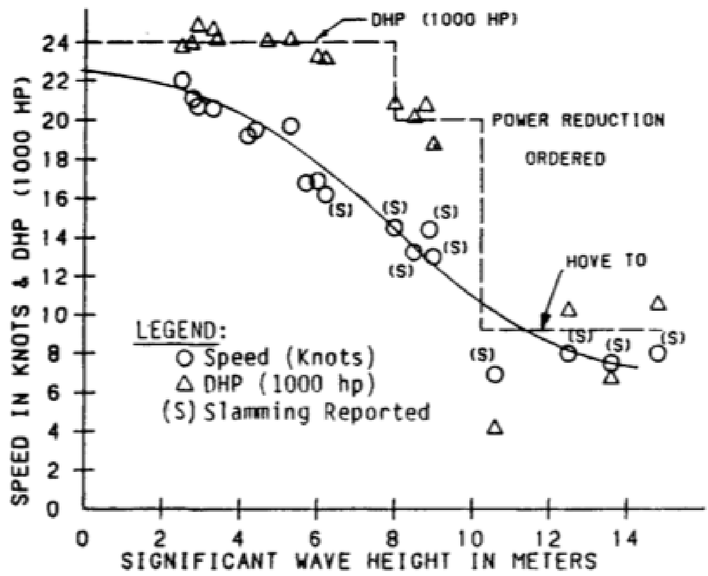

Figure 3: Exemplification of voluntary speed loss (Lewis 1989)

The speed is reduced sufficiently until the objectionable motion(s) are eliminated. This action of lowering the ship-speed is considered independent of ship size (Guedes Soares 1990). How the speed reduction is done on the other hand differs and will be discussed further in Section 4.1 and 4.3.

Voluntary speed loss, when enforced, incur a more significant speed loss compared to involuntary speed loss, as indicated in Figure 2. Voluntary speed loss will lead to a more significant increase of transit time, although time lost in heavy seas can, to some extent, be made up for by forcing the ship beyond its service speed (Lewis 1989)

On the other hand, a delay should in principle not be a main concern for the ship master. This is particularly true if the delay can be anticipated so that port authorities can be informed in time for a new arrival schedule. Often, even when arriving on time, the ship is made to wait due to traffic congestion or for other reasons at the port in interest (Prpić-Oršić, Parunov, et al. 2014).

Transit time can also be increased by choice of alternative routing which seeks to avoid storms or which, although longer, will result in more favorable track-to-wave angles from the standpoint of sea kindliness. Sea kindliness refers to a lowering of objectionable motions connected with both involuntary and voluntary speed loss. Currently there seems to be few formalized or established procedures for assessing when the objectionable motions, or operability criteria of a ship is exceeded, and intervention needed either in form of a speed reduction, change of ship heading or both.

3 Factors influencing voluntary speed loss

Effort has been made to categorize responses in regards to limiting performance on board. This is due to different vessels being expected to perform different tasks and activities at sea (A.R.J.M. Lloyd 1998). The operability criteria will therefore vary for a given ship type, mission and size.

3.1 Objectionable motions

As a starting point for objectionable motions, Tables 2 and 3 present a good overview (NORDFORSK 1987):

Table 2: Common limiting criteria for different ship systems (NORDFORSK 1987)

Ship subsystem	Criteria with regard to								
	Slam	Deck wetn.	Vert. acc.	Lat. acc.	Roll	Pitch	Vert. mot	Vert. vel.	Rel. mot.
Ship hull	∅	∅	∅						
Propulsion machinery									o
Ship equipment		o[1]	∅	∅	∅	o			
Cargo		o[2]	∅	∅	∅	o			
Personnel effectiveness		o[3]	∅	∅	∅	o			
Passenger comfort			∅	∅	∅	o			
Helicopter					o	o	o	o	
Sonar									o
Lifting operations			o		o	o	o	o	

[1] *For equipment on foredeck.*
[2] *For deck cargo.*
[3] *For operations on open lower decks.*
∅ *Indicates higher importance.*

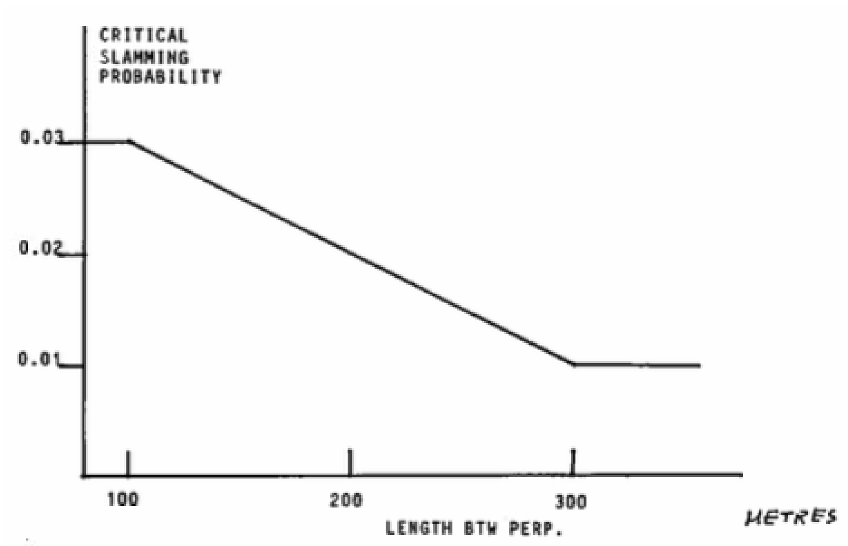

Figure 4: Critical slamming probability criteria (NORDFORSK 1987)

Table 3: Importance of physical location on the ship (NORDFORSK 1987)

Criterion	Hull safety	Equip. operat.	Cargo safety	Personnel safety and efficiency
Slamming	∅			
Deck wetness	∅			
Roll		∅	∅	∅
Vert. acceleration, FP	∅		∅	
Vert. acceleration, bridge		∅		∅
Lateral acceleration, bridge		∅	∅	∅

3.1.1 Slamming

Slamming occurs mainly in head seas for high speeds when the bow pitches out of the water and re-enters with a sudden impact (Brown 1999). It is categorized as a short-duration impact between water and structure, and is a complex non-linear phenomenon causing high local pressure peaks and is a problem for the structural integrity of the ship (Faltinsen 1990).

The slamming phenomena is an especially conspicuous phenomenon, easily distinguished anywhere on board the ship and able to cause high local damage, even tearing of plates at impact or cracking at highly stressed areas near amidships. A speed reduction is regarded as the wisest decision to ease the motions of the vessel and reduce the likelihood of more slams. Slamming is especially dependent on the draft of the ship, hull fullness, extend of flat bottom and shape of bow (Brown 1999).

Slamming can in addition onset elastic oscillations of the structure, called whipping and springing. This is an excitation of wave bending moments of a transient or steady-state oscillation respectively, which are associated with linear and nonlinear excitation mechanisms (Greco 2011). Both whipping and springing needs to be considered in ship design, as the associated stress effects the global hull girder stress (Aertssen 1967).

Whipping and springing can also have negative consequences for masts and antennas, machinery, delicate electronic equipment, loss of sleep and fatigue of crew (Andrew and A.R.J.M Lloyd 1980).

When looking at slamming location, literature suggests 15% of ship length abaft the bow (Ochi and Motter 1973). An example of slamming criteria is given in Figure 4

3.1.2 Deck wetness

Deck wetness, green sea, shipping of water, water on deck etc. will occur if water exceeds the freeboard of the vessel. Water on deck is highly dependent of the draft as well as the ratio of freeboard to length (Brown 1999).

If work needs to be done in exposed positions, even slight deck wetness (spray) can lead to crew injury and loss overboard, result in damage to exposed equipment and mountings/fittings, impose a hazard or inhibit essential maintenance of equipment as well as hinder normal operating tasks and crew mobility (Andrew and A.R.J.M Lloyd 1980).

Principally, deck wetness is of main concern for the fore part of a ship going in head seas at high speed, but it can include the aft part of a ship. Broaching waves may flood the quartering deck with the same effects as deck wetness in fore part (Andrew and A.R.J.M Lloyd 1980). Another example being when waves are travelling faster than a fishing vessel is deploying fishing gear, resulting in water flooding the entire aft part of the ship (Vinge 2017). Having the bridge close to the fore part of the ship pre-exposes the ship to loss of sight because of sea-spray (Brown 1999). Thus, forcing a speed reduction earlier to ensure clear sight. However, in heavy seas some deck wetness must be accepted (Aertssen 1967).

3.1.3 Propeller racing

For a working propeller, the relative motions are important. If they become too large, propeller racing, ventilation and emergence can occur. This will cause off-regime conditions, limit the power output, reduce thrust with strong influence on the ship efficiency and the ship-speed (Prpić-Oršić, Faltinsen, et al. 2016).

Propeller racing is critical for all load conditions, and are found to be most frequent for a medium-loaded cargo ship. Sometimes, it will be the chief engineer who intervenes first in lowering the power output to prevent damage to bearings, gears and the power plant (Aertssen 1966).

3.1.4 Vertical Accelerations

For accelerations, there are several standards outlining the safety acceleration criteria for a ship. Such standards can for instance be found in the IMO code of safety, and are mandatory for operation in international routes (Jullumstrø et al. 1999).

These do however not say anything of voluntary speed loss prediction. It is suggested to take the standards as criteria when lack of other criteria are not present or readily available.

Limits vary accordingly to type of vessel and activities. In general, accelerations associated with longer periods are more difficult to tolerate, so limits for a larger ship is stricter than for a smaller ship with typical shorter natural periods (Greco 2011). This can be seen in Figure 5.

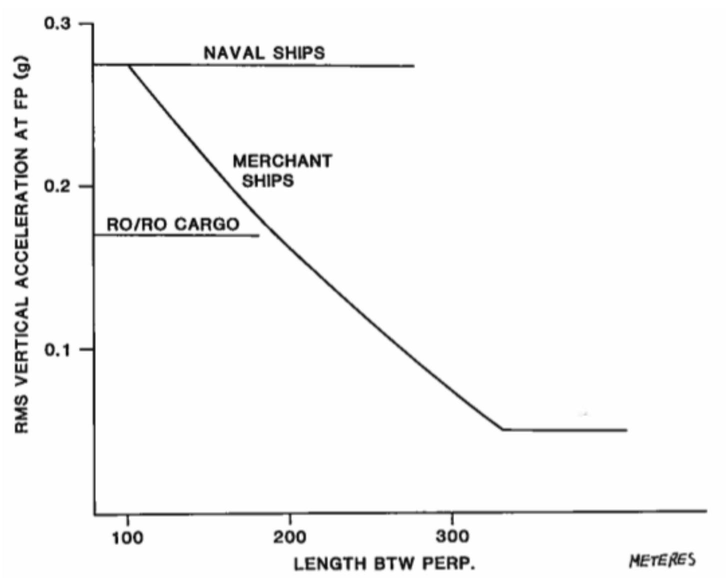

Figure 5: Vertical acceleration versus ship length (NORDFORSK 1987)

3.1.5 Lateral Accelerations

Lateral accelerations influences mainly the personnel on board a ship in relation to balance, and poses therefore a threat to safety. The criteria are estimated based on crew safety and performance, and are valid where people eat, sleep and work (and recreational areas on a passenger ship). Lateral accelerations are usually strongly coupled to vertical acceleration and motion sickness incidences (discussed in 3.2.2) (NORDFORSK 1987).

3.1.6 Roll

Roll is an apparent response, especially when the amplitudes exceed a few degrees. In terms of the ship hydrodynamics, the inherent ship usually has little roll damping because of symmetry and a streamlined body. This means that most of the roll damping is provided by viscous effects and forces from bilge keels, anti-roll tanks and active roll-fins (Greco 2011). For increasing roll amplitudes, a fast degradation of human performance follows. Large roll amplitudes can become very unpleasant and have been found to be the most important criteria for a course change, favoring head and following seas to reduce rolling motions (Prpić-Oršić, Parunov, et al. 2014).

For a ship with active stabilization system, speed reduction does not necessarily reduce the roll amplitude. An active stabilization fin system works better for increased speeds. A reduction in speed will thus increase the roll motion (Engvik 2017).

Large roll amplitudes are also a concern for cargo safety where excessive rolling can lead to shifting cargo. This shift may have various impacts, such as listing and unexpected ship responses, which will dramatically change the situation of the ship and jeopardize the inherent ship safety (Ryrfeldt 2004).

Resonant rolling in beam seas (parametric rolling), is an instability phenomena linked to large amplitudes with coupled motions of roll and pitch that in a worst-case scenario can lead to capsizing (France et al. 2003). As of scarcity and difficulty in modelling, it has been difficult to include. It is assumed that other operability criteria will limit the ship's performance before parametric rolling occurs.

3.1.7 Liquid sloshing in tanks

Sloshing is a resonance phenomenon of fluid movement in a confinement (on-board tanks, ship decks with bulwark etc.) that is excited when the natural period of the confinement is close to the wave period. The fluid in the confinement is subjected to nonlinear effects that can cause large fluid forces with very limited damping (Greco 2011).

In some cases, extreme external excitation is possible. The resulting effect is a very high impact pressure in the confinement and supporting hull structure with a coupling to large global loads. In addition, sloshing may lead to slamming, wave breaking and other complex phenomenon that can influence both the local and global loads (Greco 2011).

Sloshing is a particularly important behavior on modern LNG vessels, which may have many tanks with little internal damping (Hirdaris et al. 2014).

Although sloshing is an important non-linear phenomenon, the ship hydrodynamics can be handled well by linear theory, except for motions and loads connected to viscous roll damping (Faltinsen and Timokha 2009). As of the rare incidence and little reference in literature, liquid sloshing has been excluded in operability criteria for voluntary speed loss.

3.2 Human performance - comfort and seasickness

The human performance will degrade as objectionable motion continues. This can result in crew injury, fatigue, low morale, degradation in manual and mental dexterity and test the endurance of the personnel (Andrew and A.R.J.M Lloyd 1980). For instance, an increase of motion amplitudes will in most cases lead to higher accelerations that in turn pose a threat to normal working conditions (A.R.J.M. Lloyd 1998). A summary of different motions related to human comfort and safety with a short description are presented in Table 4 (Fathi 2017).

Table 4: Operability criteria regarding human safety and comfort (Fathi 2017)

DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Vertical Acc. versus MSI			
Exposure: 1/2 hour	0.1g	10% motion sickness incidence	ISO 2631/3
1 hour	0.08g	ratio (MSI) (vomiting) among	1987 & 1982
2 hours	0.05g	infrequent travellers of the	
8 hours	0.025g	general public	
Vertical Acc.			
Simple light work possible	0.275g	Most of the attention devoted to keeping balance	Conolly 1974
Light manual work possible	0.20g	Causes fatigue quickly. Not tolerable for longer periods.	Mackay 1978
Heavy manual work possible	0.15g	Limit in fishing vessels	
Work of more demanding type	0.10g	Long term tolerable for crew	Payne 1976

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DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Passengers on a ferry	0.05g	Limit for people unused to ship motions	Goto 1983
Passengers on a cruise liner	0.02g	Older people. Lower threshold for vomiting to take place.	Lawther 1986
Lateral Acc.			
Passenger on a ferry	0.025g	1-2 Hz frequency. General public.	ISO 2631/1 1987
Navy crew	0.050g	Non-passenger and navy ships.	ISO 2631/1 1987
Standing passenger	0.07g (max)	99% will keep balance without need of holding	Hoberock 1977
	0.08g (max)	Elderly person will keep balance when holding	Hoberock 1977
	0.15g (max)	Average person will keep balance when holding	Hoberock 1977
Seated passenger	0.15g (max)	Nervous person will start holding.	Hoberock 1977
	0.25g (max)	Average person max. load balance when holding	Hoberock 1977
	0.45g (max)	Person will fall out of seat	Hoberock 1977
Roll			
Light manual work	6.0°	Personnel effectiveness	Comstock 1980
Heavy manual work	4.0°	Personnel effectiveness	Comstock 1980
Demanding work	3.0°	Personnel effectiveness	Hosoda 1985
Passenger on a ferry	3.0°	Short routes. Safe footing	Karppinnen 1986
Passenger on a cruise liner	2.0°	Older people. Safe footing	Karppinnen 1986
Pitch			
Navy crew	3.0°	Personnel safety	Comstock 1980
Light manual work	2.0°	Personnel effectiveness	Hosoda 1985
Demanding work	1.5°	Personnel effectiveness	Hosoda 1985

end of Table

3.2.1 Accelerations

Accelerations are given in reference to human comfort in Table 4. The reason for this is that accelerations usually becomes a problem concerning human comfort before impairing the ship structure or subsystems. This is not always true however, as some ship systems such as a sonar in a navy ship can be impaired even for low accelerations (Andrew and A.R.J.M Lloyd 1980).

3.2.2 Motion Sickness

Motion Sickness Incidence (MSI) is a collective designation of vomiting and nausea, drowsiness, headaches, sweating, stomach awareness, loss of appetite and various cardiovascular and endocrinal changes. MSI is regarded as the worst discomfort phenomena for individuals imposing a habituation problem (Alkan 2011).

MSI, Motion Induced Interruptions (MII) and Motion Induced Fatigue (MIF) are used to quantify the effect of ship motions on human performance and comfort (Tezdogan et al. 2014). MSI refers to incidents of vomiting due to wave motions. It was originally proposed by O'Hanlon and M. E. McCauley 1974, following by mathematical expression developed by M. McCauley et al. 1976. MII refers to incidences where a person is forced to interrupt an allotted work task to avoid falling or loosing balance. MIF is a measure to quantify the effect of the physical fatigue under an extended period in sub-optimal working conditions (Alkan 2011).

Humans are most sensitive to vertical accelerations, caused by heaving and pitching of the ship in the frequency range between 0.18-0.30 Hz (cycles per second). Most people will be ill when accelerations are 0.8g and higher, or if exposed to smaller accelerations for a longer period. Figure 6 is a graphical characterization of accelerations and its influence on motion sickness. In the figure one can see that the lower acceleration limit seems to be 0.25 m/s^2 (corresponding to approximately 0.025g), with no MSI for lower accelerations. Dallinga et al. 2002 found that this traditional estimate might under-estimate the effects of MSI, because roll and transverse motions contribute significantly to the over-all MSI but are not accounted for in Figure 6.

Accelerations of a ship will vary over the length with maximum values at the ends where the pitching contribution is largest (Brown 1999). Therefore, it will be important to account for the physical location of the people when evaluating MSI, MII and MIF. If exposed to heavy seas for longer periods, fatigue, uncomfortable and unsafe situation arise from both cargo and personnel (Andrew and A.R.J.M Lloyd 1980). If severe enough, ship motions can inhibit or even make sleep impossible. This in turn will lead to a ship crew not able to perform a given task and ultimately the ships' mission (Michelet 2013).

As of adaptation, MSI is less likely to break out for extended time at sea. Figure 7 is taken from Pattison and Sheridan 2004 and is a habituation graph which shows the adaptation phenomena of motion sickness for sailors after subjected to heavy seas right after starting sailing. It is clear from the figure that it is the initial 24 hours that are critical, which seems to agree well with other literature, for instance from Andrew and A.R.J.M Lloyd 1980.

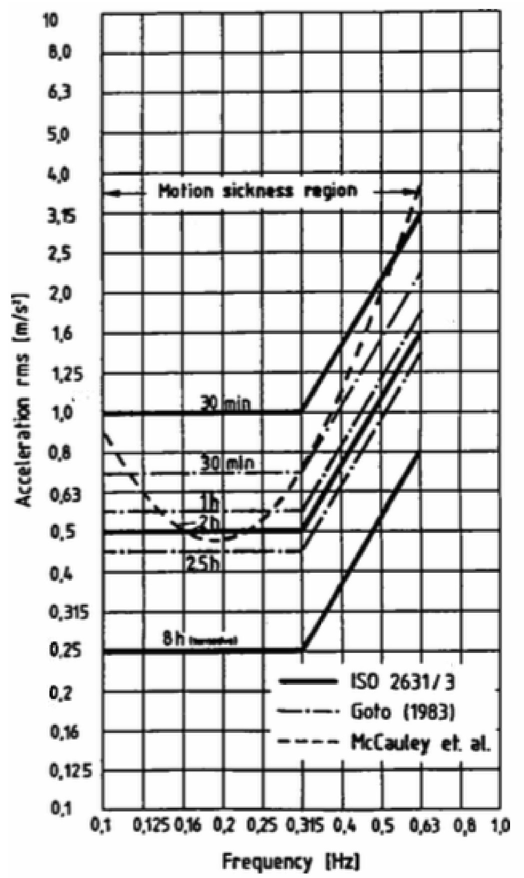


Figure 6: MSI criteria from ISO, Goto and McCauley (NORDFORSK 1987)

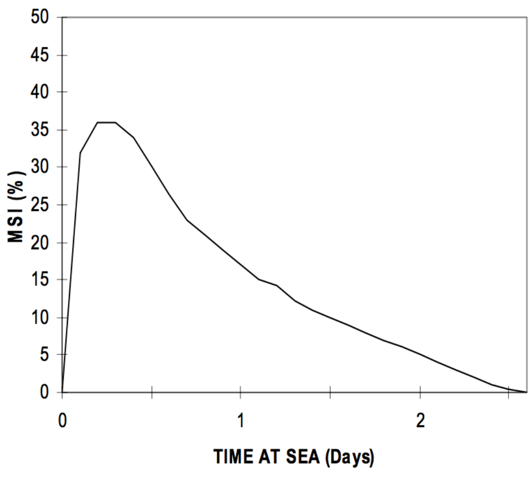


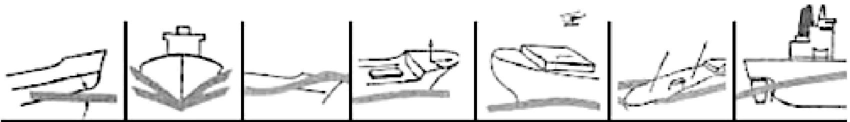
Figure 7: Adaptation to MSI for time spent at sea (Pattison and Sheridan 2004)

3.3 Factors influencing operability criteria

In this thesis, an operability criterion will be that response which, severe enough, will degrade the performance of the ship to an unacceptable level. This can be a sudden changes from violent motions (such as slam, deck wetness or propeller racing), that the effectiveness of the personnel have dropped markedly or that the habitability has been significantly reduced. In this way, the governing operability criteria for any given ship will be guided by the following:

- Ship type
- Loading condition
- Sea state
- Operability criteria, which will determine the ship-speed and the ship heading.

The ship type is a strongly influencing factor. It should be obvious that a passenger ferry will have different operability criteria compared to a cargo ship (as suggested in Table 4). The loading condition will influence which criteria are most prominent. For a passenger and cruise ship, the draft is generally constant. This is not the case for a cargo ship where there will be significant changes from a fully loaded and a ballasted condition. Due to natural reasons, large motions will be more important for the ballasted ship, and water on deck for the loaded one (Greco 2011). Importance of ship type and loading condition are exemplified in Figure 8.



		Bottom slamming	Bow flare slamming	Deck wetness	Vertical accel.	Vertical motion	Roll	Propeller emerg.
Large oil/bulk carrier	laden			Yes				
	ballast	Yes						Yes
Large container vessel			Yes	Yes	Yes		Yes	
General cargo ship		Yes		Yes	Yes			Yes
Ro-Ro			Yes		Yes		Yes	Yes
Passenger vessel			Yes		Yes	Yes	Yes	

Figure 8: Overview of important motions for different vessels (Greco 2011)

The sea state is the most influencing factor in operability, and has been discussed in Section

2.1.2. Operability criteria can be categorized as presented in Table 5, following Lewis 1989 example:

Table 5: Motions in waves

Operability criteria	Affected Elements	Performance degradation
a. Absolute Motions Amplitude		
1. Roll angle	People, Mission, ship system	Personnel injury, reduced task proeficiency, system degradation
b. Absolute Velocities and Accelerations		
3. Vertical accelerations	People and ship systems	Personnel fatigue, reduced task proficiency, system degradation
4. Lateral acceleration		
5. Human comfort, MSI	People	Reduced task proficiency
6. Human comfort, MII		
c. Motions relative to Sea		
7. Slamming frequency	Ship system	Hull whipping stresses and damage to sensors on masts etc
8. Water on deck frequency	People, ship system	Injury or drowning of personnel, damage to deck-mounted equipment
9. Propeller emergence	Ship system	Damage to main propulsion plant

Response categories in Table 5 are divided as follows:

- Absolute motion amplitudes (i.e. roll angles of the ship).
- Absolute velocities and accelerations (such as absolute vertical and lateral velocities and accelerations). Location can be anywhere on the ship, but in general location is set where the effects are most prominent (i.e. places where the effect on the people or the ship are most critical).
- Motions relative to sea (i.e. motions and velocities relative to the vessel-sea coordinate system) where the ocean surface is important.

A fourth category not covered in Table 5 is vertical, transverse and longitudinal displacements, velocities and accelerations of payload components with respect to the ship, caused by ship motions. This category includes for instance the motions of payload components sliding or shifting on a ship's deck because of motions of the ship. Data for this is scarce and will therefore not be taken into account although numerical calculations are possible and feasible to incorporate. In addition, it is argued that this will somewhat jeopardize the inherent ship safety and pose a problem not entirely within the scope of this thesis. It must be emphasized however, that shifting of cargo is certainly capable of jeopardizing the inherent ship safety and causing a voluntary speed loss.

An effort has been made to list the responses that limit performance of the ship. To determine the numerical values of the operability criteria it is vital to monitor the apparent performance of the ship at sea (A.R.J.M. Lloyd 1998). Ideally, the limits should be set from ship service data from operations, but because of scarcity of such data this is not always possible. It is therefore assumed that people with a wide knowledge of ship and ship performance prescribe the values. This includes, but is not limited to, the medical profession concerned with human performance, the naval architects and the engineers concerned with the design and performance of the ship and its subsystems as well as the officers and men who operate the ship and its systems (Lewis 1989).

3.3.1 Operability criteria limits

In this section, an example of operability limit criteria is given followed by a discussion of it. At the end of this section, operability criteria deemed reasonable are given. They will be judgment values from literature up to present date. Final operability criteria limits are presented in Section 6.1, where data from both the questionnaire and numerical calculations have been considered.

An example of operability limiting criteria found from NORDFORSK 1987 is presented in Table 6.

Table 6: Operability criteria given in NORDFORSK 1987.

	Merchant ships	Naval vessels	Fast small craft
Vert. acc. rms, FP	Fig. 4.1	0.275 g	0.65 g
Vert. acc. rms, bridge	0.15 g	0.2 g	0.275 g
Lat. acc. rms, bridge	0.12 g	0.1 g	0.1 g
Roll rms	6.0 deg	4.0 deg	4.0 deg
Slamming, crit. prob.	Fig. 4.3	0.03	0.03
Deck wetn., crit. prob.	0.05	0.05	0.05

Note: Fig 4.1 and Fig 4.3 in the table are Figures 5 and 6 respectively in this thesis.

All values of response (angles, displacements and accelerations) are Root Mean Square (RMS) peak-to-mean (single amplitude) values unless otherwise noted.

Some operability criteria are related to human decisions and have no physical precise level. An effort has been made to make the criteria universal in as much as they can be applied to any type of ship, but it is important to emphasize that the criteria limit is dependent on the specific ship, its heading and its configuration. The threshold criteria limits, when specified in literature, are not always uniformly defined, so an effort has also been made to distinguish and restrict to general port-to-port vessels where minimum elapsed time of transit is of importance.

Limits are assumed to be reasonable, average operational limits associated with no significant impairment of the operability in one of the three categories given in Table 7 (Lewis 1989):

Table 7: Operability impairment categories (Lewis 1989).

The ship	Personnel	Ship payload
Hull damage	Comfort	Cargo shifting
Deck equipment damage	MSI, MII and MIF	
System damage	Safety	
System efficiency	Task proficiency	
Propulsion plant		

All impairment categories in Table 7 are completely independent of sea, wind, and weather conditions; or the presence or absence of active motion controls. They are dependent on ship function (mission) and crew experience and may be dependent on ship type, size and mission duration (Lewis 1989).

The operability criteria are given in in Table 8.

Table 8: Operability Criteria

DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Vertical Acc. versus MSI			
Exposure: ½ hour	0.1g	10% motion sickness incidence	ISO 2631/3
1 hour	0.08g	ratio (MSI) (vomiting) among	1987 & 1982
2 hours	0.05g	infrequent travellers of the	
8 hours	0.025g	general public	
Vertical Acc.			
Work of more demanding type	0.10g	Long term tolerable for crew	Payne 1976
Lateral Acc.			
Seated passenger	0.15g (max)	Average person will keep balance when holding	Hoberock 1977
Roll			
Light manual work	6.0°	Personnel effectiveness	Comstock 1980

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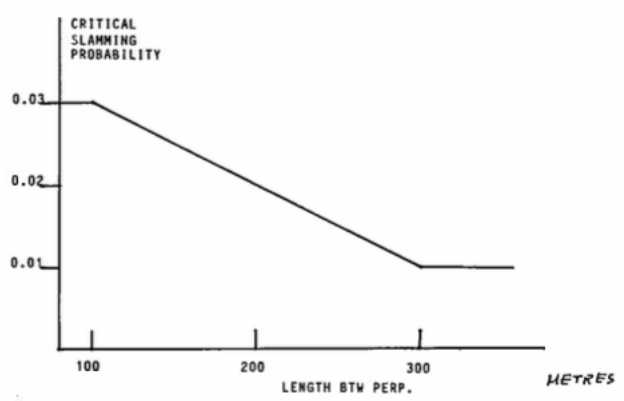
DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Slamming			
			NORDFORSK 1987
Water on deck			
Probability of occurrence	7%	i.e. 7 incidents/incoming wave	Fathi 2017
Propeller racing			
Probability of occurrence	5%	i.e. 5 incidents/incoming wave	Prpić-Oršić n.d.

end of Table

3.3.2 Ship responses not included

Some responses have been deliberately exluded, simply because of lack of ship data or difficulty in verification. Some responses were also excluded because of strong correlation to motion parameters described. Objectionable motions mentioned, but not included as an operability criteria are:

Table 9: Objectionable motions not included in operability criteria

Objectionable motion
RMS pitch angle
Motion Induced Fatigue
Shifting of cargo on deck
Vertical displacement and velocity
Lateral displacement and velocity
Liquid sloshing in tanks

4 Individual Studies and Results

4.1 Questionnaire

A questionnaire was conducted to look at trends in voluntary speed loss, and particularly the subjectivity involved. The questionnaire used is given in Appendix A. The questionnaire has very minor changes from the original questionnaire made by Ph.D student Natalija Vitali at University of Rijeka in Croatia.

There were in total 26 answers, 24 from cargo vessels and 2 from a cruise vessels. Only answers from the cargo vessels have been used in this analysis, because of few answers from the cruise vessels. The cargo vessels varied from ship length of 180 - 230m, width of 29-32m and depth/draft of 10-35m.

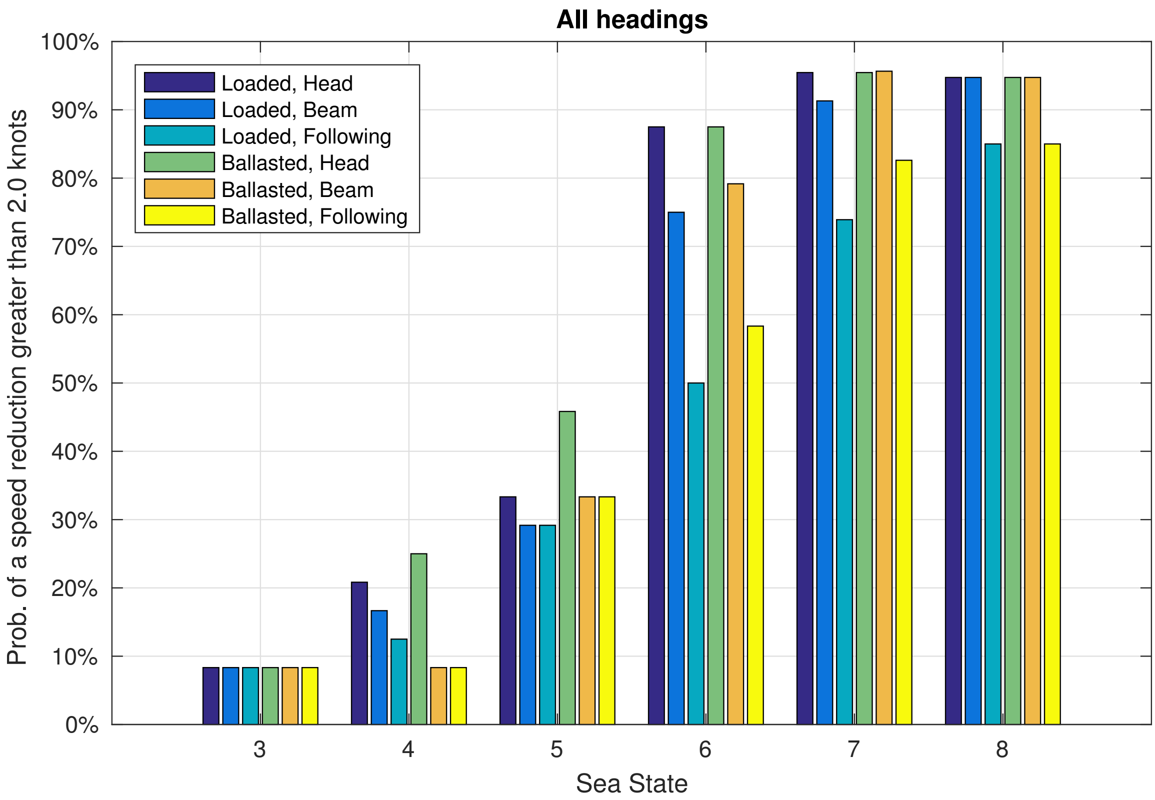
The results vary substantially even for answers from the same ship. As an example, one officer indicated as a safe speed, 6 knots speed reduction for $H_{1/3}$ = 9 meters and higher. Another officer on the same ship indicated a 10 knots speed reduction for $H_{1/3}$ = 4 meters and higher(!) (No answer were given for $H_{1/3}$ larger than 6 meters).

4.1.1 Probability of a speed reduction compared to sea state

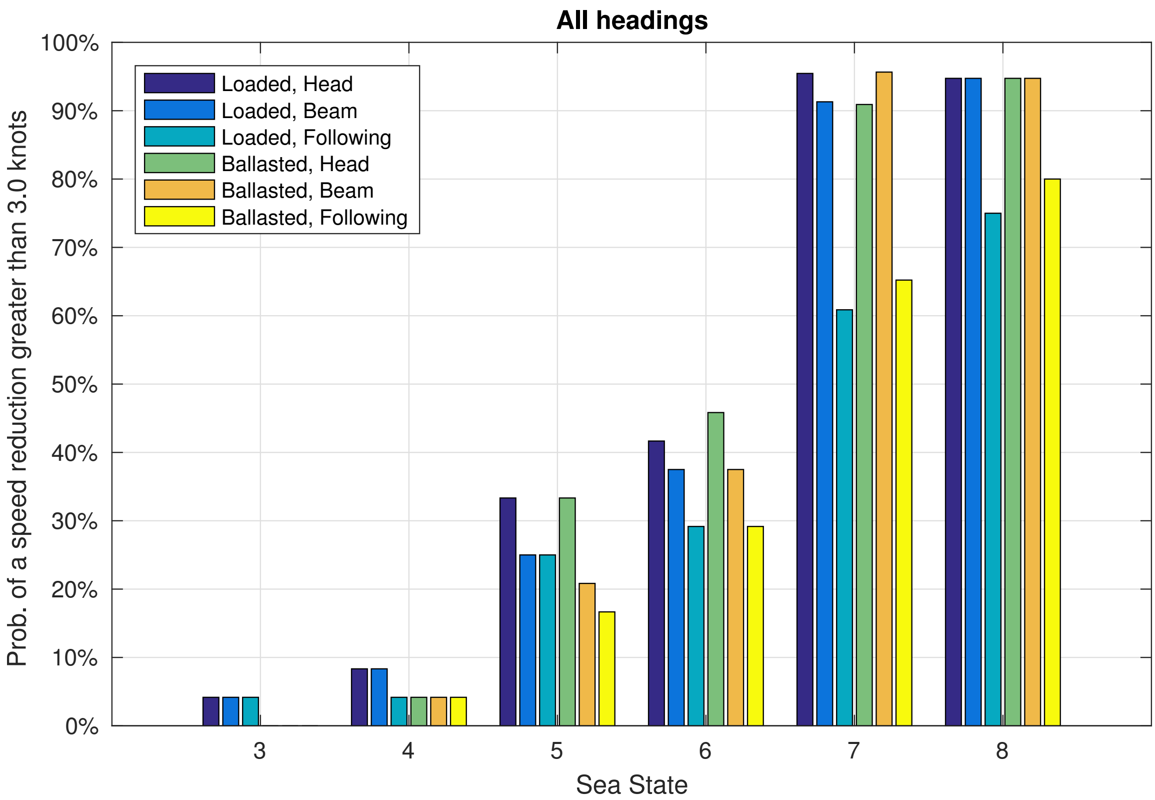
As a speed loss in the magnitude of 2-3 knots can result in substantial financial losses, Figures 9 and 10 show results for these speed losses. Answers to question 1 in the questionnaire have been used in making theses plots, which is important because effects from an involuntary speed loss might be present. Even so, probability of a speed reduction of 2 and 3 knots, depending on heading, load condition and sea state is presented in Figure 9. Identical plots for speed loss greater than 4, 5 and 6 knots are given in Appendix A.

Figure 9 shows a significant chance of speed loss greater than 2 knots in sea state 6. For a ship in ballasted condition, the probability is slightly higher in sea state 5, and equal in sea state 6. Note that in Figure 9 this particular officer did not indicate any speed reduction due to safety, which causes the results to be lower than 100% for sea state 7 and 8. Due to fewer answers on sea state 8 (5 answers were not filled out), the answer of no speed reduction due to safety has had a larger influence in sea state 8. This is the reason for a reduced probability of speed loss in some headings going from sea state 7 to sea state 8.

Figure 10a gives average speed reductions compared to sea state. A similar plot showing probability of course change compared to sea state are given in Figure 10b. Figure 10b shows that a course change is most likely for beam heading for both load conditions and in all sea

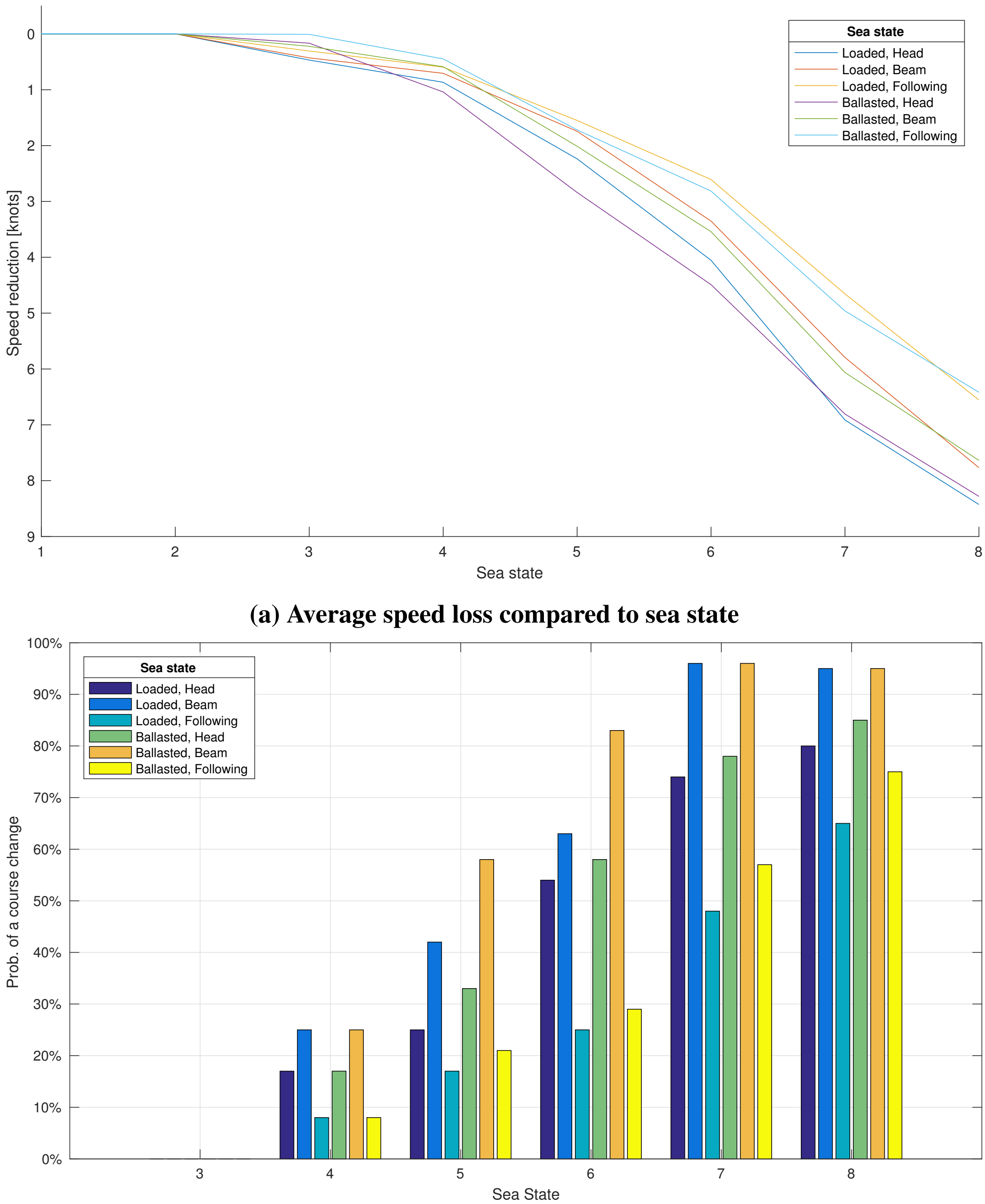


(a) Probability of a speed loss greater than 2 knots



(b) Probability of a speed loss greater than 3 knots

Figure 9: Sea state and speed loss



(a) Average speed loss compared to sea state

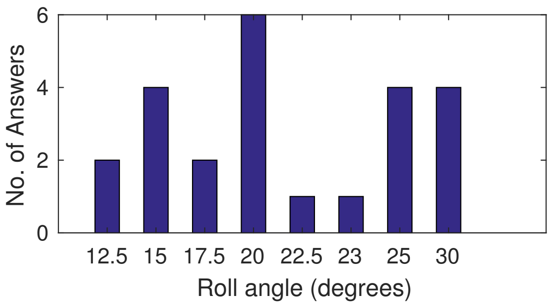
(b) Probability of a course change compared to sea state

Figure 10: Sea state results

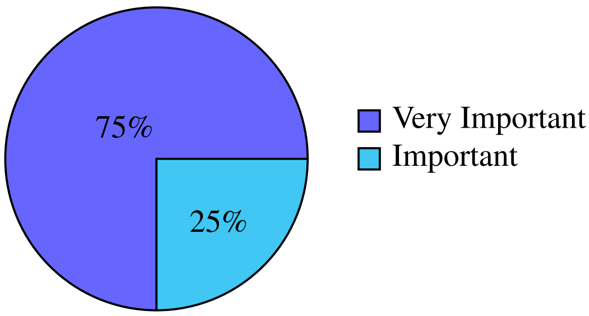
states. The heading with least probability of a course change is following seas for both load conditions and all sea states.

4.1.2 Excessive rolling

The results from excessive rolling are presented in Figure 11. Figure 11a indicates which roll angle is needed before a course change or speed reduction is made. Figure 11b indicates the relative importance of excessive rolling in regards to a voluntary speed loss.



(a) Roll angle commencing action



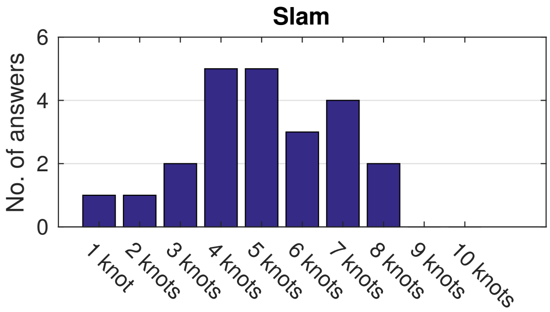
(b) Importance of roll angle

Figure 11: Roll results

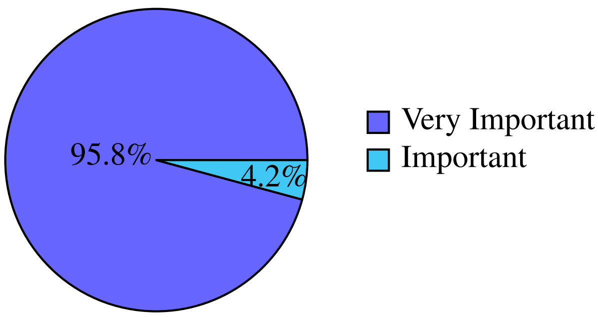
The average roll angle needed for an action was around 21 degrees with a standard deviation of 5.5 degrees. It was pointed out that the safety of the crew, the cargo and the ship must always be implemented.

4.1.3 Slamming

Slamming and bow emergence results are given in Figure 12. Figure 12b shows that slamming was regarded as the most important response inducing a voluntary speed loss.



(a) Speed reduction when slamming occurs



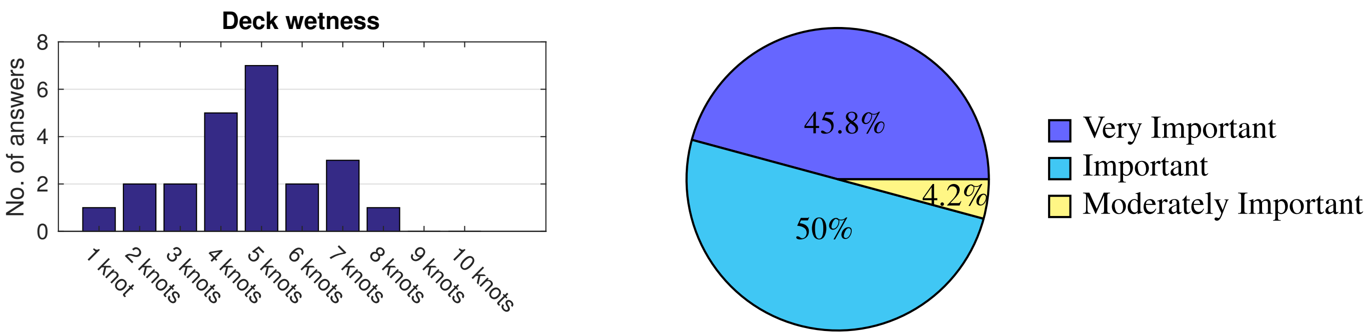
(b) Importance of slamming

Figure 12: Slamming results

When slamming occurs, a slight adjustment of course to bow quarters was pointed out as preferable before a speed reduction was made. If a course change alone did not reduce the occurrence of slamming, a speed reduction would be made until slamming no longer was present (to avoid whipping and springing). One officer indicated that a hove to situation might be needed to avoid slamming.

4.1.4 Deck wetness

Results for deck wetness are given in Figure 13.



(a) Speed reduction when deck wetness occurs

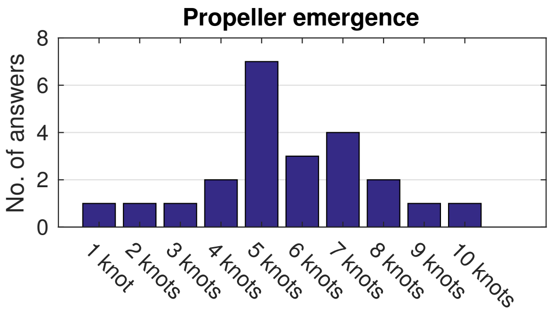
(b) Importance of deck wetness

Figure 13: Deck wetness results

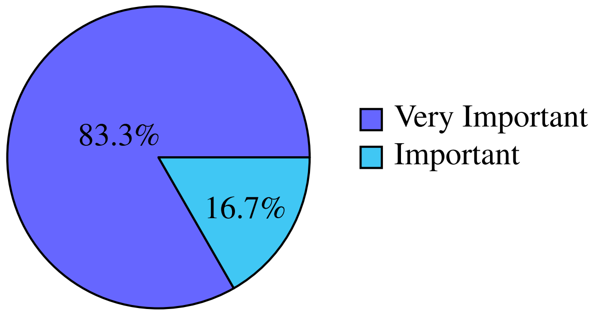
In the answers received, it was pointed out that a course change would be made in order to avoid structural damage whereas a speed reduction can be undertaken to lower the probability of occurrence. If possible, a course change is made before speed reduction.

4.1.5 Propeller racing

Propeller racing results are given in Figure 14.



(a) Speed reduction when propeller racing occurs



(b) Importance of propeller racing

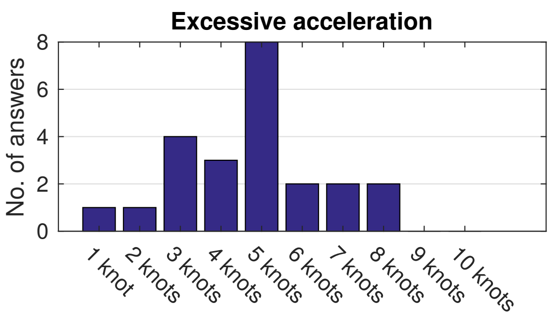
Figure 14: Propeller racing results

Although not being regarded as the most important factor for speed reduction (second to slamming), propeller racing on average imposes the largest speed reduction (see Figure 18).

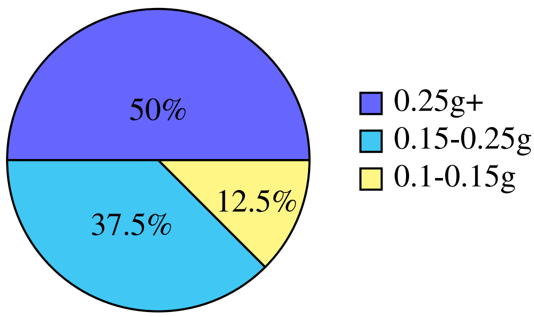
From comments, and as can be seen in Figure 14b, propeller racing is a serious problem where several answers indicate a large speed reduction and even reduction to minimum RPM (ensuring sufficient speed for steering). However, the complete opposite was also indicated: a reduction of 1 knot with further reduction if needed.

4.1.6 Excessive accelerations

Lateral accelerations were investigated in the questionnaire. In this question, the scale from Table 4 are used to relate physical phenomena to acceleration limits. Results are given in Figure 15.



(a) Speed reduction when excessive accelerations are present



(b) Acceleration needed before speed reduction occur

Figure 15: Excessive accelerations results

From Figure 15b, it can be seen that most captains tolerate relative high accelerations.

The question about acceleration highlighted the necessity of navigation preparation, where a longer route was preferred. It was also highlighted that a speed reduction in beaming seas sometimes generates higher accelerations, and that slimming, deck wetness and propeller racing usually occurs before excessive accelerations.

4.1.7 Human comfort

Human comfort had the largest spread in opinion of importance (see Figure 16), with ranges varying from slightly to very important.

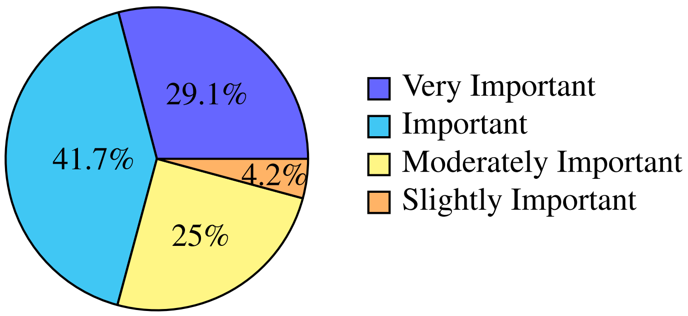


Figure 16: Human comfort needed for a course or speed change

Human comfort becomes increasingly important for an extended period, especially during rest hours (if large rolling amplitudes or especially uncomfortable motions are present). A course change is more likely to be made, so that the vessel is in a better headway. It was pointed out that slamming, deck wetness and propeller racing are events that usually call for speed reduction before human comfort.

Individual tolerance is a factor that was pointed out and depends on physically condition and adaptation. Notes highlighted that MSI and MII should be considered part of a sailor's job with consequent adaptation over time. However, the ship's crew needs to be able to deal with the weather. MSI poses a considerable hazard to the ship's safety because of reduced manpower in a potential emergency situation. A crew suffering from MSI is also more vulnerable to accidents and injuries, as well as being less effective at performing daily tasks. In regards to MII, the questionnaire indicated that it is better to let the crew rest during heavy seas, if possible, until the seas subsides.

One officer mentions that the most important factor in regards to human comfort is that everything on board feels safe and comfortable (regardless of the actual situation) when sailing.

4.1.8 General about the questionnaire

A course change seemed to be the result of wanting to adjust to a favorable heading relative to sea direction to minimize objectionable motions. However, it was pointed out that a sudden course alteration can sometimes cause speed loss and not get the desired effect. Therefore, it was pointed out that small course changes are generally preferred. If motions do not improve, a speed reduction would be made. Answers indicate that reductions are not made for single waves, but should at least consist of a minimum of 5 consecutive incoming waves and will depend on frequency, length of wave and wave height.

It was pointed out that the master should alter the course in advance if heavy seas are expected, by which heavy seas and potential storms are avoided altogether. If caught in a storm, the master should try to avoid or at least minimize objectionable motions. This will naturally make the actual speed loss vary in every situation.

The extent of a reduced speed lasts until the sea state is calmer. The operability criteria found from the questionnaire is given in Figure 17, and relates how likely an objectionable motion needs to be before an action of speed lowering is predicted to be made. The probability is given as a percentage of exceeding the operability criteria. The probability can be converted to number of incidences per 100 incoming waves by multiplying with a factor of 100. This probability has been derived by assuming that the mean zero-crossing wave period is 10 seconds (Prpić-Oršić n.d.). This is not necessarily true, but given the wide range, the difference between using mean zero-crossing wave period equal 10 seconds and actual mean zero-crossing wave period will be negligible.

A summation of the mean speed reduction for a given event is given in Figure 18. These numbers are based on the average sum from Figures 12a, 13a, 14a and 15a and should be used with care. It should be clear that the way a speed reduction is made differs significantly depending on preferences. Some officers indicated a relative small initial speed reduction awaiting ship responses with further reduction if needed. Other officers indicated a large and immediate speed reduction to be on the safe side regarding safety.

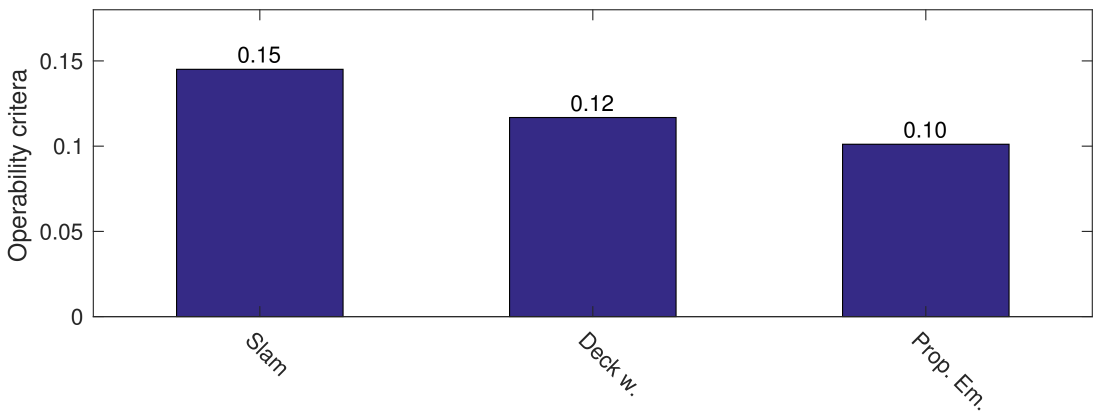


Figure 17: Operability criteria for slam, deck wetness and propeller racing

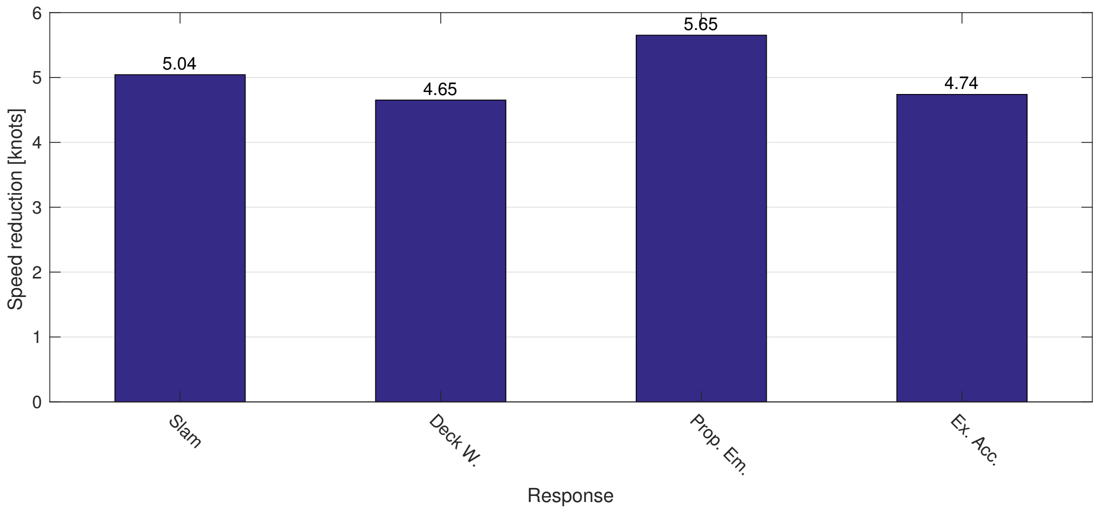


Figure 18: Average speed reduction for some objectionable motions

4.2 Ship service data

Through cooperation with SFI SmartMaritime, ship service data has been collected on 24 general cargo vessels operating in international waters across the Atlantic, Indian and North Pacific Ocean. The ship service data has been analyzed in combination with sea state, location, speed, engine revolution and other relevant information. Plausible incidences of voluntary speed reduction can be detected from the ship service data, but relating cause and action is at best educated guesswork. There is no information of ship responses from service data, making it impossible to relate reduced speed to factors described in this thesis.

The ship service data was used to indicate at what sea state plausible incidences of voluntary speed loss are made, and how often a voluntary speed loss might occur. The sea state yielding likely speed reductions for most of the cargo-vessels was around Beaufort number 8, corresponding to $H_{1/3}$ of 5.5 meters. Table 10 gives a comparison of the different scales (Office 2017), which can be seen in Figure 19a (Note that the Beaufort number is used in giving the sea state in this figure).

Table 10: Conversion from of Beaufort number, sea state and corresponding wave height

Beaufort Number	Sea State	Probable wave height	Probable maximum wave height
6	5	3	4
7	5-6	4	5.5
8	6-7	5.5	7.5
9	7	7	10
10	8	9	12.5
11	8	11.5	16

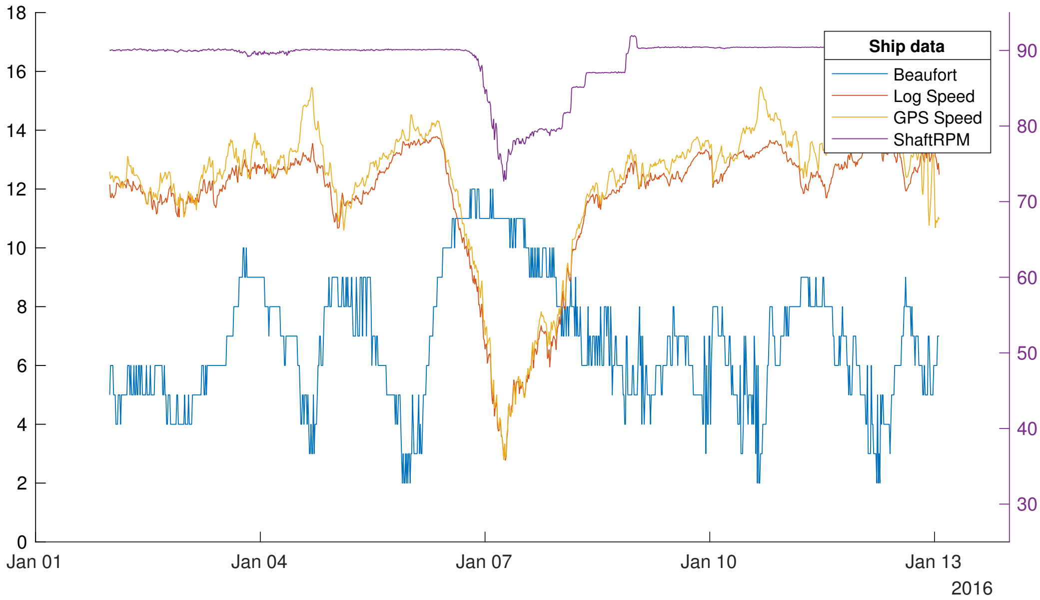
The occurrence of voluntary speed loss seems to be small. There are recognizable incidences from the service data, where one of the most prominent one is presented in Figure 19a. Other shorter probable incidences can be detected, but they appear to be minor in extent, and the vessels are able to continue with somewhat similar RPM making voluntary speed reduction difficult to detect and differentiate.

Figure 20 shows the distribution of the ship service data for Beaufort numbers, where the percent represent the probability of given Beaufort number and higher (i.e. 11.8% of the data are from Beaufort 6 and higher).

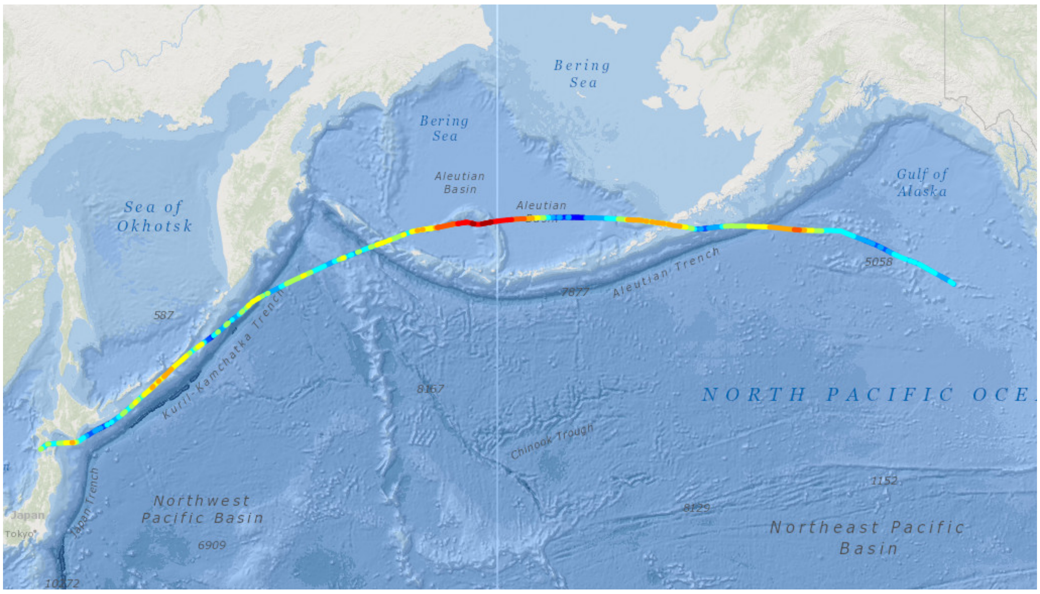
The probability of a speed loss for each Beaufort number for different speed loss criteria was calculated and plotted (only data from sea passage was included). The results are given in Figure 22. The plots are made in a similar way as Figure 9, but the results are for all headings combined. The route of sailing is presented in Figure 21.

Figure 22 shows that the probability of a speed loss greater than 2 knots in any sea state is high (it occurs 70% of the time spent in Beaufort 1). When the limit becomes greater the results look similar to those found in the questionnaire. Although this is clear for the ship presented here, an identical plot for another ship is given in Appendix B, where the extent of a voluntary speed loss is not as easily detected and voluntary speed reduction only occurs to a minor extent.

The last subplot in Figure 22 shows the distribution of the Beaufort numbers the ship has logged data from with the cumulative probability showed in blue. This plot is helpful in estimating the importance of how often a ship is expected to sail in different sea states.



(a) Ship service data of a general cargo ship. A possible voluntary speed loss is detected around Jan 07



(b) Route travelled in Figure 19a. Red indicates higher sea state. Sailing direction is from east to west.

Figure 19: Ship service data results

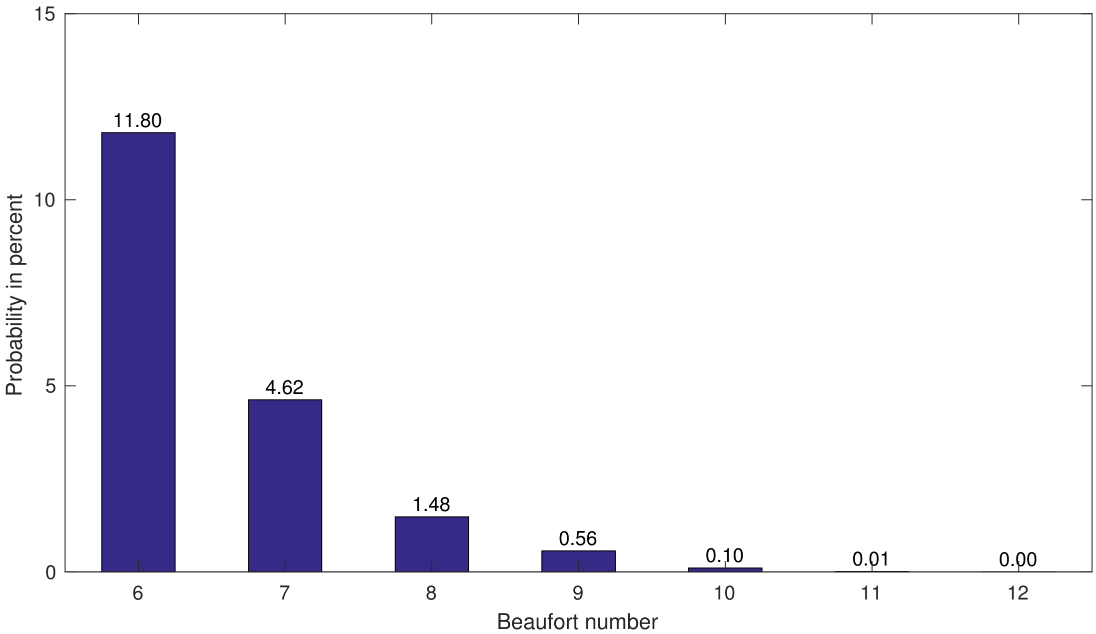


Figure 20: Distribution of Beaufort number for the service data

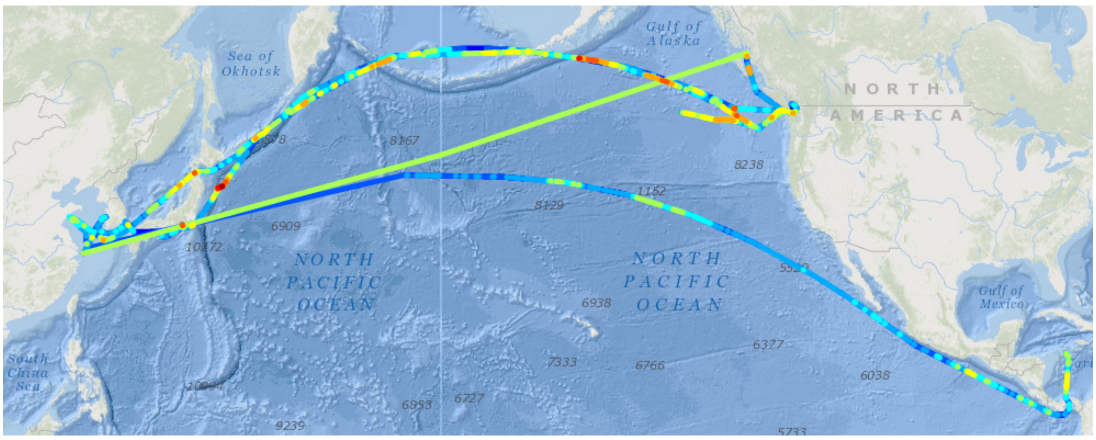


Figure 21: Sailing route for data in Figure 22. Blue to red indicate increasing sea state. Green line is a result of missing data

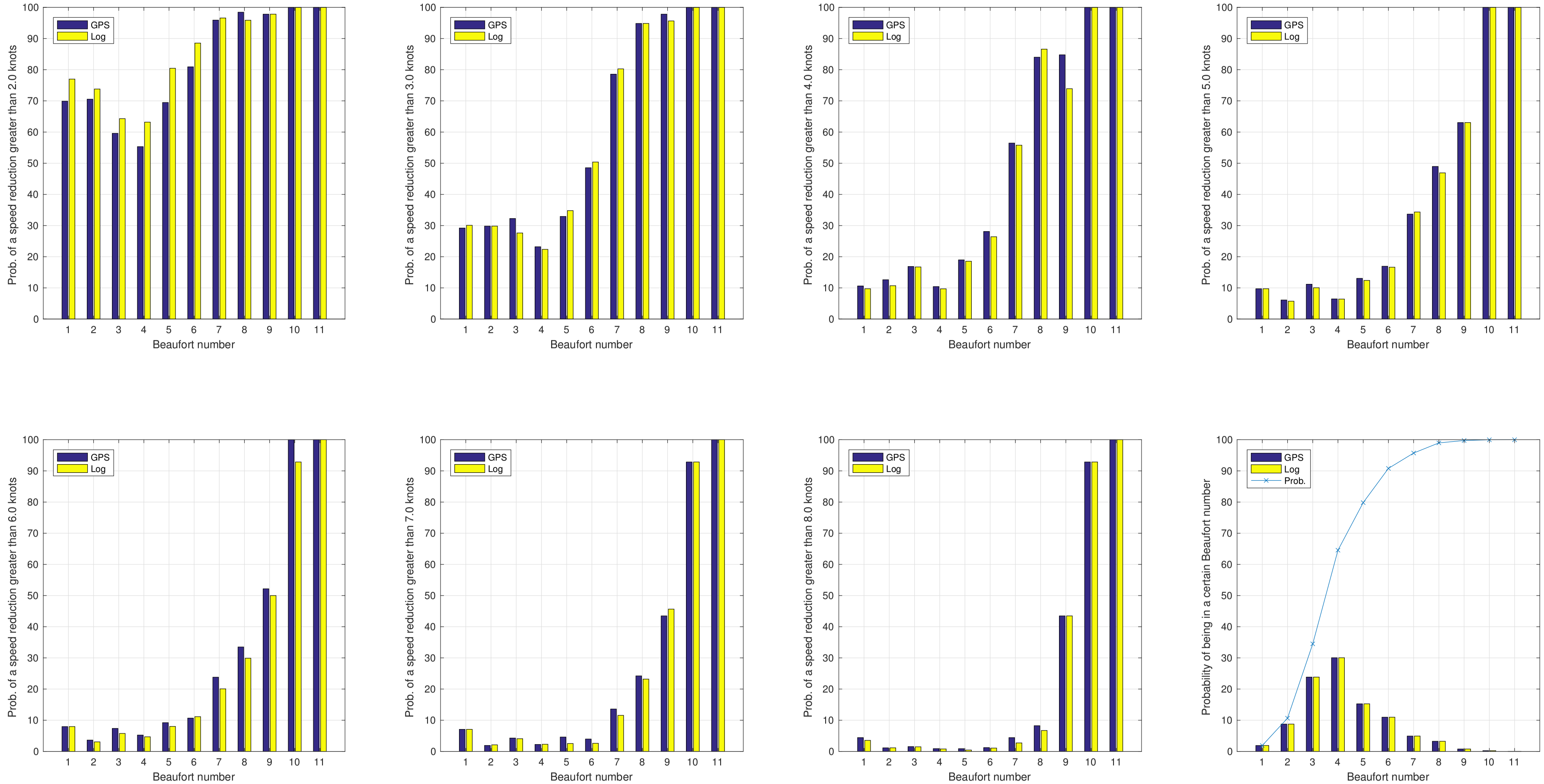


Figure 22: Probability of a speed loss greater than 2-8 knots for given Beaufort number. The last plot is a distribution plot of the different sea states

4.3 Numerical calculations

In this subsection, a short description of the method will precede the result from numerical calculations.

4.3.1 Method

The software program ShipX vessel response (VERES) version 3.1 build 172, licensed to NTNU by SINTEF Ocean was used in numerical calculation in this thesis. The principal calculation flow is presented in Figure 23, where the problem has been solved in the frequency domain.

From vessel data information, motion transfer functions in all degrees of freedom are calculated. By combining the motion transfer function with the specified wave spectrum, response spectrum (short term statistics) are calculated. Then, response spectra are combined with the seakeeping operability criteria to obtain the operability boundaries. The operability limit boundaries can be combined with a wave scatter diagram summed over the sea states (long term statistics) to obtain percentage operability. The problem has only been solved to limiting operability boundaries, so plots will only be shown from the operability criteria.

Operability criteria used in numerical calculations are given in Table 11. Ship specification is given in Table 12. The ship used in the numerical calculation is a general cargo ship with similar dimensions as the ones from the questionnaire and service data. The location of operability criteria is placed at location found reasonable from literature and the questionnaire, however because of little detail information about the ship used, it cannot be guaranteed that the specified responses have been taken exactly where the physical location is. This is particularly true for the bridge and the propeller.

Table 11: Operability criteria used in numerical calculation

Operability criteria	Location	Limit
Vertical acceleration	At FP	0.15g
Water on deck	At deck in front of bow	7%
MSI ISO	Bridge	20% at 2 hours
MSI McCauley	Bridge	20% at 2 hours
MII	Bridge	2 per/minute
Bottom Slamming	FP at bottom	5%
Propeller racing	Top part of propeller	10%
Roll angle	Bridge	6°

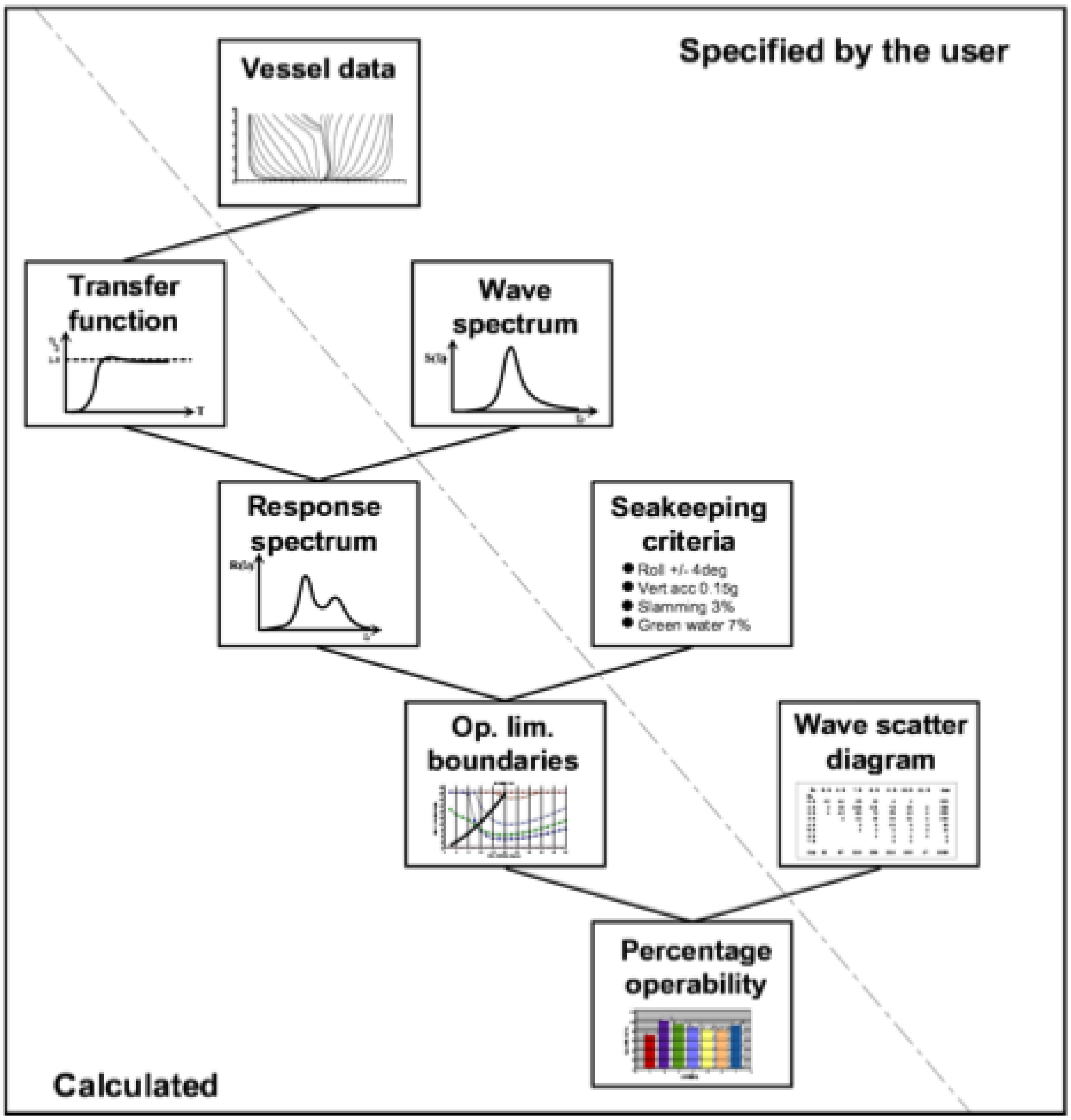


Figure 23: Principal workflow in ShipX Veres (Fathi 2017)

Table 12: Ship specification for the ship used in numerical calculations

Length	Beam	Draft	Depth	C_B	Speed
209m	32m	12m	19m	0.796	16 [knt]

4.3.2 Remarks on operability criteria

The limit for vertical acceleration was taken from literature. Since 0.2g are intolerable for longer periods, a value of 0.15g was chosen (Mackay 1978). Vertical acceleration in regards to human performance is included in both MSI and MII. Deck wetness were taken at the bow, with a higher limit than literature, but significantly lower than that found from the questionnaire. Slamming criteria is set to 5%, slightly higher than literature, but only one third of that found from the questionnaire. For propeller racing, the limit found in the questionnaire was used. For roll, the angle from literature was taken.

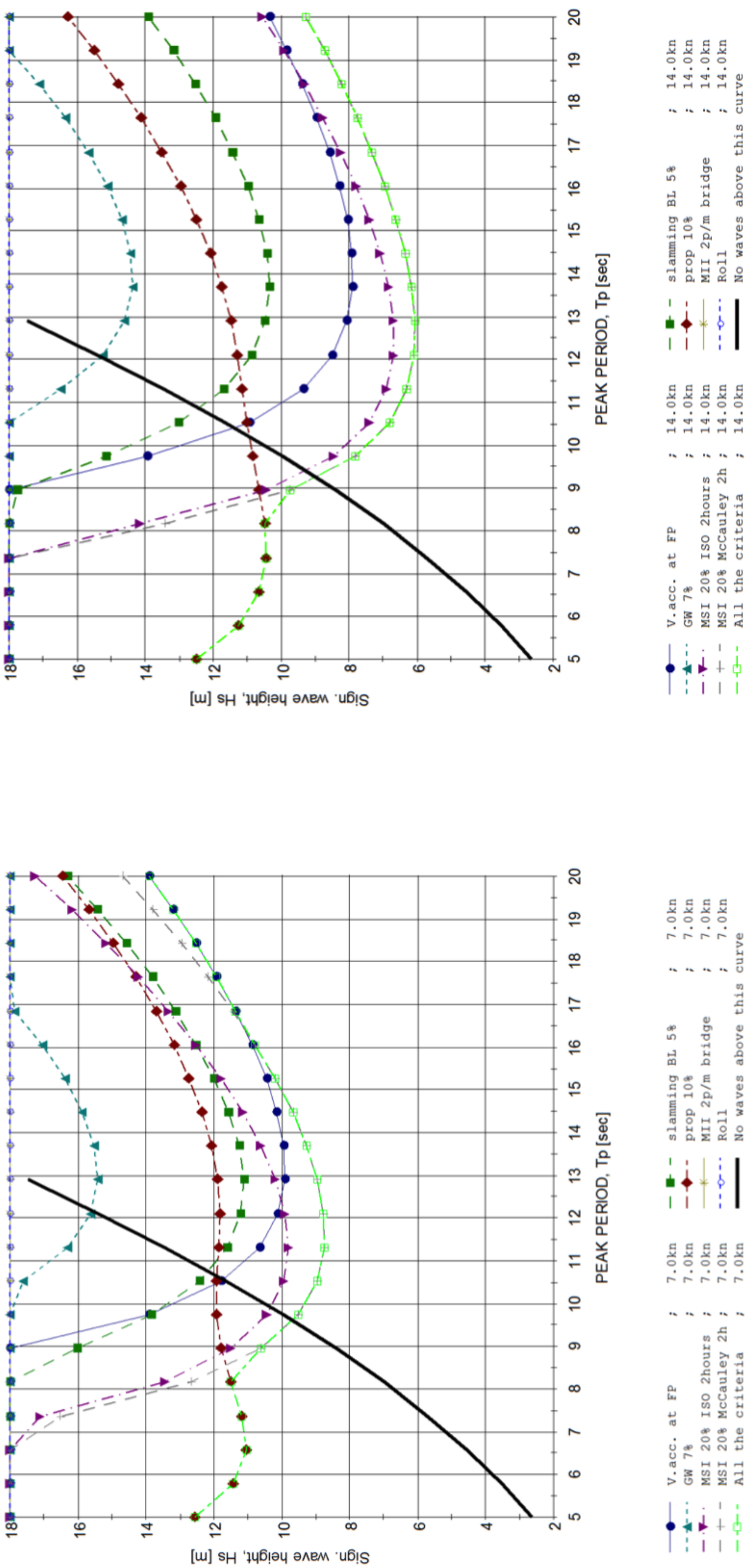
4.3.3 Results from ShipX

The results from the numerical calculations are given in Figures 24, 25 and 26. Results are given for head, beam and following seas to possibly verify limits from the questionnaire. The results are plotted for a speed of 14 knots because a 2 knot speed reduction was found to be prominent in almost every sea state, especially for the higher ones which are of interest in this thesis. A plot of 7 knots is included to see if there are changes in limiting operability criteria for a significant speed reduction. The black curve in the plots indicates the limit for when breaking waves occur, and no waves will be found in the area to the left of that curve. This has to do with steepness and energy within the wave (Fathi 2017).

Figure 24 shows that for a speed of 14 knots in head seas, the limiting operability criteria is MSI which occurs for a wave height of 6m (corresponding to sea state 6-7). The next response limiting the performance are vertical accelerations at FP, then slamming and after that propeller racing. For a speed of 7 knots, the limiting operability criteria are MSI for wave periods shorter than 16 seconds and vertical accelerations at FP for wave periods longer than 16 seconds. The lowest limiting wave height at reduced speed is 8.5m with a wave period of 11.5 seconds.

Figure 25 shows that for a speed of 14 knots in beam seas, the limiting operability criteria is MSI which occurs at a wave height slightly higher than 6m with a wave period of 9 seconds. Other limiting operability criteria are not present until wave heights begin to near to 14m, such as vertical acceleration at FP. For a ship-speed of 7 knots, MSI is still the limiting operability criteria, which occurs at close to identical conditions. Limiting vertical acceleration occurs slightly earlier, at wave heights around 11-12 meters.

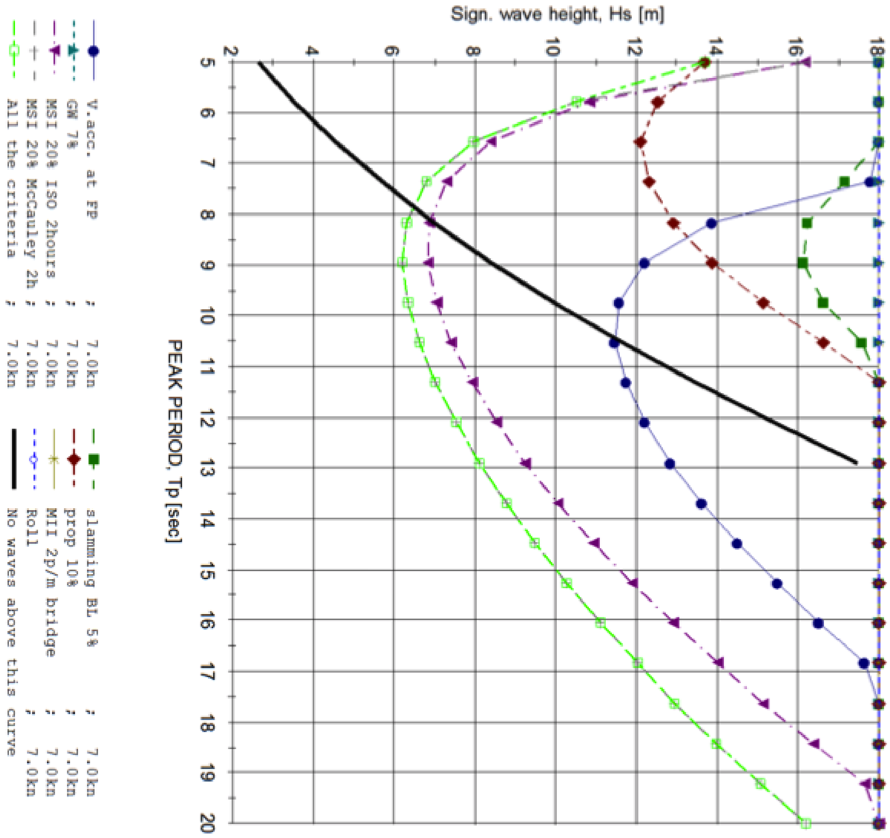
Figure 26 shows that for a speed of 14 knots in following sea, the limiting operability criteria is propeller racing at a wave height around 10 meters and a wave period around 11 seconds. There are no other limiting operability criteria within reasonable wave heights. For a ship-speed of 7 knots in following sea, propeller racing is still the limiting operability criteria, but with a smaller wave height; 9 meters with wave period around 11 seconds.



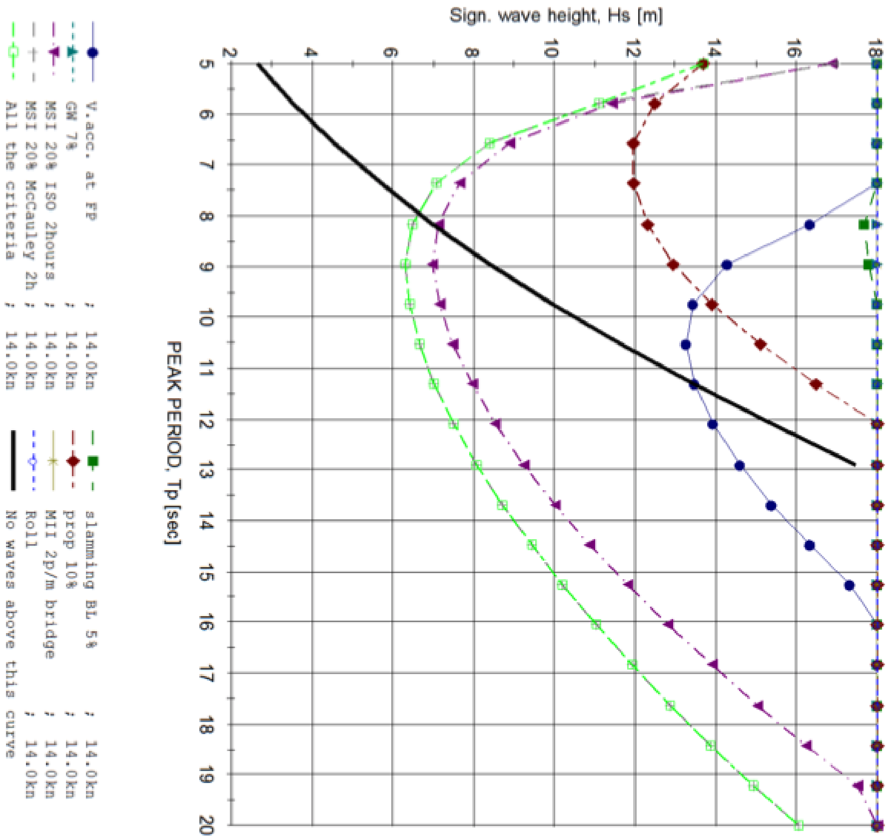
(a) Ship-speed of 7 knots

(b) Ship-speed of 14 knots

Figure 24: Numerical results in head seas

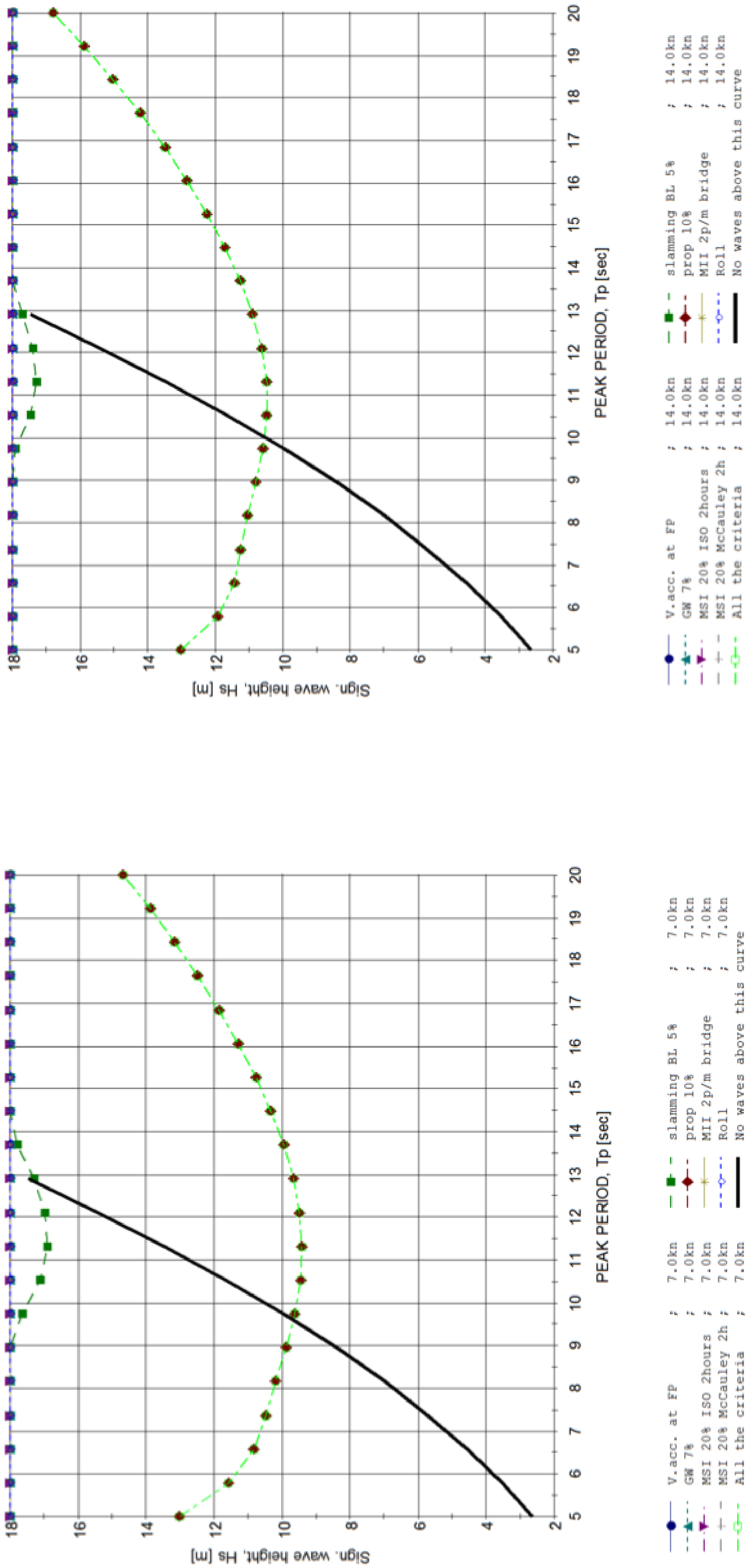


(a) Ship-speed of 7 knots



(b) Ship-speed of 14 knots

Figure 25: Numerical results in beaming seas



(a) Ship-speed of 7 knots

(b) Ship-speed of 14 knots

Figure 26: Numerical results in following seas

5 Discussion

5.1 Highest safe speed

5.1.1 Significant wave height

The results from the questionnaire, although from a relatively small group show some interesting trends. From Figure 9 one can see that a voluntary speed loss is plausible for $H_{1/3}$ around 5.5 meters in head and beam seas, and is certainly likely for $H_{1/3}$ = 7 meters. The heading is however important as a voluntary speed loss is most likely to occur in head and beam seas, while in following seas voluntary speed loss occurs at higher $H_{1/3}$. The loading condition also affects voluntary speed loss, where a loaded ship will tolerate slightly heavier seas than that in a ballasted condition.

The questionnaire highlighted that objectionable motions would on average induce a speed loss around 5 knots. It is important to note that the answers vary substantially between 1-10 knots as can be seen in Figures 12-15. It can be seen from Figure 10 (based on answers received from the questionnaire) that a speed loss of 5 knots is predicted for $H_{1/3}$ = 5.5m, depending on heading. Figure 28 in Appendix A shows the probability of a speed loss greater than 5 knots compared to sea state. From this figure a voluntary speed loss occurs later, for $H_{1/3}$ = 10 meters, depending on heading.

From ship service data, it seems that a voluntary speed loss would occur for $H_{1/3}$ around 5.5 meters, but individual differences are certainly present. Some service data suggests a voluntary speed loss first at $H_{1/3}$ as high as 10 meters, but $H_{1/3}$ as low as 4 meters was also found. A pertinent detail is that ship heading is not recorded in the service data, which from the questionnaire can be seen is an important factor for inception of voluntary speed loss. The data from the questionnaire is ideally free from involuntary speed losses, whereas ship service data most definitively contains involuntary speed losses. This helps explain why there is a higher speed loss from service data than from the questionnaire.

The likelihood of a course change is given in Figure 10 and shows that a speed change is most likely to occur for beam seas in all $H_{1/3}$. With increasing $H_{1/3}$, following seas are the heading with the least amount of speed changes, but for increasing $H_{1/3}$, even following seas will experience change of heading. For the ship service data, a research in change of heading was not performed because of difficulty in determining when a course change was made due to objectionable motions.

The likelihood of a given $H_{1/3}$, or more precisely Beaufort number is given in Figure 20.

This figure shows that the amount of data containing Beaufort 7 ($H_{1/3}$ = 4 meters) and higher is only 4.6%, and for Beaufort 8 ($H_{1/3}$ = 5.5 meters) and higher it is as little as 1.5%. The time between each data-entry is consistent so that the distribution also gives the amount of time spent in Beaufort numbers. Thus, only 4.6% of the time is spent in Beaufort 7 (and higher), and as little as 1.4% of the time are spent in Beaufort 8 (and higher). The last plot in Figure 22 shows the distribution for Beaufort numbers and the blue line is the accumulated probability for that particular ship. It can be seen that for that ship, approximately 10% of the time is spent in Beaufort 7 and higher.

In following seas, only propeller racing seemed to be of importance from the numerical results. Following sea is often the preferred ship-wave heading when wanting to reduce the objectionable motions. However, a lowering of the speed seemed to give a more responsive ship, which can explain why propeller racing on average was found to give the highest speed reduction from the questionnaire.

5.1.2 Influence of ship length

The influence of ship length compared to $H_{1/3}$ suggests that a voluntary speed loss occurs earlier for the vessels investigated in this thesis than for ULCS. For ULCS the limiting $H_{1/3}$ were 6-8 meters. Thus, the data indicates a higher tolerance of $H_{1/3}$ before a voluntary speed loss occurs. This is reasonable given that ULCS by their dimensions have large freeboard and deep draft making the probability of slamming and water on deck less likely because a higher significant wave height is needed to induce these phenomena.

Another reason given by Guedes Soares 1990 for the higher tolerance is that officers of larger vessels feel safer and thus tolerate more violent motions before a speed reduction occurs. Yet, this contrasts with literature such as NORDFORSK 1987, where tolerance criteria for vertical accelerations and slam go down for increasing ship length (see Figures 4 and 5). Thus, the human influence is certainly present and makes it difficult to set operability criteria.

There are large differences in answers received. Although differences were expected, question 1 highlighted the subjectivity in particular. Some officers regarded little to no speed reductions due to safety for increasing wave height. At the same time, a total of 5 answers were not filled out for wave heights larger than 9 meters (one of which was not filled out for wave heights larger than 6 meters).

In the ship service data the sampling rate was 15 minutes. This is a frequent sampling considering the time over several months where the data has been collected. The amount of data is overwhelmingly large. A 15-minute sampling rate when regarding voluntary speed loss is on the other hand not always high enough. This becomes particularly important for smaller vessels (L < 180m) where throttling can occur for single waves with particularly large amplitude (Winther 2017). It is therefore not unlikely that some incidences of voluntary speed loss are not captured. Objectionable motions discussed in this thesis are short-time incidences needing a higher sampling rate to be captured if speed reductions are done for singular waves. However, it is argued that the scope and influence of throttling is irrelevant in terms of transit time, but may have its purpose in regards to safety. From the questionnaire however, no answers indicated occurrences of throttling. As it was impossible to differentiate reasons for speed loss, the service data could not be used to set operability criteria.

5.2 Excessive rolling

The questionnaire found a considerably higher tolerance for rolling than that from literature. This might be a result of excluding human comfort and MSI in judgment of maximum rolling angle before a course or speed change would occur and that the limit given in the questionnaire is mostly accounting for cargo and ship safety. This will help explain the large discrepancy between the questionnaire and literature. From Table 4 it can be noted that rolling is given in terms of personnel effectiveness and not cargo or ship safety.

From numerical analysis, this certainly seems to be the case since the operability criteria from roll is not a limiting criterion in any heading or speed. In fact, it is not even close to limiting the performance. This might be a result of wrong input in the numerical calculations, however the general trend from the questionnaire suggests very large roll angles before rolling limits the performance of the ship.

Although the questionnaire gave a high rolling amplitude, it was pointed out that personnel effectiveness is always important in case of an unexpected emergency situation. For that reason, it is argued that the operability criteria of roll angle found through the questionnaire is too high and the operability criteria from literature should be used.

5.3 Slamming

In regards of occurrence, slamming avoidance seems to aim at hindering not just structural damage but also whipping and springing. The questionnaire gave an operability criteria almost 5 times as high as that from literature, which is quite interesting given that slamming was regarded as the most important factor for a voluntary speed loss. Exactly why is hard to say, but there are certainly weaknesses with the question asked as officers are to give their own opinion of tolerance and occurrence. The range of the operability criteria varies from 0.006 - 0.5(!), i.e. extreme individual differences. One possible explanation can be the difficulty in judging a tolerance as well as individual perception of the situation, preference and willingness to expose the ship to dangerous situation. Another possible explanation can simply be the fact that humans are remarkably poor at judging statistical occurrence of events (Kahneman 2011).

As slamming was regarded as the most important factor for a voluntary speed reduction and considering that single slam events can excite the structure, a strict limit is preferred to avoid springing and whipping. The operability criteria from literature have therefore been taken as a reasonable operability criterion, whereas the one found through the questionnaire strongly underestimate the tolerance and importance of slamming.

5.4 Green water on deck

Water on deck also showed big differences in operability criteria found through the questionnaire and that from literature. An operability criteria of 0.12 was from the questionnaire, which is almost twice as high as literature suggests. This is most likely from the same reasons as commented under slamming. The tolerances vary from 0.011-0.5.

The questionnaire highlighted that a course change is done before a speed reduction if possible. This can help explain why the importance of deck wetness has such spread in answers in both importance and amount of speed reduction.

5.5 Propeller racing

In the literature research and from research done by Prpić-Oršić n.d., a reasonable operability criteria were given at approximately 0.05 (5 incidences/100 incoming wave). This is half of that found from individual studies. The belief is that this is down to the same reasons as for slamming and green water on deck. The tolerance varies from 0.006-0.5.

Propeller racing was in the questionnaire found to give the largest voluntary speed loss and judged as the second most important factor for a voluntary speed loss. Numerical calculations showed that in following seas, it is the singular limiting operability criteria. Numerical results also showed that a speed reduction will result in lowering the significant wave height needed to induce air ventilation at the propeller. This implies that that a speed reduction will not decrease the likelihood of propeller racing but increase it. In addition, setting a stricter limit in the numerical analysis will result to an additional lowering of tolerable wave height. This is in contrast to the questionnaire, so a possible error might be present. It was however prioritized to spend more time on the questionnaire and service data than finding possible sources of errors.

From the questionnaire, speed reductions up to 8 knots were found for incidences of propeller racing. Propeller racing was also found to be the second most important factor. A strict limit for propeller racing will therefore be used in numerical calculations.

5.6 Vertical accelerations

Vertical accelerations were not addressed in the questionnaire, as there was a wealth of data on this limit from literature. As can be seen in Figures 24 and 25 vertical accelerations are the limiting operability criteria if MSI is ignored.

In the questionnaire, vertical accelerations were not addressed. The operability criterion from literature of 0.15g was therefore used in numerical calculations. In head seas, vertical accelerations are the limiting operability criteria if MSI is ignored. This is not surprising since MSI is highly dependent on vertical accelerations. A lowering of the operability limit of vertical accelerations will result in a lower significant wave height needed for the criteria to be exceeded.

From literature, acceleration at FP for displacement vessels is often given in terms of unsafe conditions for the ship hull before they pose a hazard to the personnel. This agrees well with comments from the questionnaire, namely that human comfort is not important when looking at general cargo vessels where ship personnel have had time to adapt to MSI and are used to being at sea.

5.7 Lateral accelerations

Through the questionnaire, a relative high tolerance for lateral accelerations was found. One explanation, as mentioned, can be that other phenomena are often more prominent and occurs before lateral accelerations becomes large enough to safety hazard and thus induce a voluntary speed loss. The other phenomena have already lowered the ship's speed.

5.8 Human comfort

The questionnaire has certainly highlighted differences in importance and opinion for human comfort, as can be seen in Figure 16, where there were answers varying from slightly, to very important.

Although differences were expected, the wide spread in opinion can possibly be explained by preferences, perception of the situation and willingness to expose the ship and its crew to hazardous situations. It was also commented in the questionnaire that other objectionable motions often occur long before human comfort is considered, and human comfort as such is therefore not so important.

In regards to human performance, such as MSI, MII and MIF, these responses do not require a high sampling frequency because they occur over a longer time-period. There is however no collection of MSI, MII or MIF in the ship service data, and it is not possible to deduce such results from the data provided.

6 Conclusion

In this thesis, an effort has been made in explaining what a voluntary speed loss is, its implications and typical phenomena that usually results in a voluntary speed loss. Literature, ship service data, numerical calculations and an independent questionnaire have been used in acquiring the results.

It was found that a voluntary speed loss is a result of unwanted or objectionable motions and a voluntary speed reduction is enforced to reduce or eliminate these objectionable motions.

The way of setting operability criteria for vessels is traditionally done by setting an operability criteria that if exceeded will jeopardize the safety of either the ship, the cargo or the people. By setting safety as the limiting factor, a safe speed can be predicted for a given significant wave height ($H_{1/3}$).

Although this is a good method in terms of design and numerical analysis, it was shown through the questionnaire that setting operability limits from officers judgment of occurrences were not feasible. However, operability limits can be found from observing service data where ship responses are recorded, because officers actions show that the difference is significantly less when compared to service data.

The results of this thesis were found for general cargo vessels with ship size length from 180-230 meters, width of 29-32 meters and depth/draft of 10-35 meters.

It was indicated from the questionnaire and ship service data that voluntary speed loss become prominent for significant wave heights of around 5.5 meters. Voluntary speed reductions varied from a few knots to over 8 knots. The amount of speed loss was found to be dependent on heading, load condition, significant wave height, ship dimensions and officers preference.

Objectionable motions found to incur an action either in the form of a course change or a speed reduction are rolling, slamming, water on deck, propeller racing and vertical accelerations with slamming being the most important one. It is believed that this is a result of slamming being coupled with whipping and springing. The speed reduction is likely to happen when a course change alone does not reduce the objectionable motions enough. The likelihood of a course change also increase for increasing wave height, and is most likely to occur for head and beam seas.

Human comfort, MSI, MII, MFI and lateral accelerations, although important were often not factors inducing a voluntary speed loss for the ships investigated. A speed reduction was usually made for other objectionable motions before the effect of human comfort became a problem.

Numerical results showed that motion sickness would be the most important operability criteria for head and beam seas, and propeller racing in following seas. It was however decided to emphasize results from questionnaire and ship service data.

All results show high subjectivity. In the questionnaire it is believed that this has to do with the difficult nature surrounded by human element, ship motions, ocean environment and the ship itself making it difficult to give statistically correct judgments. For instance, the MSI constitutes the most dominant influence on the comfort on board in numerical calculations, yet from the questionnaire it was deemed as the least important factor with a large spread of opinion. One explanation pointed out that that people on these vessels have experience from sailing and usually had time to adapt to sailing before being exposed to heavy seas. For other types of vessels, it is believed that MSI will have a greater influence in setting operability criteria.

The ship service data did not have an influence in setting the operability criteria, since no correlation could be made as to why a speed reduction was done. Instead, the data has been used to emphasize obtainable speed, inception of voluntary speed loss, amount of speed reductions and occurrence. Results are specific towards ship type as previously stated.

Through the questionnaire conducted, it was found that throttling for singular waves is only done for shorter vessels (Length around 100m), whereas longer vessels (L>180meters) need a wave amplitude of at least 5 successive waves to be high enough to onset objectionable motions before a speed reduction occurs. How the speed reduction is made varies greatly: One example being small reductions of 1 knot until objectionable motions are eliminated (or likelihood of occurrence significantly reduced). Another example is a large speed reduction from the first occurrence of an event.

The amount of time spent in sea with significant wave height greater than 5.5 meters is minimal, only constituting approximately 4.6% of the time. This is obviously very dependent on the area the ship is operating in and season of sailing. For some vessels, the amount of speed reduction can be as large as 10 knots, so even voluntary speed loss is of minimal occurrence, this thesis has showed that it is of importance when validating ship-speed in actual seaway.

More research is definitively needed in setting better operability criteria. The initial purpose of this thesis was to look at general displacement vessels with transit time as the prime parameter. As the answers from the questionnaire and ship service were mostly from general cargo vessels of similar dimensions, the results in this thesis are mostly valid for general cargo vessels with dimensions as previously stated.

Literature suggest that a feasible way of setting operability criteria is through observation of operational data of vessels. This was highlighted in the questionnaire conducted, as the judgment values for operability criteria showed extreme individual differences making it impossible to put forth reasonable operability criteria.

Full scale trials where responses are recorded will as such represent a tool which provides accurate and comprehensive information on seakeeping performance. and can be used to assess whether a degradation of performance is critical for a speed and heading the ship is following.

It has also been shown that ship safety and operability limiting values vary greatly for type of ship, and recommending limiting values has been a difficult task because operability criteria are generally highly ship type specific.

Although the most common factors have been evaluated in this thesis, it must be emphasized that operability criteria can be set for many reasons and vary with type of vessel, mission and area. Examples of missions that will require specific operability criteria includes crane vessels, helicopter landings, use of sonar in navy vessels, use of fishing equipment or danger of cargo displacements. The list is endless, and limiting operability criteria must be evaluated for each case where special operability criteria will be introduced.

Since results from the questionnaire are based on relatively few answers, one should be careful in stating solid facts. Care should be made when transferring results between ship types.

More research should be done on specific ship type, as well as obtaining an increased trend of more ship service monitoring where responses are recorded. This will make it possible to find feasible operability criteria from ship service data.

6.1 Final operability criteria

Table 13 is a summary of operability criteria found reasonable for a general cargo ship with ship size length from 180-230 meters, width of 29-32 meters and depth/draft of 10-35 meters.

Table 13: Final Operability Criteria

DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Vertical Acc. versus MSI			
Exposure: ½ hour	0.1g	10% motion sickness incidence	ISO 2631/3
1 hour	0.08g	ratio (MSI) (vomiting) among	1987 & 1982
2 hours	0.05g	infrequent travellers of the	
8 hours	0.025g	general public	
Vertical Acc.			
Heavy manual work possible	0.15g	Limit in fishing vessels	Mackay 1978

continued on next page…

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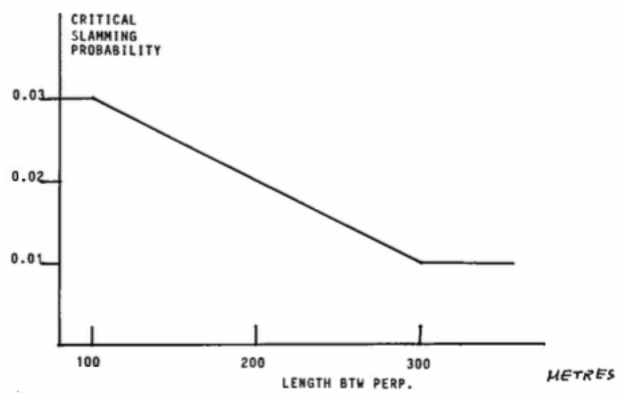
DESCRIPTION	CRITERIA (RMS)	COMMENT	REFERENCE
Lateral Acc.			
Seated passenger	0.25g (max)	Average person max. load balance when holding	Hoberock 1977
Roll			
Light manual work	6.0°	Personnel effectiveness	Comstock 1980
Slamming			
			NORDFORSK 1987
Water on deck			
Probability of occurrence	7%	i.e. 7 incidents/100 incoming wave	Fathi 2017
Propeller racing			
Probability of occurrence	5%	i.e. 5 incidents/100 incoming wave	Prpić-Oršić n.d.

end of Table

7 Further work

It should be apparent that more research should be done in the field of voluntary speed loss, and an increased trend toward installing motion monitoring instrumentation on vessels will greatly help in judging and setting feasible operability criteria for more types of vessels, dimensions and missions. This will help develop and gather useful and reliable limiting values of the various performance criteria discussed as well as operating guidance to ship masters.

This is particular true for setting operability criteria limit from judgment values from officers as the tolerance for different events vary extremely. Another wording of the question may bring a different outcome, but the judgment value is and will always be highly influenced by the officers opinion and perception of a situation and sea state. It could therefore be interesting to do simulator test where vessel, environment and human actions can be recreated, monitored and logged. Identical scenarios can be replicated, making it possible to only look at the human influence. This would potentially bring better understanding of the subjectivity involved.

Implementation of results into a calculation program should be done, so that voluntary speed loss can be added in ship-speed calculations. A potential calculation program will greatly benefit from a wider range of ship type, ship dimensions and ship operation.

More extensive numerical calculations can be done to verify results. The questionnaire and service data was emphasized in this thesis on the cost of the quality of the numerical calculations.

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Appendices

A Questionnaire

The questionnaires used are included in the end of this Appendix. The questionnaire has but minor changes from the original questionnaire made by Ph.D Student Nataljia Vitali at University of Rijeka in Croatia.

There are two examples, one for a general cargo ship and one for a passenger ship where the draft is generally constant with no significant difference between ballasted and loaded condition. The difference between the two questionnaires is page 2, and for simplification only the page with a difference is included for the passenger ship.

Continued results from question 1 in the questionnaire are given in Figures 27, 28 and 29. They show the probability of a speed loss greater than a certain value for different conditions, headings and sea states. The results may contain both voluntary and involuntary speed loss, but as have been discussed - involuntary speed loss generally incur only a small speed reduction, and not thaat of several knots as is the case with voluntary speed loss.

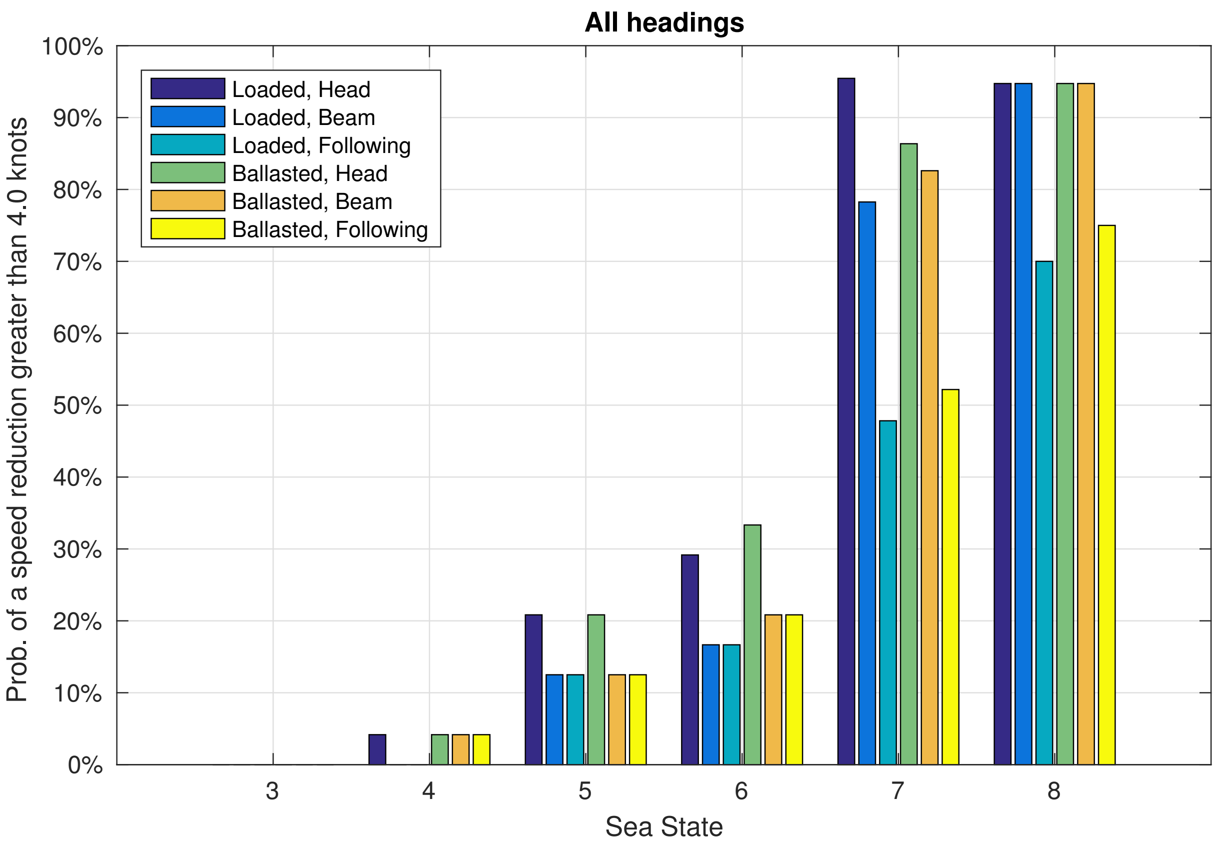


Figure 27: Probability of a speed loss greater than 4 knots

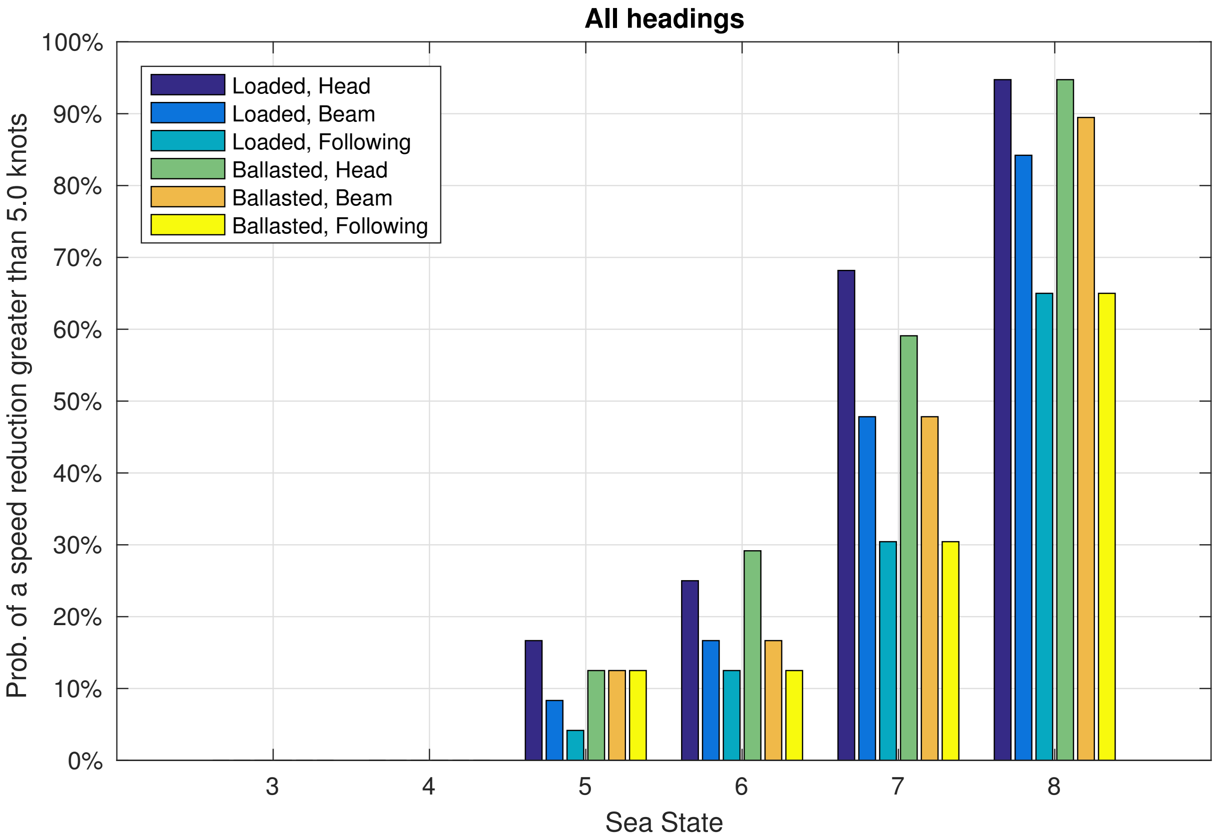


Figure 28: Probability of a speed loss greater than 5 knots

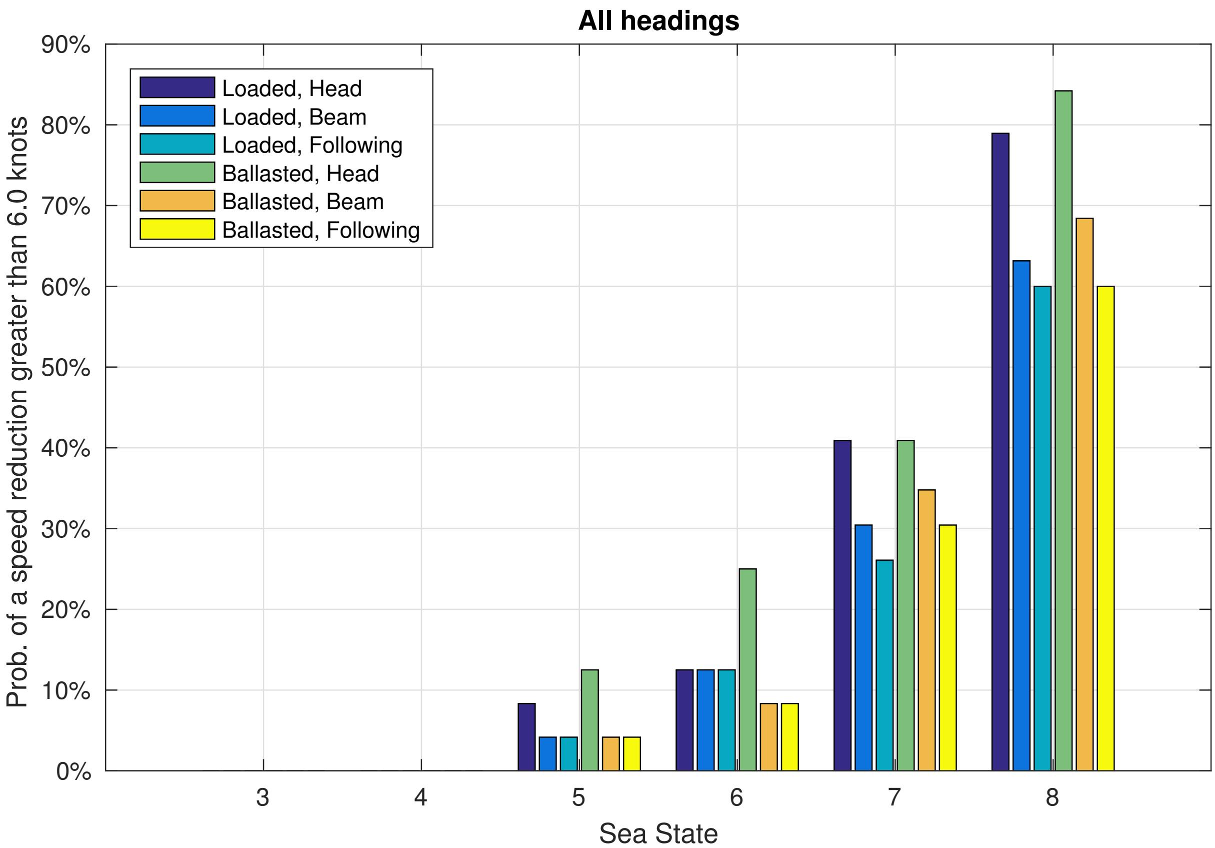


Figure 29: Probability of a speed loss greater than 6 knots

ABOUT THIS QUESTIONNAIRE:

When a ship is caught in rough weather, speed loss usually follows. This questionnaire focuses on voluntary speed loss in an effort to establish limits to some objectionable motions and the importance of them. This is done to add voluntary speed loss into speed calculations and transit time estimations.

Speed loss can be ascertained to involuntary and voluntary speed loss as follows:

Involuntary: A consequence of reduced performance. At a given engine setting, speed decrease as weather worsens, regardless if a ship captain wants it or not.

Voluntary: Throttling of the main engine to reduce objectionable motions.

Because throttling of the main engine is highly subjective, more information from the ship users are needed. This questionnaire is part of a master thesis at NTNU to determine realistic limiting values and attainable speed in seaway. The answers will be handled confidential, and the questionnaire is made anonymous. Your contribution is much appreciated and will help improve knowledge around voluntary speed loss. It helps bridge the gap in theory to practice.

Time scale that can help assess time between events

You can use the scale to help yourself assess frequency more accurately, or you can propose your own time frame that you believe is closest to the reality (e.g. 45 slams/h, 2 events per minute, single event)

Number of events in 10 minutes	*Events per x minutes*	*Numbers of events per hour*
1 in 10 min		6 per hour
2 in 10 min	1 event every 5 minutes	12 per hour
3 in 10 min	1 event every 3 minutes	18 per hour
4 in 10 min	1 event every 2,5 minutes	24 per hour
5 in 10 min	1 event every 2 minutes	30 per hour
6 in 10 min	1 event every 1-2 minutes	36 per hour
7 in 10 min		42 per hour
8 in 10 min		48 per hour
9 in 10 min		54 per hour
10 in 10 min	1 event every minute	60 per hour
11 in 10 min	More than 1 event per minute	66 per hour
12 in 10 min		72 per hour
13 in 10 min		78 per hour
14 in 10 min		84 per hour
15 in 10 min		90 per hour

WMO Sea state code

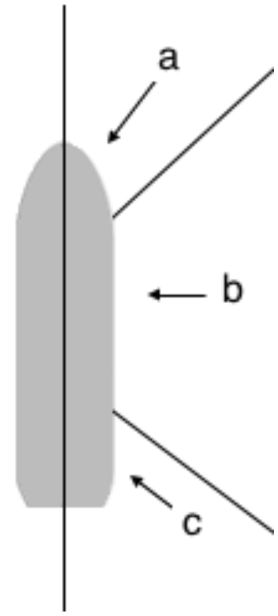
WMO Sea State Code	**Significant wave height**	**Characteristics**
0	0 metres	Calm (glassy)
1	0 to 0.1 metres	Calm (rippled)
2	0.1 to 0.5 metres	Smooth (wavelets)
3	0.5 to 1.25 metres	Slight
4	1.25 to 2.5 metres	Moderate
5	2.5 to 4 metres	Rough
6	4 to 6 metres	Very rough
7	6 to 9 metres	High
8	9 to 14 metres	Very high
9	Over 14 metres	Phenomenal

SHIP MASTERS AND OFFICERS EXPERIENCE IN ROUGH WEATHER

YEARS OF MARITIME EXPERIENCE: ______________________
TYPE OF SHIP YOU LAST SAILED ON: ______________________
SHIP DIMENSIONS (L,B,D): ______________________
SHIP SERVICE SPEED: ______________________
TYPE OF PROPULSOR:
Pod, propeller with rudder, other ________________________________
ACTIVE STABILISER SYSTEMS:
Roll fins, u-tanks, other ________________________________

Note: the questionnaire below apply to your experience on the above mentioned ship

Indicate at what highest safe speed you would sail through an area described by different sea states and wave encounter angles described for a fully loaded and a ballasted ship. Indicate if you would change course for each case.



Cases are:
a – head sea
b – beam sea
c – following sea

1.1 **Sea state 0-3** (significant wave height from **0 − 1,25m**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

1.2 **Sea state 4** (significant wave height from **1,25 − 2,5m**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

1.3 **Sea state 5** (significant wave height from **2,5 − 4m**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

1.4 **Sea state 6** (significant wave height from **4 − 6m**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

1.5 **Sea state 7** (significant wave height from **6 − 9m**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

1.6 **Sea state 8 and higher** (significant wave height from **8 − 14m and higher**)

	Fully loaded ship			Ship in ballast		
	Head	Beam	Following	Head	Beam	Following
Speed (kn)						
Course Change (YES/)						

Your notes on speed reduction (Is it reduced for a single incoming wave? Until sea state is calmer?)**:**

2. Excessive roll

Not important   Slightly important   Moderately important   Important   Very important

Please indicate maximum roll angle after which you will most likely make a decision for course change or speed reduction:

___________ deg

3. Bow emergence and bow slamming

Not important   Slightly important   Moderately important   Important   Very important

Imagine you are sailing in rough weather and bow emergence with resulting slamming occurs. Please indicate how many slams are needed before first considering to reduce speed, and how much you will reduce it with.

I will most likely lower ship speed if I experience ___________ bow slams in ___________ (minutes/hours/seconds).

I will reduce approximately ___________ knot(s).

4. Green water on deck

Not important   Slightly important   Moderately important   Important   Very important

Imagine you are sailing in rough weather and you experience green water on deck. Please indicate how many events of green water on deck are needed before you first consider to reduce the speed, and how much you will reduce it with.

I will most likely lower ship speed if I experience ___________ events in ___________(minutes/hours/seconds).

I will reduce approximately ___________ knot(s).

5. Propeller emergence

Not important   Slightly important   Moderately important   Important   Very important

Imagine you are sailing in rough weather and you experience propeller emergence. Please indicate how many events of propeller emergence you will first consider to reduce speed, and how much you will reduce it with.

I will most likely lower ship speed if I experience ___________ emergences in ___________ (minutes/hours/seconds).

I will reduce approximately ___________ knot(s)

6. Excessive accelerations on bridge

Indicate the approximate location of the bridge:

Stern   Aft midships   Midships   Forward midships   Bow

Imagine you are sailing in rough weather and you experience excessive accelerations. Please indicate the case you will first consider to reduce speed, and how much you will reduce it with.

1. Average crew member on bridge standing up starts losing balance (0.1g - 0.15g)
2. Average crew member on bridge standing up has to hold on to something to maintain balance (0.15g - 0.25 g)
3. Average crew member on bridge standing up has to hold on to something with extra effort to maintain balance (0.25g and higher)
4. Average crew member on bridge sitting comfortably would fall off his seat (0.45 g and higher)

I will reduce approximately ___________ knot(s).

7. *Human comfort*

Human comfort are important for the people (in number, kind and training) on board a ship. Motion Sickness Incidences (MSI) (vomiting) and Motion Interruption Incidences (MII) (a person is forced to interrupt an allotted work task to avoid falling or losing balance) is a measure of human comfort. Indicate how important MSI and MII are for the ship speed.

Not important Slightly important Moderately important Important Very important

Notes:

8. *Are there effects not mentioned, which are important for voluntary speed loss?*

Thank you for your time and effort

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ORIGINAL QUESTIONNAIRE MADE BY PH.D STUDENT NATALIJA VITALI,
UNIVERSITY OF RIJEKA, CROATIA.
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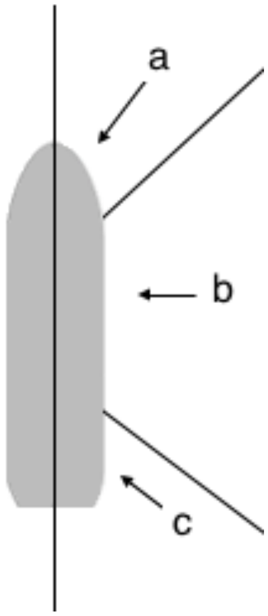
SHIP MASTERS AND OFFICERS EXPERIENCE IN ROUGH WEATHER

YEARS OF MARITIME EXPERIENCE: ______________________
TYPE OF SHIP YOU LAST SAILED ON: ______________________
SHIP DIMENSIONS (L,B,D): ______________________
SHIP SERVICE SPEED: ______________________
TYPE OF PROPULSOR:
Pod, propeller with rudder, other ________________________________
ACTIVE STABILISER SYSTEMS:
Roll fins, u-tanks, other ________________________________

Note: the questionnaire below apply to your experience on the above mentioned ship

Indicate at what highest safe speed you would sail through an area described by different sea states and wave encounter angles described. Indicate if you would change course for each case.



Cases are:
a – head sea
b – beam sea
c – following sea

1.1 **Sea state 0-3:**

Significant wave height from **0 – 1,25m**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

1.2 **Sea state 4:**

Significant wave height from **1,25m – 2,5m**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

1.3 **Sea state 5:**

Significant wave height from **2,5m – 4m**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

1.4 **Sea state 6:**

Significant wave height from **4m – 6m**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

1.5 **Sea state 7:**

Significant wave height from **6m – 9m**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

1.6 **Sea state 8 and higher:**

Significant wave height from **9m – 14m and higher**

	Head sea	Beam sea	Following sea
Speed (kn)			
Course Change (YES/)			

Your notes on speed reduction (Is it reduced for a single incoming wave? Until sea state is calmer?)**:**

B Ship service data

Figure 32a is the data-plot used in Figures 22 and 21.

Although data presented in the main body of the thesis, not all the data had trends as prominent. As mentioned, Figures 31, 30 and 32b are identical plots but for another ship. As can be seen, the trend of speed loss is certainly not as prominent. However, slight increased chance of speed reduction can be noted for higher sea states.

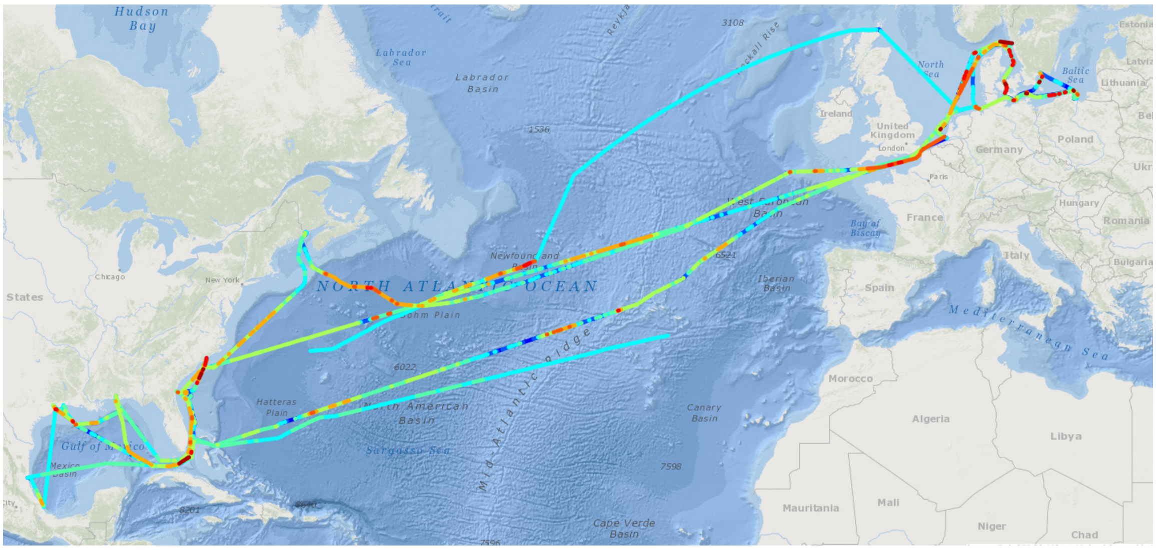


Figure 30: Route of travel for the ship in Figures 31 and 32b

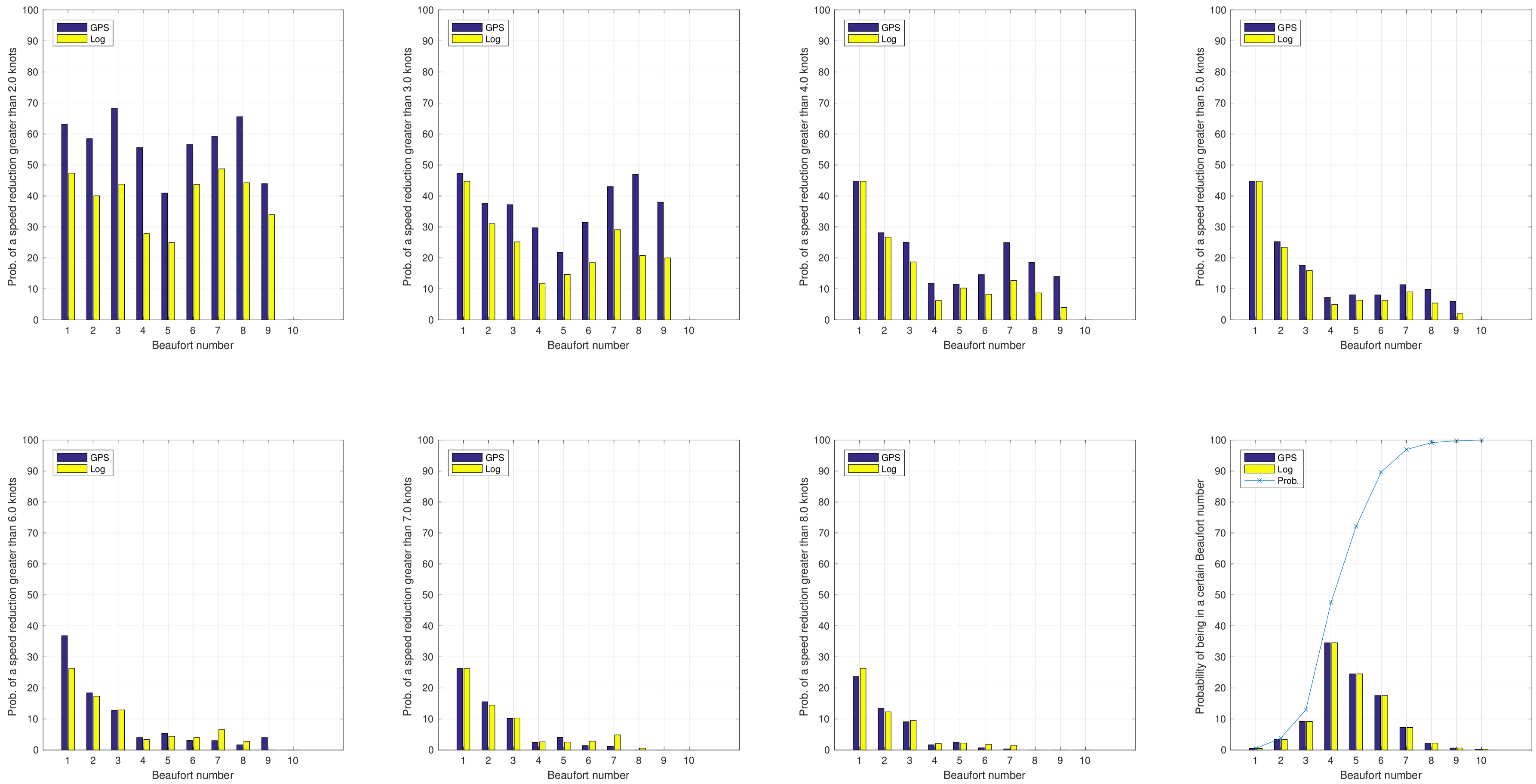
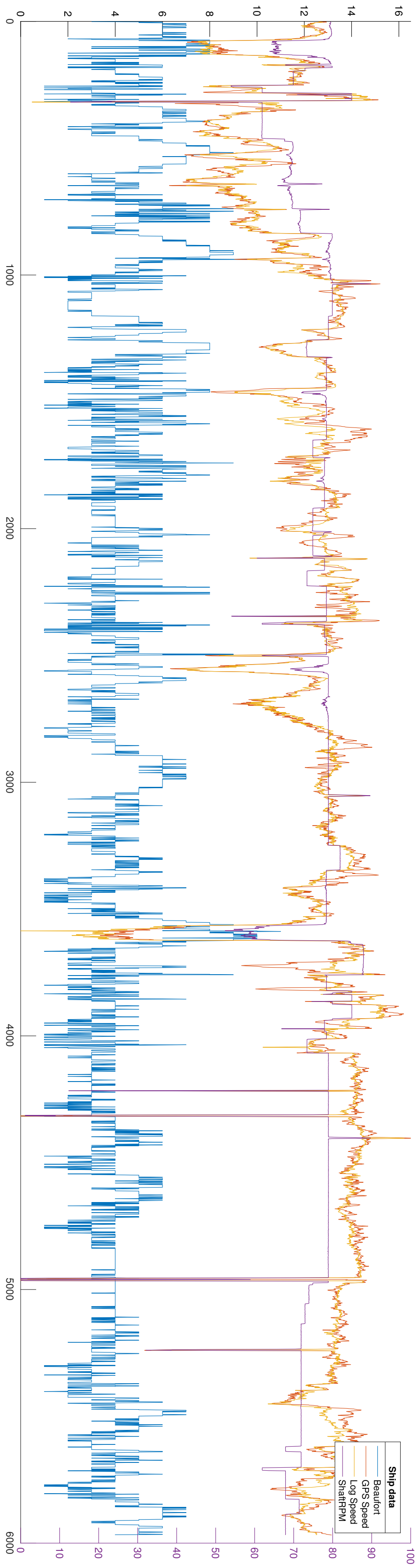
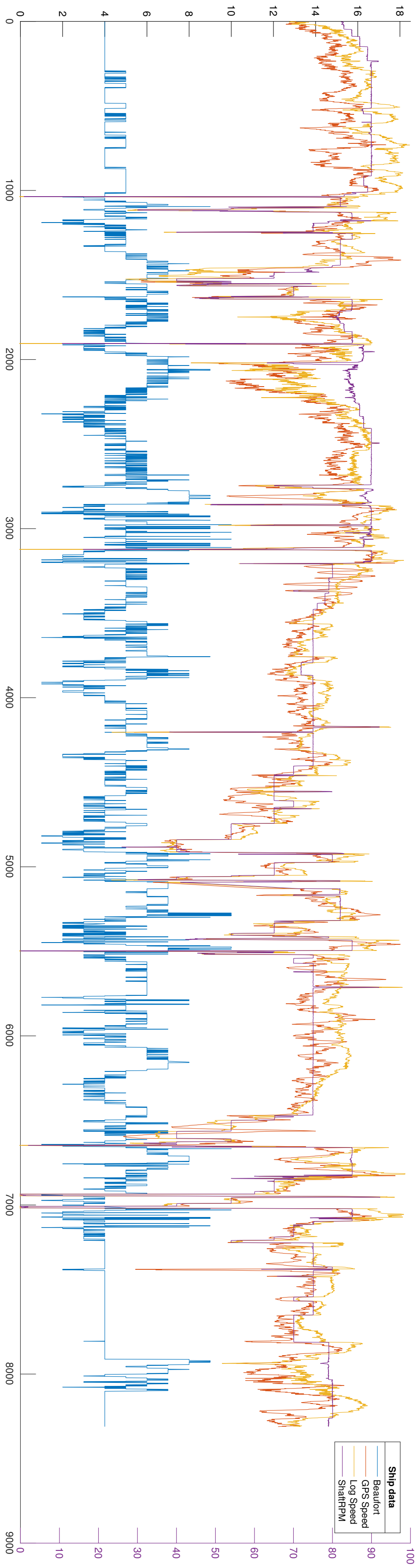


Figure 31: The probability of a speed reduction greater than a certain value, with sea state distribution plot given last.



(a) Raw-data used in plotting Figure 22



(b) Raw-data used in plotting Figure 31

Figure 32: Raw data, where only sea passage is included.

C Operability limits

Because of ongoing research and copyright of material, the collection of operability criteria by Prpić-Oršić n.d. cannot be reprinted in this thesis.

If you have any questions, please send an email to: sigbjorw@stud.ntnu.no

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