Cover photograph:

Overview of a part of Maasvlakte I, Port of Rotterdam

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Application of AIS data in a nautical traffic model

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Preface

This master thesis is the last piece of work in my master education in Hydraulic Engineering at the Delft University of Technology. The largest part of the research has been carried out in Delft and Wageningen, although I have had several thesis-related meetings at other locations in the Netherlands.

In the report a case study of an analysis of AIS (Automatic Identification System) is given. By doing this analysis, more insight is obtained into the path that vessels take and the accompanying vessel speed, in port areas. The results of the analysis are made generic, to make it possible to implement them in maritime models.

I would like to thank the members of my graduation committee, Prof. ir. H. Ligteringen, Dr. ir. W. Daamen from the Delft University of Technology, Ir. R.W.P. Seignette from the Port of Rotterdam and Ir. C. Van der Tak and Ir. Y. Koldenhof from Marin for their support and feedback given during the timespan of my thesis.

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Thijs de Boer
Delft, June 2010

Summary

From December 2004 onwards every seagoing vessel over 300 Gross Tonnage (GT) is obliged to be equiped with an Automatic Identification System (AIS). Nowadays also inland vessels are increasingly using AIS. The main functions of AIS are collision avoidance and an aid to navigation. Also coastal authorities (security) and Vessel Traffic Services (traffic management) use AIS. The system is valuable for search and rescue actions and in maritime modelling as well.

The quality of AIS messages has been topic of several researches. An AIS message can be divided into three types of data: static, voyage related and dynamic. Most errors are found in the description of Destination, Estimated time of arrival, Draught, Vessel Type and Navigational Status. Except for vessel type, these data are voyage related. This type of data has to be changed manually, which is a source of errors. The static data are added during installation of the system and do not change hereafter and are thus less prone to errors. The dynamic data depend on the vessel's navigational instruments and are quite reliable.

Maritime models use AIS data mainly to determine the traffic input. AIS data also improve the insight into the nautical networks that have to be modelled. In port areas, AIS data is not often used for these purposes, as in these areas the traffic image is disturbed by vessels that are not AIS equipped. AIS data can potentially be used to investigate individual vessel behaviour, but no extensive use is made of this yet.

Roughly two types of maritime models exist. One type simulates the overall nautical traffic and the other uses individual vessels. A problem for the models that simulate vessel behaviour is the so called human factor. Most models try to simulate this behaviour using Fuzzy-technology or Bayesian networks.

A case study is performed to see if an analysis of AIS data can describe vessel behaviour in the Port of Rotterdam area. As case area, the path between the North Sea and the Amazonehaven (Maasvlakte I) is used. The vessel path and speed, as well as the influence of vessel size, wind, current and visibility is determined. The influence of the vessel size is taken into account, by creating five different classes (<10,000; 10,000-40,000; 40,000-70,000; 70,000-100,000; >100,00 dwt).

There are significant diferences between the size classes, as well for the vessel path as the vessel speed. In general, larger vessels sail more to the middle of the channel and sail slower. They also have a more narrow distribution over the waterway. The vessel position and the vessel speed are normally distributed over the waterway. There is no significant relationship found between the location in the cross section and the vessel speed.

There are some exceptions to the general conclusions described in the previous paragraph. Vessels of the size class 70,000-100,000 dwt sail significantly slower than vessels of the largest size class. This might be caused by the fact that the largest vessels use more tugs and therefore have a larger manoeuvrability in the port area. This makes it possible for them to maintain a higher speed.

Incoming vessels sail backwards or forwards into the Amazonehaven, depending on how they are loaded. This causes roughly two different vessel paths in the Beerkanaal, because in both cases the vessels want to take the widest bend, as this is a more easy manoeuvre. Vessels that leave the port clearly show some deviation towards the north or south. This indicates that they already adapt their course towards their next destination (e.g. direction of Antwerp or Hamburg).

Also the influence of the external circumstances wind, current and visibility are examined. All three are found to have an influence on both vessel path and speed. Except for the visibility no significant differ-

ences in influence are found between the different size classes. In the Maasmond, high cross winds and cross currents lead to a deviation from the average path in the direction the external influence is working and to a lower speed. In general, wind and current from behind the vessel lead to a higher vessel speed.

To obtain more generic rules, The case area is split into several parts. In every part, the generalised vessel distribution and vessel speed distribution are derived in a number of cross sections. The influence of the external circumstances is generalised as well. These cause a shift in the normal distributions over the waterway. Finally, the interaction between vessels can be analysed by using AIS data. In this thesis an example of this is given.

Four currently existing maritime models (Samson, HarbourSim, Martram and Dymitri) are tested to the output of the case study, to see if the results can be implemented. None of the models can immediately implement the results. In Martram, the results can be implemented by making only a small amount of adjustments. HarbourSim needs to be adapted more, mainly to include the vessel (speed) distribution over the waterway. It is very difficult to implement the results in the other two models, as they are not meant for nautical traffic simulation (Samson) or have a different approach for simulating (Dymitri).

There are three important recommendations for future research. First, different types of vessels should be investigated, as in this thesis only container vessels where taken into account. Secondly, more research should be performed to obtain a better insight in the influence of the external circumstances. In this way, external influences can be described more precise and also relationship between them and the vessel size might be derived. Finally, the vessel-vessel interaction should be examined. This clearly is the next step in describing the vessel behaviour in a port area.

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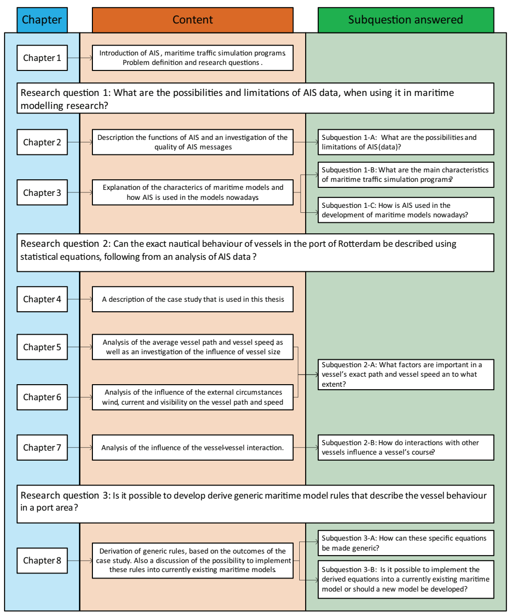
Chapter 1



Introduction

1 Introduction

1.1 Background

Maritime transport has always been very important in international trade. Especially since the introduction of the container in the fifties, maritime transport has rapidly increased due to its cost-efficiency (Figure 1.1). This has led to an enormous growth of the traffic intensity in ports all over the world. Not only the number of vessels has increased, also the vessel-size has been developing.[1]

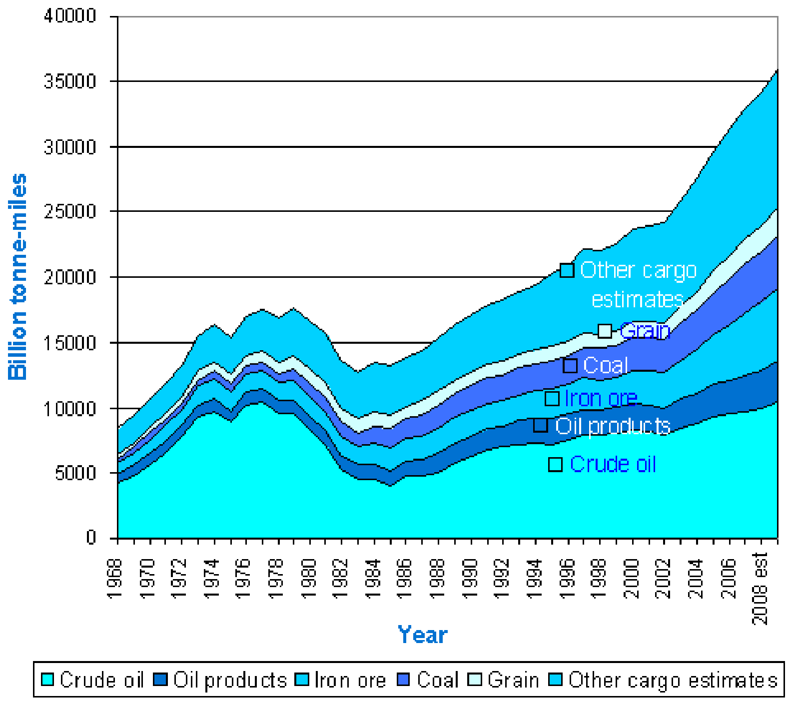


Figure 1.1 World seaborne trade 1968-2008, source: www.marisec.org

With the above mentioned developments in maritime transport, safety and capacity issues come up. The International Maritime Organization (IMO)[2] has been very important for the improvement of safety at sea. This organisation, established in 1948 in Geneva, maintains several treaties that aim to improve the nautical safety. An example of such a treaty is SOLAS (Safety of Life at Sea), which gives rules and guidelines to prevent accidents. One of these rules is the obligation for seagoing vessels larger than 300 Gross Tonnage (GT) to carry an Automatic Identification System (AIS) since December 2004.

Vessels equipped with AIS carry an instrument which transmits and receives data about the vessel over a dedicated VHF (Very High Frequency) radio band. The time interval in which this is done depends on the speed of the vessel and ranges from 2 seconds to 10 seconds when sailing. The data contains the general information of a vessel as well as its position, speed, heading, origin and destination, cargo and current draft. This information is picked up by other vessels and coastal authorities. The other vessels use it for navi-

1 International chamber of shipping (ICS) & International shipping federation (ISF), http://www.marisec.org/shippingfacts/, accessed: 26/1/2010

2 More information regarding the IMO and the SOLAS treaty can be found in Appendix A.

gational purposes, while the authorities can use it for identification (security) and communication.[3] More information regarding the characteristics and use of AIS can be found in chapter 2.

1.2 Nautical traffic modelling programs

Besides international rules and guidelines, a way to improve and determine safety and capacity is by the use of maritime models. Especially in port planning and design, modelling programs can be a very valuable tool. They can for example demonstrate the effectiveness of different risk control measures; thereby assisting the evaluation of alternatives (Seignette, 2005). Different types of models exist to support decisions in the development of port infrastructure. Some of these models (Fast Time Manoeuvring Simulation Programs) describe a vessel's motion in great detail, by taking into account external influences such as wind and currents. An important output of such a model is the precise path a single vessel takes in a certain port area and the controls it applies. The risks following from the interaction between vessels however is not simulated, because mostly the modelling of multiple vessels simultaneously is not done (Pimontel, 2007).

In another type of model, the maritime traffic modelling programs, multiple vessels are taken into account. This makes it possible to calculate safety and capacity of a certain waterway. These programs however do not reach the same level of detail of the fast time manoeuvring models. Some models try to approximate the vessel behaviour, but most of them do not simulate exact vessel movements. This means that also the vessel interaction with other vessels and infrastructure is not simulated. Especially in busy, closed waterways like ports this makes it very difficult to quantify nautical risks sufficiently.

1.3 Problem definition

As mentioned above, current maritime models do not sufficiently simulate the exact vessel behaviour and interaction with other vessels. With the introduction of AIS, a new possibility is available to get more insight into this nautical behaviour. AIS messages are sent on a very regular base and therefore a lot of precise data is present. This makes it potentially possible to statistically describe vessel behaviour. AIS however is not originally developed for research purposes. It is not sure which errors and uncertainties are present and if and how this limits the possibility of using it in modelling. Therefore these data should be examined very critical before using. This leads to the problem definition of this research:

The exact course of a vessel and its interaction with other vessels and infrastructure is not always simulated in sufficient detail in current maritime models, an analysis of AIS data may improve the insight in and modelling of the exact nautical behaviour.

1.4 Research questions

The problem definition is split up into three research questions. Because modelling exact vessel behaviour is especially important in port areas, the port of Rotterdam area is used as a case study. Each of the questions is divided into several sub questions.

3 International maritime organization (IMO), www.imo.org, accessed: 26/1/2010

1. What are the possibilities and limitations of AIS data, when using it in maritime modelling research?

    1-A What are the possibilities and limitations of AIS (data)?

    1-B What are the main characteristics of maritime traffic modelling programs?

    1-C How is AIS used in the development of maritime models nowadays?

2. Can the detailed nautical behaviour of vessels in the port of Rotterdam be described using statistical equations, following from an analysis of AIS data?

    2-A Which factors are important in a vessel's exact path and speed and to what extent?

    2-B How do interactions with other vessels influence a vessel's path and speed?

3. Is it possible to derive generic maritime model rules that describe vessel behaviour in a port area?

    3-A How can these specific rules be made generic?

    3-B Is it possible to implement the derived equations into a currently existing maritime model or should a new model be developed?

1.5 Research approach

The approach used in this thesis to answer the three main research questions, can also be split into three sections. First, a literature study is needed to obtain insight into AIS and maritime models. A factual description of AIS (messages) is given, but also insight in the quality of AIS data, to answer subquestion 1-A. To get information regarding maritime models, an overview is given of the approach of maritime models nowadays. Also the use of AIS data in these models is investigated.

Research question 2 is answered by using a case study. By using a specified area, a selection in vessel tracks that are examined can be made. It makes it also possible to compare the derived results with each other more easy. In this case study, first the influence of the vessel size is investigated. This is done, because after this is known, the vessels can be brought together in suitable size classes. The average vessel path and speed is calculated for the different size classes.

When the average behaviour is known, it can be researched what other influences do exist that influence a vessel's path and speed. Main focus will be on the influence of external circumstances, like wind. Also the vessel-vessel interaction will be taken into account. This is different from the other influences, as interaction situations are mostly very case specific. The calculation of the influence of interaction will therefore need an approach that focusses on the detailed analysis of individual situations.

Research question 3 is divided into two subquestions. The first subquestion handles the derivation of generic rules. These can be made, by simplifying the nautical infrastructure from the case study to more standard types of waterways. The results from the case study can than be generalised. The second questions concerns the possibility to implement these rules in an existing maritime model. To answer this question, the specific characteristics of several maritime models used nowadays are elaborated.

1.6 Report outline

Research questions 1 and its sub questions will be answered in chapters 2 and 3. Question 2, including sub questions, is handled in chapters 4-7. The answer to question 3 and its sub questions is given in chapter 8. Figure 1.2 shows the report outline graphically.

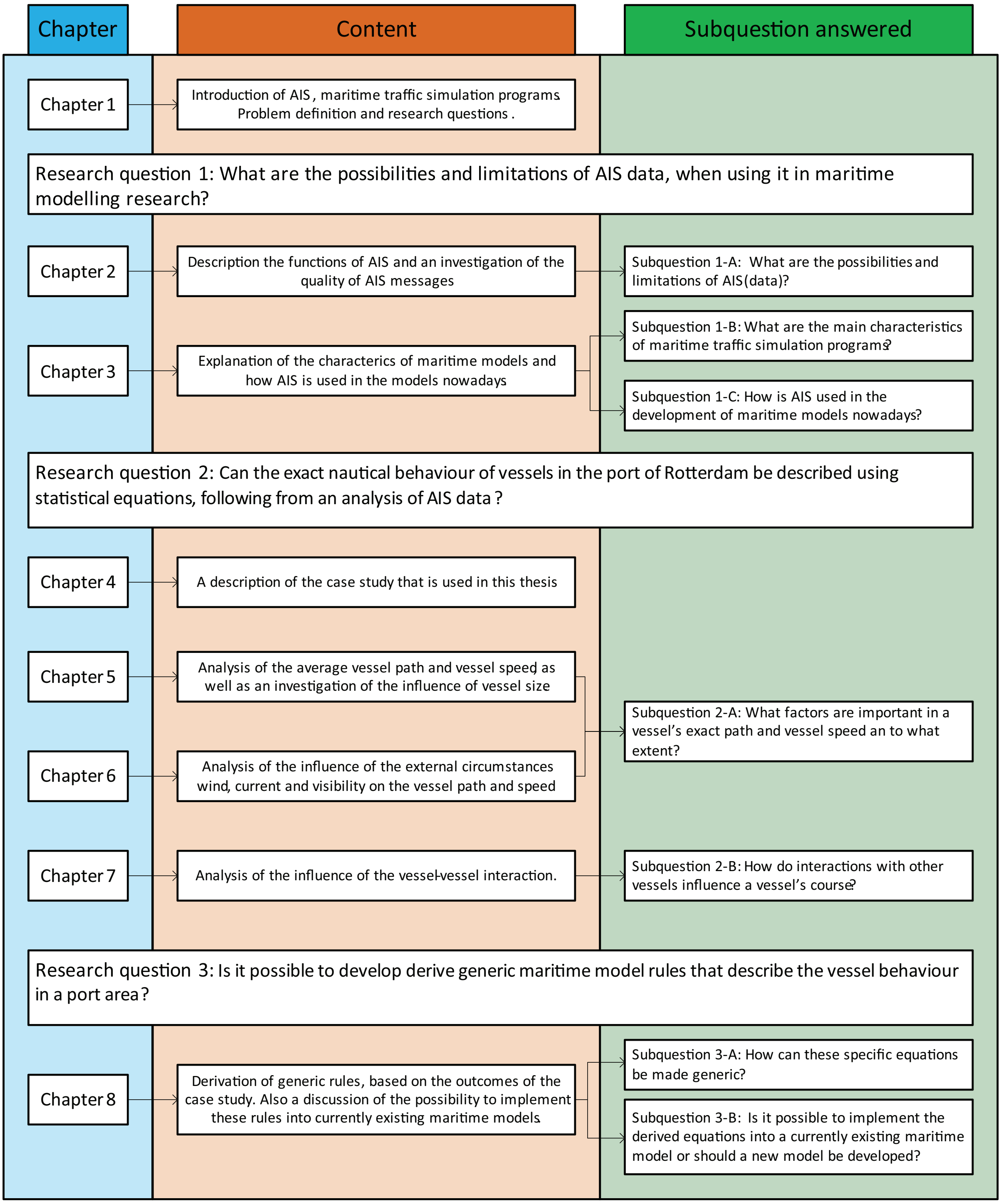
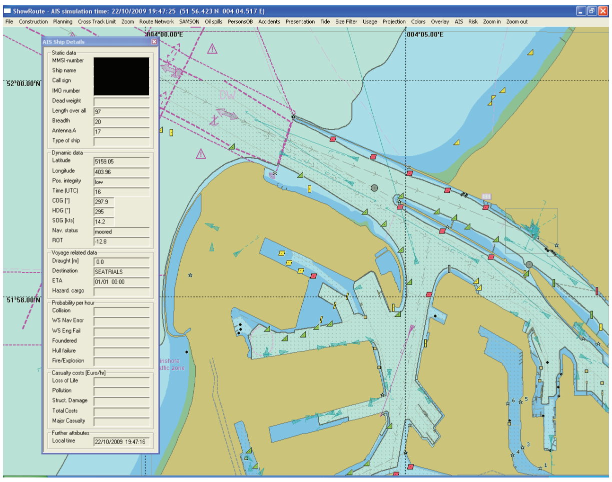


Figure 1.2 Report outline

Chapter 2



Automatic Identification System

2 Automatic Identification System

This chapter explains the working of the Automatic Identification System (AIS). It indicates the several functions of AIS and how the messages are transmitted. Also the data included in a message and the quality of the data is described.

2.1 Introduction

In December 2000 IMO decided to start implementing AIS in the international sea trade. The objectives for the implementation of AIS were 'to enhance safety and efficiency of navigation, safety of life at sea, and maritime environmental protection through better identification of vessels, assisted target tracking, and improved situational awareness and assessment through simplified and additional information. AIS can also improve the quality of vessel traffic surveillance (VTS) and waterway management'. (Harati-Mokhtari, et. al. 2007, p.374)

From the objectives mentioned above roughly three functions of AIS can be distinguished.

1. To assist in navigation and collision avoidance.
2. To pass information about a vessel and its cargo to coastal states.
3. To help in traffic management as a VTS tool.

Especially the first function is a very important characteristic of AIS. By receiving AIS messages from nearby vessels, a precise overview of the traffic situation around the vessel is derived. Because identification is done automatically, communication is easier. This makes it possible to solve potentially dangerous situations much quicker. This and other advantages are elaborated more into detail in the next section.

The time scheme of the introduction of AIS is described in the SOLAS treaty. From December 2004 onwards all sea-going vessels larger than 300 gross tonnages (GT) are obliged to have AIS on board. In practice almost every sea-going cargo vessel exceeds this weight limit and carries AIS nowadays. Fishing and inland vessels as well as pleasure yachts use AIS less often. The use of AIS by -especially- inland vessels is however expected to increase rapidly.[4]

2.2 AIS message

Vessels that have an AIS carry a transponder which transmits messages about the vessel over a dedicated VHF (Very High Frequency) radio band. The frequencies in the VHF range are much lower than the frequencies used by marine radar (which uses Super High Frequencies). This means that AIS messages are sent with a larger wave length as well. Due to this larger wave length AIS is able to detect targets in situations where radar detection is limited. This is the case around bends, behind hills and other vessels and in conditions of restricted visibility in ports and restricted waterways.

4 Currently 3 % of the inland vessels that visit the port of Rotterdam are equipped with iAIS (inland AIS). The expectation is that, due to national and European stimulation programs, at the end of 2012 this number has increased to almost 80%. Source: R.W.P. Seignette, port of Rotterdam.

There are three types of data in an AIS messages: static data, voyage related data and dynamic data. The categories are valid for different time periods and therefore have different update intervals. Static data and voyage related data are transmitted every 6 minutes, on request of a competent authority and when the data are changed. The time interval of the dynamic data message depends on the speed, course alteration and navigational status of the vessel. When the vessel is moored a message is sent every 3 minutes. When sailing, this time interval ranges from 2 seconds (speed > 23 knots ≈ 11.8 m/s) to 10 seconds (speed < 14 knots ≈ 7.2 m/s and no course alterations). If needed also short safety-related messages can be sent.

Static data are entered into the system during the AIS installation and need only to be changed if the name of a vessel changes or if the vessel undergoes a conversion to another ship type. Examples of static data are name, MMSI-number (Maritime Mobile Service Identity), vessel type, length and position of the AIS transmitter on the vessel. Voyage related information concerns issues like the vessel's draught, destination and ETA (Estimated Time of Arrival). This information needs to be kept up to date manually by the ship's crew, which makes it sensitive to errors and uncertainties.

Dynamic data originate from the vessels navigational instruments; examples are the vessel's position, heading and rate of turn. The position of the vessel is reported by three parameters: longitude, latitude and a position accuracy report. The longitude and latitude are given in 1/10,000 minute, which is -in latitudinal direction- equal to approximately 20 cm. In longitudinal direction this number depends on the distance to the equator (Netherlands ≈ 11 cm).   The position accuracy report indicates how accurate the two mentioned position reports are (IALA and AISM, 2004).

A detailed overview of the data inside an AIS message can be found in Appendix B.

2.3 Errors in AIS messages

To investigate the quality of the data in AIS messages some surveys have been undertaken. Most surveys only look at the errors that occur in a limited number of parameters. Bailey, et al. (2008) study the influence of the introduction of AIS. In this study AIS messages transmitted by vessels in the Dover Strait are judged in three different years. Harati-Mokhtari et al. (2007) investigated errors in AIS messages by using three different datasets. In their study, static, voyage-related and dynamic data are examined.

Bailey, et al. (2008) looked to the maritime traffic of one week in the Dover Straits. This was done in three different years, leading to datasets of 806 (2004), 901 (2005) and 940 (2007) vessels. After analysis, errors were found in MMSI-number, Call Sign, Name, Draught, Destination and Course. By far the most errors occurred in the categories Destination and Draught.   Errors in Destination included misspelling, empty data fields, incomprehensible abbreviations and references to the previous port. Most of the errors in draught were less than 1 meter, but in some cases a difference of more than 3 m was found.

Because there were data from three different years, it was possible to create a comparison between those years. By doing so, they found that the percentage of vessels that transmitted errors decreased from 10.4 % in 2004 to 3.5 % in 2007. However the authors remark that, due to several reasons, this last number may to some extent underestimate the actual number of errors. This does not influence their conclusion that the number of errors is decreasing year on year. The numbers are summarised in Table 2.1.

Table 2.1 Numbers of vessels transmitting errors by year.
Source: Bailey, Ellis et al., 2008

Year	Total number of vessels	Number of vessel transmitting errors	Percentage of vessels transmitting errors	Number of errors
2004	806	84	10.4 %	122
2005	901	71	7.9 %	99
2007	940	33	3.5 %	44

Harati-Mokhtari et al (2007) use three different datasets to investigate errors and inaccuracies in the different fields of an AIS message. In one of the used datasets ('Data-mining study'), 8 % from a total of 400,059 reports contained errors concerning MMSI number, IMO number, position, course over ground (COG), and speed over ground (SOG).These erroneous reports were investigated further. Another dataset (VTS-based study), containing information from 94 different AIS equipped vessels, was used for the investigation of the MMSI number, vessel type, ship's name and call sign, length, beam and navigational status. A third dataset (Proactive AIS study) was present, but only used to investigate errors in MMSI-number.

In the static data, errors were found in MMSI-number, vessel type, vessel name, call sign, length and beam. Main source of errors was the vessel type, which description was found to be vague or incorrect in respectively 74 % (VTS-based study) and 56 % (Data-mining study) of the cases.

In the analysis of voyage-related data, the focus of the authors is on destination, ETA (Estimated Time of Arrival) and draught. In the data-mining study, 49% contained errors concerning destination and ETA. In 31% of the investigated messages obvious errors in the vessels draughts were reported. The analysis of dynamic data focuses only on the errors in the category 'Navigational Status', which for example indicates if a vessel is sailing or anchored. Incorrect navigational status information was given by 30 % of the vessels (VTS-based study).

Solvsteen (2009) also shows some results about the quality of AIS data. He concludes that most errors occur in ETA (21.7 % of the observations were wrong), IMO-number (14.1 %) and Destination (11.0 %). He also found errors in Rate of Turn (8.9 %), Heading (7.1 %), Dimensions (6.2 %), Draught (5.7 %), Course over Ground (0.8 %), Speed over Ground (0.8 %) and a missing ship name (0.04%). It is not sure if Solvsteen did not find any errors in the other parameters, like the Navigational Status, or did not take them into account.

2.4 Improving safety of navigation and other applications

As described in the first section of this chapter, the primary function of AIS is to assist in navigation and collision avoidance. Other functions are passing information to coastal authorities and helping VTSs in traffic management. Next to these three functions, other applications have come up that use AIS. In search and rescue operations for example, SAR (Search & Rescue) aircrafts transmit their position by AIS.

The use of AIS by VTSs, coastal authorities and Search & Rescue operations is described in Appendix C. Another example, already mentioned in the first section, is the use of AIS data in maritime modelling; this subject is handled in chapter 3. Below a description is given how AIS fulfils its primary function and improves safety of navigation.

There are several ways in which AIS improves the safety of navigation. One of them has to do with the information exchange between vessels. Vessels automatically pick up AIS messages from nearby equipped vessels. Other applications make use of the fact that an AIS signal can also originate from other sources than vessels, for example a buoy.

When vessels receive an AIS message they automatically decode and display the information to the officer on watch. In this way a complete picture of all AIS equipped ships within VHF range can be derived. Before AIS was used, the traffic situation around a vessel was derived by plotting a radar image. The advantage of AIS compared to this radar image is that the vessels are automatically identified. In this identification not only the name of other vessels is provided, but also other characteristics such as ship type and size. Next to this advantage AIS is also able to detect targets on places where the radar detection is (temporarily) limited.

This gives a better overview of the situation around the vessel. Because the identity of the surrounding vessels is known it also is easier to call on other vessels and communicate. Therefore evasive manoeuvres can be agreed upon quicker, which reduces collision risk. This clearly shows the advantages of AIS over radar. It is however not possible to rely completely on the traffic image derived from AIS. This has to do with the fact that AIS messages are sent actively. If a vessel is not equipped with AIS, it will not be detected. Radar waves do not have this problem, because they are simply reflected by every obstacle.

This disadvantage of AIS is most visible in situations where a lot of vessels with and without AIS are present. This happens mainly in and around port areas, where cargo is transferred between large ocean vessels and other transport modes such as inland waterway transport. Especially inland vessels, but also fishing vesesls and recreational vessels do sometimes interfere in these places with seagoing cargo vessels. In these situations AIS does not give a sufficient traffic overview and it is better to rely on the radar image. AIS can however still be used as an additional source of information, mainly for identification purposes.

Another interesting ability of AIS is the transmitting of positions and names of objects other than vessels, for example navigational aids as lighthouses and buoys. This can be done in two ways. One option is that the navigational aid sends AIS messages with its own transmitter. Another way is that his signal is sent by a nearby base station. To passing ships this seems to come from the aid itself. This method is known as synthetic AIS and can be interesting when it is not possible to equip a navigational aid with its own AIS transmitter. AIS can also be used to give locations which are not visible, like a wrecked ship. Again a base station sends out a message and the non-visible target appears on a vessel its screen. This is known as virtual AIS.[5]

2.5 Conclusions

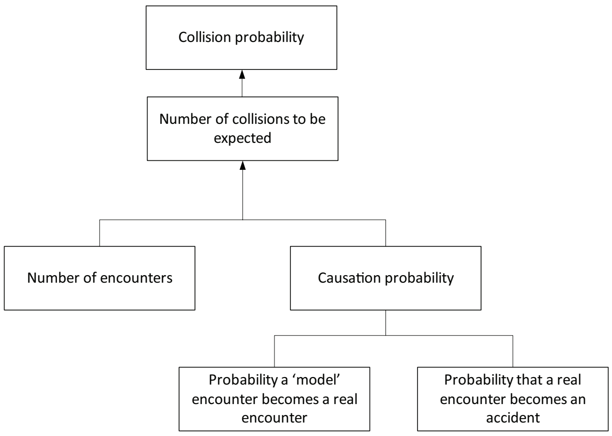
AIS is a well known system in maritime transport nowadays. Especially seagoing cargo vessels are equipped with the system. The main function of AIS is collision avoidance and aid to navigation. It is also used by coastal authorities and VTSs for respectively security and traffic management reasons. Other applications of AIS are, amongst other things, search and rescue and the use of data in maritime modelling.

5 UK Government Strategy for AIS, Department for transport, United Kingdom, http://www.dft.gov.uk/pgr/shippingports/ports/modern/ais/ukgovernmentstrategyforais?page=2, accessed: 17/12/2009

Since the introduction of AIS, several researches have been performed to investigate the quality of AIS messages. Every research focusses on different parameters and uses datasets from different years and locations. Therefore it is difficult to compare them and draw conclusions. There are however some similarities between the three researches mentioned. One common conclusion is that a significant amount of AIS messages contain errors. Most problems were found in the categories Destination, ETA, Draught, Vessel Type and Navigational Status. Except for the Vessel Type, these categories contain data that have to be updated manually.

Due to the differences between the three studies mentioned, it is difficult to conclude something about the development of the quality of AIS data. Harati-Mokhtari et al. (2007) find for example much higher error percentages than Bailey, Ellis and Sampson (2008). The findings of Solvsteen (2009) lie in between. Only Bailey, Ellis and Sampson et al (2008) look at the quality of the data in different years and from their research it is possible to state that the AIS data quality is improving. More research is however needed to support this statement.

Chapter 3



Maritime modelling

3 Maritime modelling

Most nautical safety- and capacity studies use maritime models for the modelling of nautical traffic. Almost all programs use the same basic principle, especially for the determination of collision risk. There is however a main characteristic that divides these programs into two types. This characteristic concerns the question if individual vessel movements are simulated.

The first type, the geometric model, uses statistical knowledge of traffic intensities and distributions. No individual vessel movements are simulated. However, maritime traffic simulation programs, simulate individual vessel movements. This chapter describes the basic principle of maritime modelling programs as well as the characteristics and limitations of the two types of models mentioned.

3.1 The basic principle of maritime modelling programs

Most studies that use maritime models, aim to derive the nautical safety of a certain waterway. In practice this means the calculation of collision risks within a predefined time span. For the determination of this, models calculate the number of accidents that can be expected; this is done in two steps. First a number of potential dangerous situations is calculated. Secondly, this number is used to calculate a number of collisions that is to be expected.

The potentially dangerous situations are called encounters. In practice, when two vessels come too close to each other, this is called an encounter. This raises the question how close vessels can sail to each other, before this is 'too close'. For this, the principle of vessel safety domains is used. A safety domain is a prescribed area around a vessel. If two safety domains overlap or if a vessel enters the domain of another vessel, they are too close to each other; this counts as an encounter (see Figure 3.1). So, the size of the vessel safety domain is a leading parameter in the determination of the number of encounters.

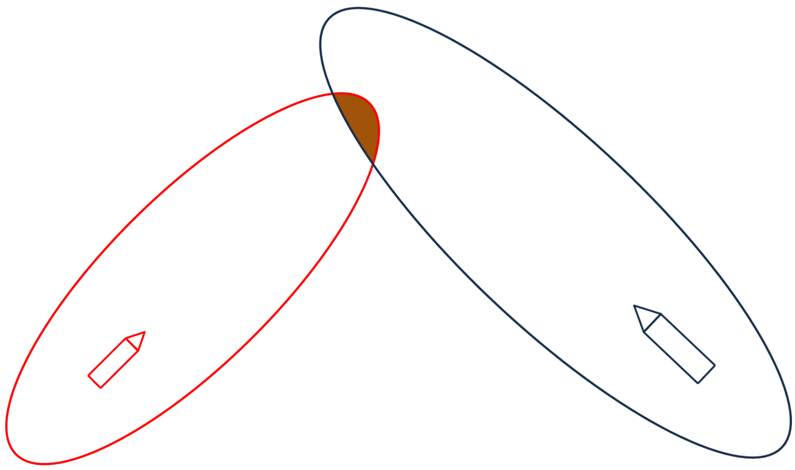


Figure 3.1 Two vessels with different, overlapping safety domains.

It is however not very easy to determine the size and shape of this domain, because it depends on a lot of parameters: characteristics of the vessels involved (e.g. speed, dimensions, manoeuvrability), the traffic situation (e.g. traffic intensity, width of waterway) and external influences (e.g. visibility, wind, waves). Different studies have been performed to determine vessel safety domains. However, no consensus has been reached yet on the size and shape of the domains (Pimontel, 2007).

Different types of maritime models calculate the number of encounters in different ways. This has especially to do with the modelling of individual vessel movements and the ability of vessels in a model to manoeuvre, thereby preventing encounters. In geometric models, where no individual movements are simulated, this leads to an overestimation of the number of encounters in reality. The other models do simulate vessel movements, but the manoeuvring possibilities are often very restricted. Therefore, they also over-estimate the number of encounters.

This over-estimation is compensated by the causation probability. This number includes the probability that an accident happens, given the occurrence of an encounter in the model. The causation probability can be divided in two parts. The first part compensates the over-estimation of the number of encounters following from a model run. This is reflected by the probability an encounter happens, given the fact that an encounters occurs in the model run. The second part concerns the fact that an encounter is not equal to an accident. This is reflected by the probability an accident happens, given the occurrence of a real encounter.

The physical meaning of the causation factor is the percentage of vessels that does not make a sufficient evasive manoeuvre when needed, to prevent an accident. This principle is used by maritime models in the calculation of the causation factor, which is done in two ways. One option is the use of Bayesian networks. These networks are built in such a way that they calculate the probability a vessel does not respond sufficiently to prevent an accident. Factors such as visibility, stress level and VTS assistance are included.

Another option for the derivation of the causation factor is the use of historical accident data. In this method the causation factor is determined in such a way that the outcome of the model (collision probability) is plausible. Historical data is also used in the first method, for the validation of the Bayesian networks. The problem of accident data is the fact that these are not always available. Without the data it is not possible to check the outcome of the model. In these situations it is not possible to quantify nautical risk; only conclusions can be drawn on the relative safety of different alternatives.

So, by combining the number of encounters and the causation probability, a number of accidents is obtained. Finally this total number of accidents is converted to a collision risk (see Figure 3.2 and Figure 3.3).

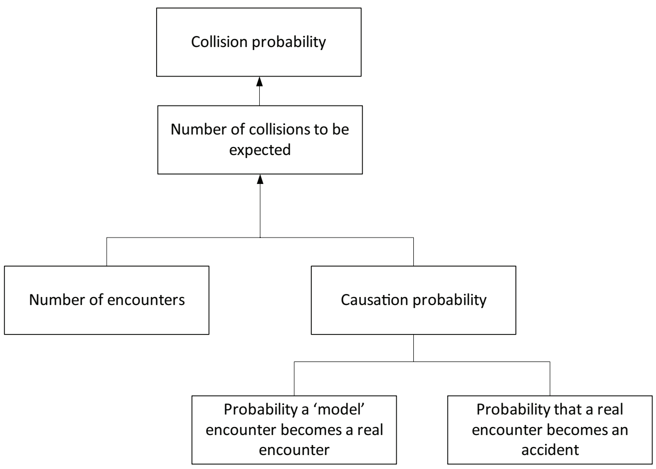


Figure 3.2 The basic principle of the calculation of collision risk.

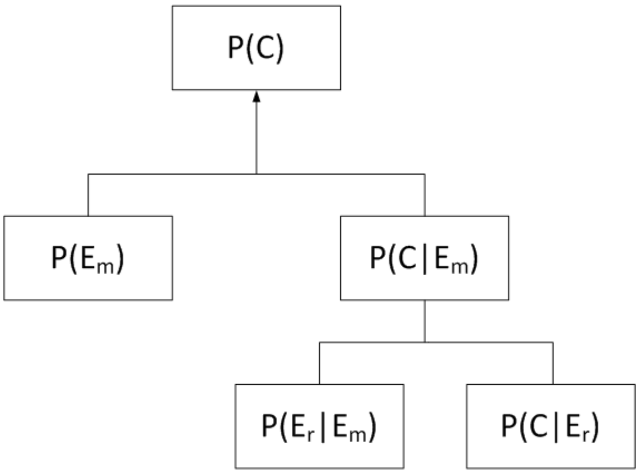


Figure 3.3 The basic principle of the calculation of collision risk, reflected in probabilities
C = Collision;
Em = Encounter in model run;
Er = Encounter to be expected in reality.

3.2 Type I: The geometric model

In some models no individual vessel movements are simulated. Vessels sail along a predefined track, according to a spatial distribution over the waterway. They do not have the ability to deviate from these standard routes. When a vessel meets an obstacle like another vessel or a shoal, it also does not react. This principle is known as the geometric model, because the calculations are based on geometric probability. The principle is rooted in the approach defined by Fujii, et al. (1974) and MacDuff (1974). (Kujala, et al., 2009, p. 1353). An example of a model that works with this principle is SAMSON (Safety Assessment Model for Shipping and Offshore on the North Sea), used by Marin[6], mainly for nautical safety studies.

The calculation of collision risk is done following the basic principle discussed in the previous section. The causation factor is derived by using Bayesian networks and historical accident data as explained. Because no individual vessel movements are simulated, it is not possible to simply count the number of encounters. The determination of this number is therefore of interest in these kind of models. This is done by using two assumptions mentioned before. (Friis-Hansen and Simonsen, 2001)

1. Vessels sail according to an assumed or pre-specified spatial distribution of the vessel traffic over the waterway;
2. Vessels are navigating blindly when these are operating at the considered waterway.

6 Maritime Research Institute Netherlands

After the distributions over the different waterways have been specified, it is possible to calculate the number of encounters. This is done by defining a risk area, where vessels can potentially encounter each other (see Figure 3.4). Subsequently, the number of encounters is calculated, using the dimensions, speeds and the spatial distribution over the waterways. This is done for all combinations of different vessel classes.

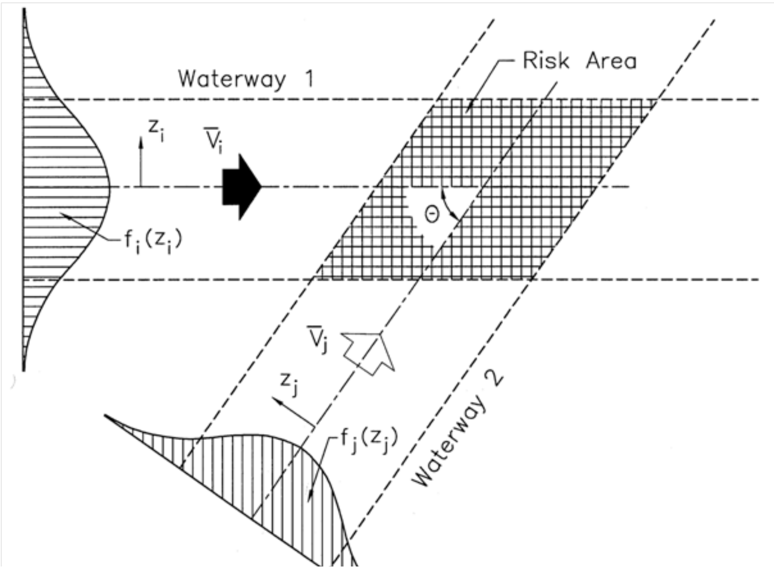


Figure 3.4 Crossing waterways with risk area of ship-ship collision.
f (z)= vessel distribution over the waterway, different vessel classes are denoted by i and j;
z = distance to the centreline of the waterway;
V = velocity of vessel;
θ = angle between the waterways 1 and 2.
Source: Pedersen et al. (1999), p. 4, figure 2.1 (Pedersen and Zhang, 1999)

The exact calculation is not treated here, because the main focus of this thesis lies on models that do simulate individual vessel movements.

3.3 Type II: Maritime Traffic Simulation Programs

The main difference between the geometric model and maritime traffic simulation programs (MTSPs) is simulation of vessel movements. In MTSPs the number of encounters is calculated by counting the number of encounters that happen in a simulation run. The output of a simulation run is not only a number of encounters, but makes it also possible to take a closer look at the encounter situation. This leads to a better insight into the different causes of an encounter. This can be valuable in evaluating the efficiency of, for example, infrastructural improvements.

Another advantage is that the number of encounters is calculated more precisely by MTSPs than by the geometric models. This is due to the fact that vessels are able to manoeuvre in order to prevent encounters, whereas this is not possible in the geometric models. The accuracy of the calculation depends on the quality of the vessel simulation. The improvement of this simulation is one of the main targets for MTSPs.

Most simulation programs use simple rules to simulate vessel behaviour. The most important rules for vessel behaviour follow from the internationally recognised Collision Regulations (COLREGs)[7] . These regulations prescribe the supposed vessel behaviour, especially regarding the interaction with other vessels.

The COLREGs give a good first indication of vessel behaviour, but two limitations come up. First, these regulations only give general guidelines how vessels should behave. No detailed information concerning the precise path of a vessel and its interaction with other vessels is given. Secondly, vessels do not always obey the COLREGs. Sometimes they deviate from these guidelines for some reason.

So, to simulate vessel behaviour in a more detailed way, additional rules and guidelines should be formulated. It is not very easy to do so, because the vessel behaviour greatly depends on the decisions that are made by the humans that control the vessel. Their decisions are based on knowledge, experience and capabilities, which are different for everyone: the human factor. Nevertheless several methods to describe vessel behaviour can be distinguished nowadays: fuzzy logic, rules based on expert knowledge, and Bayesian networks.

Fuzzy logic is a mathematical technique that is used in models for the determination of the human behaviour. "In fuzzy logic modelling, large amounts of input data are processed according to various 'If-Then' rules, similar to those that occur in the human brain. Weighting and averaging of the resulting outputs then leads to a single output signal. This ability of taking in and evaluating large amounts of data, leading to a decision on how to act is what makes fuzzy logic modelling so suitable for modelling human behaviour." (Pimontel, 2007, p.10). Nowadays, the simulation programs DYMITRI uses fuzzy technology to simulate the human element (Bolt, 2006).

Another way of simulating the human element is by using Bayesian networks. Barauskis and Friis-Hansen (2007) use dynamic Bayesian networks for the modelling of vessel behaviour in their model, called the numerical navigator. An advantage of using those networks is the possibility of having incomplete information. In the numerical navigator model the vessels are reflected by agents. Those agents have the ability to interact, anticipate and learn. To model and to train the agents, COLREGS's and AIS data analyses are used. The possibility to use AIS data in maritime simulation is handled in chapter 4.

A third option to get more insight into vessel behaviour is the use of simple logical rules. These rules are established by using expert knowledge. In interviews several captains give an overview of their behaviour in different presented situations. From this knowledge generic rules that describe vessel behaviour are derived. By doing so, it is not needed to simulate the human brain. This problem is bypassed, because it is already included by the obtained rules. SIMDAS is an example of a model that works like this.

Chauvin and Lardjane (2008) did some research on vessel movements and interaction as well. By using the RPD (Recognition-Primed-Decision) model of Klein[8] they investigated the interaction between vessels in the Dover Strait. They come up with some conclusion regarding collision avoidance behaviour. An example is at what distance from each other vessels start to change course to prevent an accident. Their vessel track data were based on motions observed by a VTS.

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7 International Maritime Organization, IMO, http://www.imo.org/conventions/contents.asp?doc_id=649&topic_id=257,accessed: 10/3/2010

8 Gary A. Klein, A Recognition-Primed Decision (RPD) Model of Rapid Decision Making, http://www.ise.ncsu.edu/nsf_itr/794B/papers/Klein_1989_AMMSR_RPDM.pdf, accessed: 8/1/2010

3.4 Use of AIS in models

Since the introduction of AIS, studies have been performed on the reliability of AIS data, for example by Harati-Mokhtari et al. (2007). Nevertheless, AIS data are already used in many researches concerning maritime models. Mostly to determine the nautical traffic demand, an important input in these programs. AIS can however also be used to analyse vessel movements, as suggested by Barauskis and Friis-Hansen (2007).

3.4.1 Traffic input

In MTSPs it is very important that the traffic demand is assumed as realistic as possible. A thorough analysis should be done about vessel type, size, destination, inter arrival distribution, etc. An AIS message contains all this information and is therefore very valuable to generate this input. A lot of risk assessments nowadays therefore use these data, but they often also mention limitations. For example Van der Tak (2009) uses other data sources than AIS to obtain information about the density of fishing vessels. Both Kujala et al. (2009) and Ylitalo (2009) mention the lack of AIS data from fishing vessels as well as pleasure boats, which makes it more difficult to derive good accident risks.

Most studies using AIS data, investigate safety at the open sea. There are far less surveys concerning ports or inland waterways that use AIS data. This is easy to understand from the fact that a lot of smaller vessels (mainly inland vessels) do not carry AIS equipment. For example Iperen and Koldenhof (2008) use radar data for their risk assessment study in the port of Rotterdam area. However, AIS data are used in a research in the port area 'Eemshaven' for the risk assessment of LNG vessels. This is only possible because the vessels that do not carry AIS are too small to damage an LNG vessel (Koldenhof and Van der Tak, 2007).

AIS data can also be used to improve route modelling. The huge amount of available data, especially regarding the positions of vessels, makes it possible to get a better insight into the routes vessels take. Van Dorp and Merrick (2009) use this possibility and explain how they deal with errors and inaccuracies in the data. Although this improves the modelling of the maritime network, it does not give more information regarding the exact vessel behaviour (e.g. the interaction with each other).

3.4.2 Vessel movement and interaction

With AIS data, the exact position, heading and speed of a vessel are known at almost every moment. This makes it theoretically possible to do statistical analyses on vessel behaviour. The most important characteristic of this method is that it does not try to simulate human behaviour, because the vessel behaviour is already known from the AIS data analysis.

Different errors that occur in the messages are a problem when using AIS data for the modelling of vessel behaviour. As said in chapter 2, most errors concern the Destination, ETA, Draught, Vessel Type and Navigational Status. For the modelling of vessel behaviour the most important information regards position, speed and heading. These fields contain fewer errors. However, it must be said that information like destination and navigational status can make the mapping of the nautical traffic much easier.

One of the models that try to improve the modelling of vessel movements is the numerical navigator. Barauskis and Friis-Hansen (2007, p. 5) conclude that 'Studies will also be initiated that by use of observed AIS tracks shall adjust and validate the way the numerical navigator operates the vessel traffic in an area'. By adjusting the Bayesian networks that describe vessel behaviour, they want to train vessels ('agents') with the results of AIS data analyses. So far no evidence has been found if this is already done.

Also Mou et al. (2010) use AIS data, to statistically analyse vessel behaviour. The focus of the authors is on the correlation of the Closest Point of Approach (CPA) with vessel size, speed and course. For the assessment of risks, they use a dynamic method based on SAMSON (see section 3.5 for explanation of this maritime model).

3.4.3 Conclusions

AIS data are potentially a very interesting source of information for maritime models. Nowadays it is mainly used in maritime modelling for the derivation of the traffic input, such as inter-arrival time. AIS data is also used to get a better insight into the nautical network that has to be modelled. In restricted waterways, like ports, less use is made of the data. This will be mainly due to the fact that in these areas a lot of vessels are present that are not AIS equipped.

There is a clear potential to use AIS data to obtain more detailed insight in vessel behaviour. Errors in AIS data mainly occur in fields that are useful, but not indispensible for this purpose. Therefore they can make the required AIS analysis more difficult, but certainly not impossible. No extensive use is made of this possibility however so far. There are plans to include it in the numerical navigator model, but the status of this model is unsure.

3.5 Existing maritime models

One of the goals of this thesis is to see if statistical equations that describe vessel behaviour, can be implemented in currently existing maritime models. This section gives an overview of different models that exist nowadays. Four of them are elaborated a bit more into detail: SAMSON, HarbourSim, MARTRAM and Dymitri.

These models are chosen, because they give a good insight in the range of models that is used at the moment. SAMSON clearly is a type I model, that does not simulate (individual) vessel movements. Dymitri is at the other side of the spectrum, as in this model the vessels are simulated and have a large freedom to manoeuvre. The 4 models are also chosen because they are 'proven technology'. All of them are working and have been used in several studies.

3.5.1 Characteristics

Results of the AIS analysis should include information concerning the vessel path and vessel speed, but also the influence of external influences like wind and currents. Besides this, it is also tried to obtain insight in the process of interaction when two vessels encounter each other. One of the research questions is to see if the obtained behavioural rules can be implemented in a currently existing model. This section describes the characteristics that are needed to do so.

Type 1 - Nautical infrastructure
 Describe vessel distribution over a cross section over the waterway.
 Describe the vessel speed distribution over and in a cross section over the waterway.
Type 2 - Vessel related characteristics
 Distinguish between static characterics as vessel size and vessel type.
 Distinguish between dynamic characteristics, for example vessel destination.
Type 3 - External circumstances
 Take external influences like wind, current and visibility into account.
Type 4 - The interaction with other vessels
 Ability to include deviation from the predefined path and speed because of interaction with other vessels.

The first type is important as the vessels will have a 'natural deviation'. This means that two vessels that have exactly the same characteristics and are both subject to the same external influences, will not choose te same route and speed. This is for example due to internal circumstances, like the training, experience and preferences of the captains of the vessels. This means that models, if they want to implement the behavioural rules, should not fixate the vessel location at one point in the cross section over the waterway. Also for the vessel speed it should be possible to describe a natural deviation from the average.

The second type handles the influence of the vessel characteristics. The vessel path and speed need to have a certain distribution over a cross section in the waterway, as explained above. This shape and location of this distribution might however very well be dependent on the vessel characteristics. A model should therefore be able to make a division in vessel classes. These classes should include vessel and vessel speed distributions over a cross section in the waterway, different for each vessel class.

The third type indicates that external influences should be taken into account. This is can be done similarly as the type handled above. External influences can alter the vessel path and speed and a model should be able to cope with those changes. Different from type two is that this one does not describe the average, general behaviour of a certain vessel class. In contrary, external influences can sometimes lead to very divergent vessel path and vessel speed. Although only a limited number of vessel tracks will be that different, it is important for a model to be able to describe them.

The last type concerns the interaction between vessels. This is the most complicated issue, as this implies a deviation from the predefined vessel path and vessel speed. Vessel classes and -to a lesser extent- external influences are constant during the examination of a certain vessel track. Interaction with other vessels is completely in contrast with this, as it can happen at almost any point in time and space. Next to this, there are a lot of different manners in which an interaction influences the path and speed of the vessels involved. This depends for example on the type of interaction (e.g. head-on, overtaking), the type and size of vessels involved and the location on the waterway. To simulate the interaction sufficiently, vessels should have a lot of freedom to manoeuvre and deviate from their path and speed.

3.5.2 SAMSON

SAMSON is a model for the risk assesment of nautical transport at sea. It evaluates the risk effects of changes in for example shipping routes and offshore constructions. The model divides the vessel accidents that are considered into different types, for example collisions, fire and stranded. SAMSON is a Type I model, in which the causation factor (which is called the casualty rate in SAMSON) is based on historical data. This means that it does not simulate nautical traffic. The model focusses on the calculation of risks at sea, but by adjusting the casualty rate also port areas can be examined. (Bolt, 2006)

SAMSON is tested to the 4 types mentioned in the previous section. The characteristics of type 1 are partly met by the model. The vessel distribution over the waterway is clearly included. This can be seen from Figure 3.4, which is an example of how this type of models determines the collision risk. It is clear that the distribution over the waterway is taken into account. Also the vessel speed is included; with a small adjustment the distribution of the vessel speed over a cross section in the waterway is implemented as well.

The influence of the vessel characteristics is also present in the model, as different vessel classes are distinguished. The distribution over the waterway is also different for the several vessel classes. The external influences are also taken into account. It is however difficult to include the influence of some situations with extreme external circumstances, as SAMSON is not meant for the investigation of individual vessel behaviour. A similar problem arises when looking at the possibility to model interaction. SAMSON is not a simulation program and therefore it is not possible to include a detailed description of the interaction between vessels.

3.5.3 Harboursim

Harboursim is a simulation model used by the TU Delft, mainly to determine waiting times. The model focusses on port areas and describes the nautical infrastructure by fixated waterways. Some characteristics are assigned to these nautical lanes, for example the number of vessels that can sail in one lane at the same moment. The model also includes the service time of vessels, which makes it possible to derive capacity and waiting times.

In HarbourSim, the vessels sail in a certain lane and do not deviate from this. Inside the lane there are also no different paths a vessel can take. There is also no ‘natural deviation’ in vessel speed. The issue from type 1 are therefore not dealt with at the moment. It might however be possible to include this in the model, by calculating vessel paths for every vessel that is created. These paths can then be made dependend on the vessel distribution over the waterway. The same can be done for the vessel speed. This is however a major mutation of the model.

The second type is partly met. There is a clear distinction in vessel classes in the model, but this distinction is mainly used for the difference in servicetime and destination. This is very logical, as the goal of this program is to calculate waiting times. If, following from issue one, individual vessel paths are included in the model, it should not be too complicated to include the influences of vessel class differences as well. The same is true for issue three, which can potentially be implemented.

The interaction with other vessels is handled in the current model, but in a very limited way. It consists of behavioural rules whether a vessel can enter a certain waterway segment. This depends on the presence of other vessels in this segment and the maximal permissible number of vessels in that specific segment. It does not include any deviations from the vessel path. To include this, a very large mutation of the model should be made.

3.5.4 MARTRAM

MARTRAM (Marine Traffic Risk Assessment Model) is developed and used by Royal Haskoning for as well risk assesments as capacity studies. It can simulate nautical traffic in different areas, in which for every new area the nautical infrastructure should be implemented in the model. The construction of the infrastructure in the model can be done by adding nodes and connecting segments. During a simulation run the number of encounters is counted, which is a measure for the nautical safety.

MARTRAM does include a distribution over the waterway. Every vessels maintains a fixed distance from the centerline of the navigation channel. This distance is randomly picked from an assumed distribution of the vessels over the waterway. Also the vessel speed has some variation, as the model keeps 10% variation around an inserted value. The model does therefore certainly keep up with the requirements of type 1.

The characteristics of issue 2 are clearly met as well, as different vessel types are distinguished in MARTRAM. For these vessels, the characteristic dimensions, speed and vessel safety domain can be set. So, a clear distinction in vessel classes is made. It is however unsure if this classes also have different distributions over the waterway, which should be a possibility in the model. Type 3, the influence of external circumstances is not included in the model. Because there is already a distribution over the waterway and a deviation in the vessel speed, it should not be a large step to include this in the model.

The interaction with other vessels is to some extent present in the MARTRAM model. If a vessels detects another vessel in his 'observation domain' (which is 5-10% larger than the safety domain), it makes a collision avoidance manoeuvre. This consists of a speed reduction, while it maintains its course (Pimontel, 2007). This is not enough to give a detailed insight in real vessel behaviour during an interaction. It is however a good starting point; most important addition is the possibility to deviate from the predefined path.

3.5.5 Dymitri

Dymitri, owned by British Maritime Technology limited, simulates the nautical traffic with the main goal to indentify collision and grouding risk. The model is based on an autonomous agent simulation of the marime traffic. Also the human element is modelled, by using (Fuzzy) technology that simulates the human brain. The vessels have a large freedom to manoeuvre. The incident risk is based on the number and nature of avoidance actions that have been undertaken during the simulation run.

The model complies with type one, as there is a lot of freedom to manoeuvre for vessels in the model. Dymitri is however not based on specific vessel distributions over the waterway, but on the individual behaviour of vessels. This behaviour is based on the simulated decisions made by the vessel's first mate. This is a different approach than the statistical which is used in this thesis. There is however no doubt that the vessels do have some distribution over the waterway.

In Dymitri it is possible to set different ship types and size classes. Also external influences can be included. Both the vessels classes and the external circumstances influence the way in which the vessels (the autonomous agents) sail. Types 2 and 3 are therefore clearly met by the model. The interaction between vessels is also simulated by Dymitri. The distance at which the interaction starts is found from mariner reviews and digital radar assessment. The interaction itself is driven by the Fuzzy logic that determines the mariners decisions (Bolt, 2006).

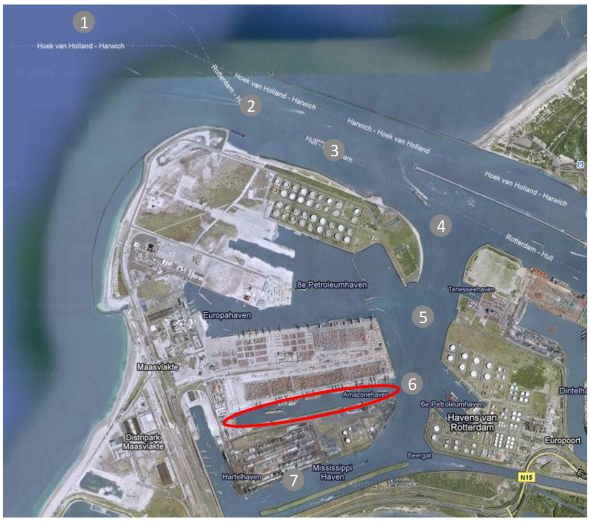
3.5.6 Conclusion

Maritime modelling programs can be divided in two groups: Geometric models and the maritime traffic simulation programs. The geometric model is an analytical calculation, which uses geometric distributions over the waterways to derive nautical safety. MTSPs simulate the individual vessels and their behaviour, to different extents. In some simulation programs vessels follow predefined tracks and are barely allowed to change speed or course in order to prevent collisions.

Other simulation programs try to simulate the vessel behaviour more in detail. It is however very difficult to do so, because this behaviour depends greatly on the decisions humans make, the human factor. There are several possibilities present to deal with this. Some solutions aim to simulate the human brain. This is mainly done by fuzzy technology and -to a lesser extent- by Bayesian networks. Other solutions try to bypass the problem of simulating the human factor, by deriving simple rules where, in practice, most vessels obey to.

In both types of maritime models AIS is used, but in a very limited way. If AIS is used, the main purpose is the derivation of traffic input or to increase the understanding of larger traffic patterns. At the moment, some attempts are made to use AIS for the analysis of individual vessel behaviour, but no clear results of this are yet found.

Chapter 4



Case study set up

4 Case study set up

This chapter explains the set up of the case study done in this master thesis. The aim of this study is to obtain more insight into the vessel path and vessel speed and how this is influenced by different factors. In the end, the results are generalised: generic rules are formulated to describe vessel behaviour in a port area. In this chapter, it is explained how the choice for this specific location was made and what the local characteristics are.

4.1 Approach case study

The goal of the case study is to describe the exact path vessels take and their corresponding speed. The results should be formulated in such a way, that they are general applicable and can be used as input for a maritime model. Therefore the case study aims to derive general rules regarding vessel path and vessel speed. It is important that the obtained set of rules is sufficient to reliably describe a vessel's path and speed in a maritime model. To do so, the different rules should comply with the following issues:

1. Describe the spatial distribution of vessels in a certain cross section;
2. Describe the lateral vessel speed distribution of vessels in a certain cross section;
3. Describe the vessel speed distribution on a certain location;
4. Take into account that the 3 distributions mentioned above depend on:
   a. Vessel type;
   b. Vessel size;
   c. Vessel heading / destination;
   d. Type of waterway segment (straight / bend)
   e. Width of the (for that specific vessel type and size) navigable waterway;
   f. Wind speed and wind direction;
   g. Current speed and current direction;
   h. Visibility;
   i. other external influences;
   j. Interaction with other vessels.
5. Describe the mutual dependence between two spatial successive distributions (to connect the different cross sections, in order to assemble an individual vessel path and correct speed development)

It can be seen from the list that the rules do not try to describe decisions made by people that are steering the individual vessels. By applying statistically derived distributions this is bypassed; only the **results** of this behaviour are formulated. In this case study not the complete list of issues mentioned above is handled fully. First, only container vessels are investigated as a vessel type. This is because only this type of vessels visits the location chosen in the case study (see 4.2). Second, no other external influences (e.g. waves, rain) are investigated. This is because -in a port area- those influences are assumed to have a small influence on the vessel path and speed compared to the other external influences (wind, current and visibility). Third, the interaction between vessels is not handled in this thesis. The results from the case study can however be used to investigate the interaction. An illustrative example of this is given in section 9.

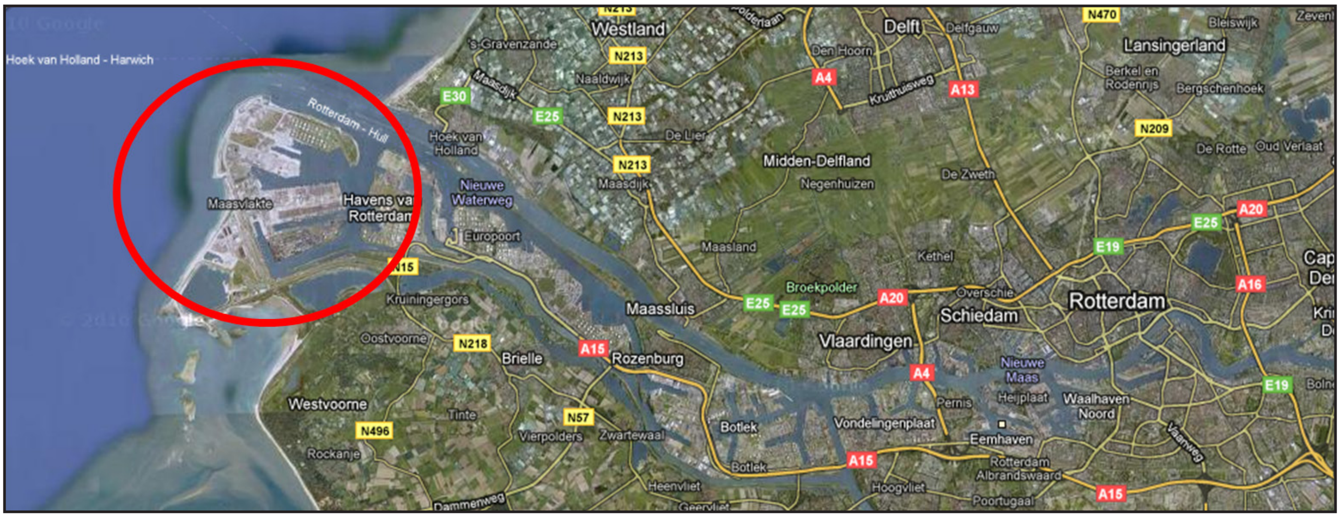


Figure 4.1 Overview of the port of Rotterdam, the Maasvlakte I is indicated by the red circle; source: Google Earth

4.2 Location

In the case study, it is tried to derive the general rules as described in the previous section. Therefore the location should comply with some conditions following from the issues listed before. At first, enough data must be available to derive the cross sections mentioned (issues 1-3). This means that the large majority of the nautical traffic that visits the chosen port location should be equipped with AIS. Next to this, the traffic image should not be too much disturbed by vessels that do not carry AIS (e.g. inland vessels). Another point of interest is the required variety in vessel size, to handle issue 4.b. Different types of waterway segments should be present in the path towards the terminal as well (issue 4.d). It is also preferable that a lot of interaction between vessels is to be expected on this path (issue 4.j).

After deliberating these conditions, the Amazonehaven is chosen as the case location. Figure 4.1 and Figure 4.2 show the location of the Amazonehaven in the port of Rotterdam, at the 'Maasvlakte I'. The vessel paths that will be investigated are the tracks from North Sea to the Amazonehaven and the other way around. Below, this is elaborated more into detail, together with a more into depth explanation why this location suits the predefined conditions.

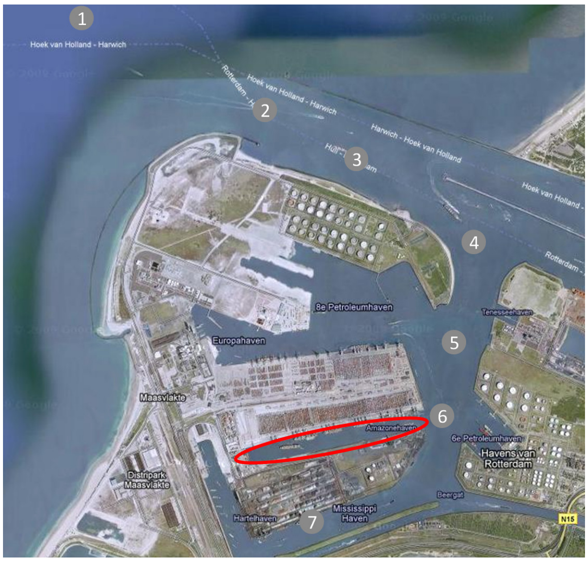


Figure 4.2 Overview of Maasvlakte I, the Amazonehaven is indicated by a red ellipse; source: Google Earth

When vessels coming from the North Sea visit the Amazonehaven, they cross several interesting locations where interesting vessel behaviour might be expected. Shortly before entering the port of Rotterdam in the Maasmond, a pilot embarks most vessels (1). After this the vessels come to sail between the northern breakwater and the Maasvlakte I (2). These offer protection from currents and waves and vessels will have to adjust their behaviour to the changed external influences.

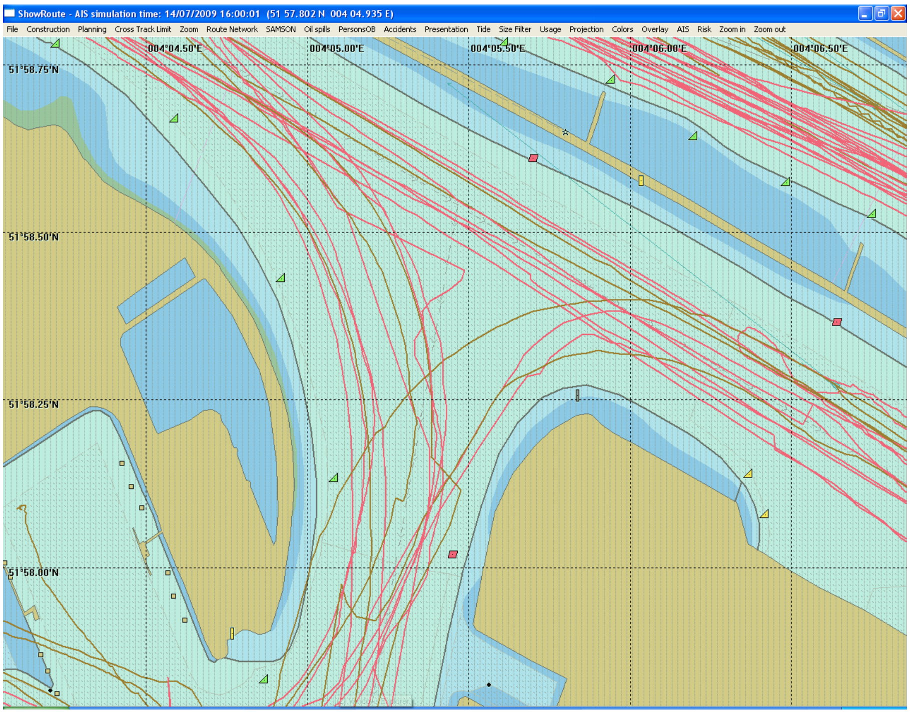


Figure 4.3 Plot of the vessel tracks at the entrance of the Beerkanaal on 14 July 2009, between 10:00 and 16:00 hours.

Every (seagoing) vessel that visits the port of Rotterdam eventually has to sail through the Maasmond (3). Therefore this is a busy waterway in which it is likely that vessels have quite some interaction with each other. This is also the place where tugs fasten to most (bigger) container vessels, a process that can influence vessel course and speed. After the Maasmond, the vessels heading for the Amazonehaven take a turn into the Beerkanaal (4). In this bend quite some interactions can occur, because there is a lot of (sometimes

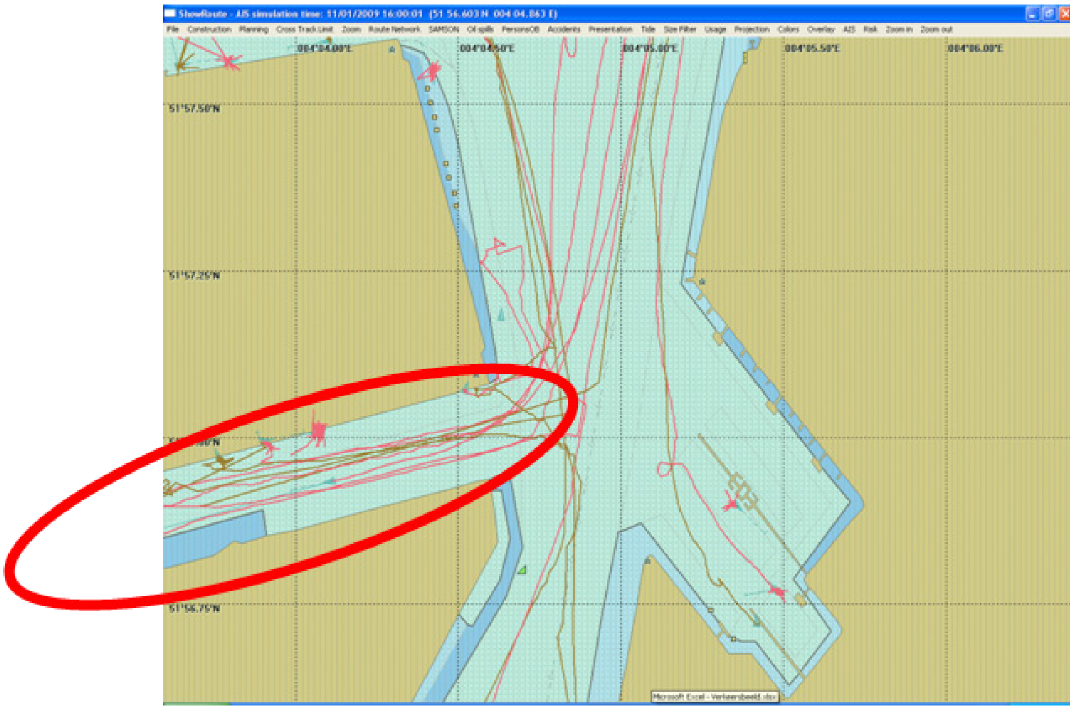


Figure 4.4 Plot of the vessel tracks at the entrance of the Amazonehaven (indicated by the red ellipse) on 14 July 2009, between 10:00 and 16:00 hours.

crossing) nautical traffic present. See Figure 4.3 for a traffic image at this location.

In the Beerkanaal (5) and at the entrance of the Amazonehaven (6) the nautical traffic intensity is lower than in the areas mentioned before. There are however still a lot of vessels that visit one of the terminals at Maasvlakte I, or are aiming for the 'Hartelkanaal'. Interaction will therefore also occur here, for example during a turning manoeuvre of a large vessel-tugs combination in front of the Amazonehaven. Figure 4.4 shows an image of the nautical traffic at this location.

As described above, there are several reasons why the vessel trajectories towards and away from the Amazonehaven are interesting in the analysis of vessel behaviour. Next to the path vessels take, also the variety in size of the vessels that visit this container terminal is a good reason. A lot of large container vessels visit this terminal, because it is easy to reach and the Amazonehaven offers enough depth for deep draught vessels. First of all, this is interesting because in this way the behaviour of the largest container vessels can be investigated. It is very likely they react different on e.g. high wind or currents than smaller vessels.

Next to this, these large vessels only visit the terminal in the Amazonehaven, after which they continue their journey on the North Sea. These are exactly the tracks that are investigated in this case study. Smaller container vessels mostly visit also other container terminals in the port of Rotterdam, tracks that are only confusing and not examined in this study.

Another advantage of the Amazonehaven is that it is located at the most Western part of the port, away from the city centre and the smaller terminals. This is advantageous because the smaller terminals are often visited by inland vessels. As mentioned before (chapter 2) most of these vessels do not transmit AIS messages nowadays. Therefore these vessels can not be seen when looking purely at AIS data. So when such a vessel interacts with an AIS equipped vessel, this makes it difficult to explain the behaviour of the AIS equipped vessel. This problem could theoretically be overcome by using radar images, but it is much more practical to choose an area were less interaction with inland vessels is to be expected.

Most of the advantages mentioned before do also apply for the dry bulk terminal that is present in the Mississippihaven (7). Vessels visiting this terminal do follow largely the same route as the vessels that visit the Amazonehaven. These dry bulk vessels are also in general very large. This terminal is however not chosen, because the number of vessels that visit it is much lower than for the container terminal. This makes it more difficult to make statistical significant calculations. Besides, dry bulk vessels (especially very large ones) are less present in ports all over the world than container vessels. It is therefore more beneficial to formulate generic rules for container vessels than for dry bulk vessels.

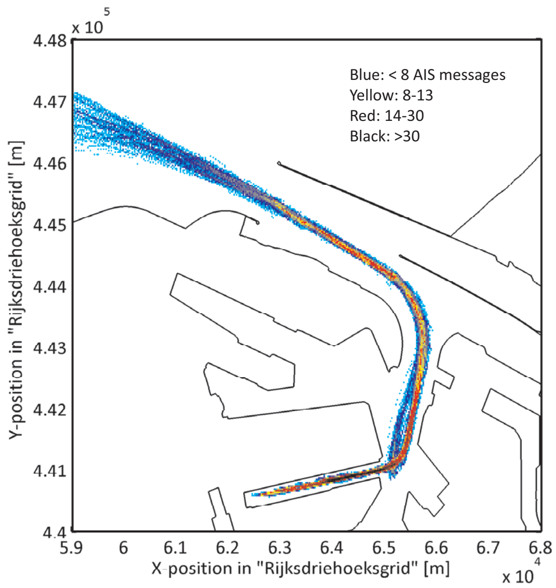
The considerations mentioned above have led to the choice to look at the container terminal in the Amazonehaven. This makes it possible to derive insight in the behaviour of container vessels of different size classes. Due to the large range in size classes also the different influences of wind, currents and visibility can be given a closer look.

4.3 Case study outline

The selected tracks (from vessels that visit the Amazonehaven) are further analysed and information regarding vessel behaviour is obtained from this analysis. First, the vessels are mapped into different vessel size classes. For each of these classes the average path is determined, for as well incoming as outgoing vessels (section 5.3). The average vessel speed is obtained for every size class as well. Also the spatial distribution of vessels over the waterway is calculated for several cross sections over the investigated waterway. Attention is paid to the vessel speed as well, by deriving the speed distributions on certain locations on the average path (Section 5.4).

With the average path and corresponding spatial and speed distributions known, attention is paid to the factors that influence these results. Several factors are investigated: wind, currents, visibility and the interaction with other vessels. First, the influence of the interaction with other vessels is left out of consideration. Several tracks of vessels that were sailing during high winds, currents or low visibility are compared to the average path of vessels from the same size class (Chapter 6). To map the influence of vessel-vessel interaction an example of a situation in which interaction occurred is examined (chapter 7).

Chapter 5



Average vessel path and speed

5 Average vessel path and speed

In this chapter the average vessel behaviour is determined. First, the data sets used for this are described (section 5.1) and their quality is checked (section 5.2). In section 5.3 the influence of the vessel size on the average path and vessel speed is investigated. In section 5.4 the spatial distribution of vessels in different cross sections is elaborated. This section also treats the vessel speed distribution in these cross sections.

5.1 Data sets

With the use of the program ShowRoute[9] a selection of AIS messages is made. The selection is set up by the messages of container vessels that visited the container terminal in the Amazonehaven in February, March, April, July, August, October, November or December 2009. These months are chosen to get information from different seasons. Finally, a total of 4,105,821 unique AIS messages is derived. These are however raw data; different improvements have to be made before the data can be analysed.

The most important operation is the removal of tracks other than between North Sea and Amazonehaven. Especially smaller container vessels cause these disturbing tracks, because they visit different terminals in the port of Rotterdam. Next to the removal of tracks, two other adjustments are made. The first one concerns the transformation of geographical coordinates to Rijksdriehoeksgrid coordinates. The Rijksdriehoeksgrid (RD) is the national grid of the Netherlands. It is used as a basis for geographical indications and files, like Geographic Information Systems. Also the port of Rotterdams infrastructure is expressed in RD coordinates. So, to evaluate a vessels position compared to the ports infrastructure it is needed to recalculate the geographical coordinates to RD coordinates.

The second adjustment is a recalculation of the vessels position, by taking into account the exact antenna position on the vessel. The position of the vessel that is shown in the AIS message reflects the position of the transmitting antenna. This antenna mostly is not positioned in the middle of the vessel; therefore a recalculation is needed to retrieve the correct position coordinates of the vessel. The position coordinates that are finally derived reflect the middle of the vessel. The operations are executed by a Matlab model, which is explained in detail in Appendix D.

After the adjustments to the raw AIS data, 805 different incoming tracks (North Sea to Amazonehaven) and 663 outgoing tracks (Amazonehaven to North Sea) are left. To investigate the influence of the vessel size, the vessels are categorised into five size classes:

1. Smaller than 10,000 Deadweight tonnage (dwt). [10]
2. 10,000 – 40,000 dwt.
3. 40,000 – 70,000 dwt.
4. 70,000 – 100,000 dwt.
5. Larger than 100,000 dwt.

---

9 ShowRoute is a software program, owned by Marin, which can be used to make selections of AIS data. It can also plot selected AIS messages, which makes it possible to replay situations. This is helpful in the judgement of interaction between vessels in chapter 9. It is also possible to calculate other characteristics, like the Closest Point of Approach (used in the CPA analysis in chapter 9).

10 Deadweight tonnage is a measure how much a vessel can (safely) carry. It is the sum of the cargo, fuel, water, provisions, passengers and crew.

The size classes are chosen in such a way that in every data set approximately the same amount of tracks is available. The only exception to this is the smallest size class, in which 2-3 times as much tracks are present. This is done on purpose, because the smallest vessels have a larger freedom to manoeuvre. It is therefore expected that more data is needed before reliable and accurate calculations can be made.

The number of tracks available in each of the 10 different datasets is shown in Table 5.1

Table 5.1 Number of tracks in each dataset

Size Class (dwt)	Incoming	Outgoing
< 10,000	307	250
10,000-40,000	173	109
40,000-70,000	89	98
70,000-100,000	124	132
> 100,000	112	119

5.2 Accuracy of the data sets

The question arises if there are enough data in each dataset to calculate a reliable average vessel path and speed. To answer this question, the average vessel path and speed are first calculated by using only 50% of the available data (the tracks used for this are chosen at random). After this, the same calculation is done, now using 100% of the available tracks. So, the amount of data that is used is doubled. The two derived averages are compared with each other. If there is no significant difference between them, apparently a good approximation of the average vessel path and speed was already given by using only 50% of the available data. In that case the conclusion is drawn that enough data are available to obtain a reliable result.

5.2.1 Accuracy average track calculation

The above described procedure is performed for every dataset. For the calculation of the average path the same Matlab model is used as mentioned before (Appendix D). In this model a grid is applied, with a distance between the grid points (grid size) of 50 meters. This means that every 50 meters the average location in a cross section over the waterway of a vessel within a certain size class is described. The path towards the Amazonehaven is in this way described by 234 data points. When comparing two average paths with each other, the difference at each grid point is determined (Figure 5.1). It should however be remarked that these differences are not independent from each other. For example, a high value for Δ_n makes it very likely also Δ_{n-1} and Δ_{n+1} have high values, because they are all linked to one average path.

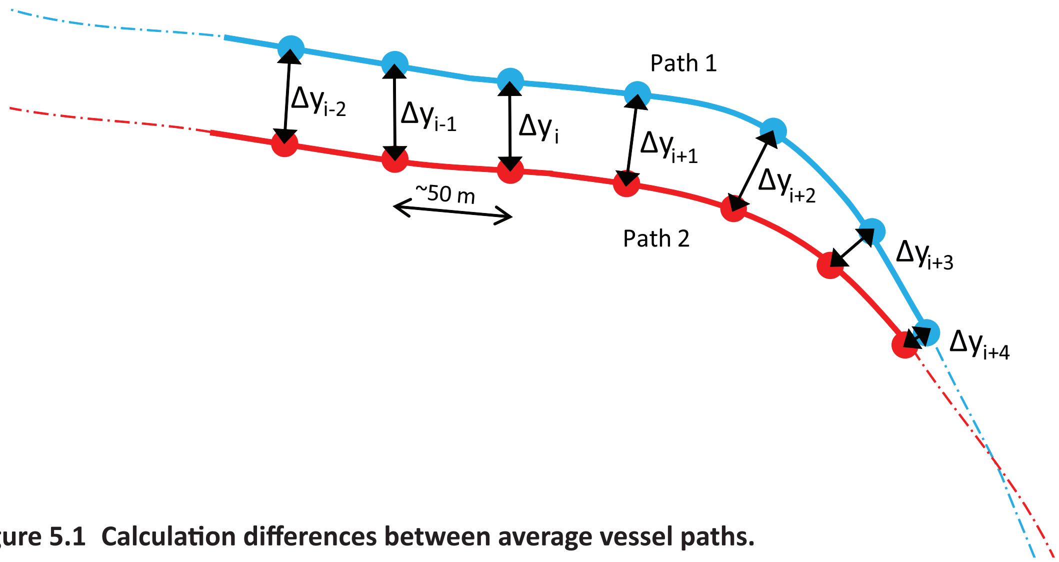


Figure 5.1 Calculation differences between average vessel paths.

From the 234 differences that are obtained, the mean and standard deviation are calculated, see equation (5.1). The mean value and standard deviation of the total of these differences are an indication how well the two vessel paths match. Table 5.2 shows for the different datasets the values of the mean and standard deviation. A negative value for the mean indicates that the path based on 50% of the data points lies, on average, on the starboard side of the path that is based on 100% of the data points.

$$\text{Mean} = \mu = \frac{1}{n}\sum_{i=1}^{n} \Delta y_i$$
$$\text{St.Dev.} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta y_i - \mu)^2}, \tag{5.1}$$
$$\text{where } n = \text{number of tracks}$$

Table 5.2 Comparison of the average tracks, calculated by respectively 50% and 100% of the data.

Size Class (dwt)	Incoming		Outgoing	
	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)
< 10,000	0.5	5.2	-5.2	4.8
10,000-40,000	0.6	9.6	1.1	8.7
40,000-70,000	2.8	5.7	8.4	7.8
70,000-100,000	3.0	6.2	-1.9	5.8
> 100,000	-1.8	10.3	-3.2	4.8

Table 5.2 shows that the maximum mean difference between the compared average tracks is 8.4 meters. The maximum standard deviation is 10.3 meters. These numbers alone are however not enough to draw clear conclusions regarding the accuracy of the data sets. For this a closer look at the outer limits of the differences is needed. By calculating confidence intervals[11] (cdf's) this can be achieved.

11 A confidence interval is the likelihood a parameter is included in a certain interval inside a probability distribution. The confidence limits are the end points of the confidence interval. A confidence interval is always preceded by a percentage, the confidence level, which reflects the likelihood.

To do so, it is needed to set up cumulative distribution functions of the differences, for every data set. An example of such a function is given in Figure 5.2.

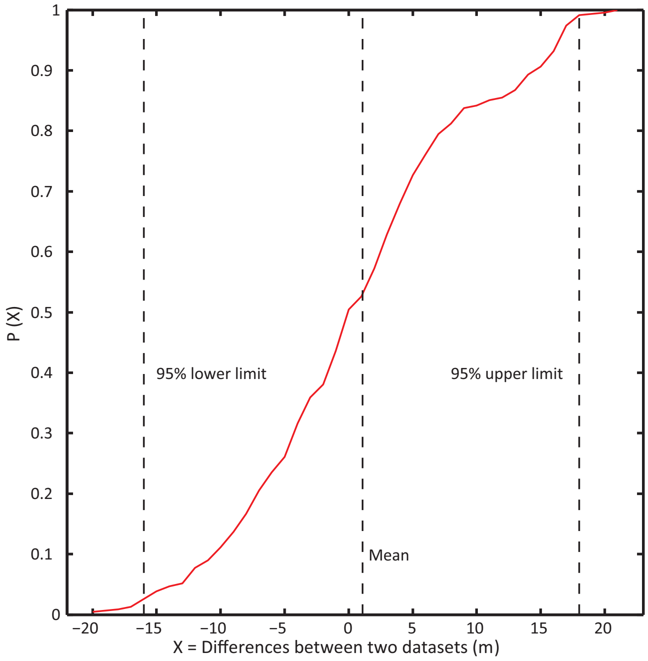


Figure 5.2 The cumulative distribution function of the differences between two average tracks,
Vessel size class <10,000; outgoing.

With this cdf, it is possible to calculate the 95% confidence interval. This means that there is a 95 % likelihood that a random chosen difference between the two average paths is within those limits. In this thesis 95% is kept as a threshold value for the determination of the accuracy[12]. The results are shown in Table 5.3. From this table it can be concluded that -for every size class- it is for 95% certain that the difference between two average tracks is in the interval [-26; 27]. Thus, the accuracy that can be derived by using only 50 % of the available data is ±30 meters at least. In the case study, all data is used and it is therefore very likely that the accuracy is even higher.

Table 5.3 The 95% confidence intervals in meters for the distance between two average tracks of one vessel size class.

Size Class (dwt)	Incoming	Outgoing
< 10,000	[-11; 10]	[-17; 4]
10,000-40,000	[-26; 12]	[-16; 18]
40,000-70,000	[-11; 13]	[-7; 24]
70,000-100,000	[-6; 18]	[-14; 7]
> 100,000	[-15; 27]	[-15; 5]

12 What confidence level is taken as a representative value is subjective and depends on the nature of the study. Most common is however to use a 95% confidence level.

5.2.2 Accuracy average vessel speed calculation

Another important outcome of the calculation of the average track is the average speed. The average speed develops along the vessel path. Values for this speed are therefore calculated at every grid point (once every 50 meters). The differences are computed in the same way as described above. Table 5.4 shows the mean and standard deviation of the differences for the several size classes (incoming and outgoing). The differences in vessel speed are given in percentages, to cope with the fact that the vessel speed ranges from almost zero in the Amazonehaven to around 15 knots[13] just outside the northern breakwater.

Table 5.4 Comparison of the speed of the average tracks, calculated by respectively 50% and 100% of the data. The speed differences are reflected in percentages .

Size Class	Incoming		Outgoing	
(*1,000 dwt)	Mean (%)	Stand. Dev. (%)	Mean (%)	Stand. Dev. (%)
< 10	-2.2	1.2	0.0	1.0
10-40	1.5	2.2	-1.0	1.8
40-70	1.7	2.1	-2.6	1.8
70-100	-2.6	1.7	0.0	2.1
> 100	1.4	3.2	-0.7	1.0

To get an indication of the accuracy that can be obtained in average speed calculations, the 95 % confidence levels are calculated. Table 5.5 shows the results for the different size classes. At the 95% confidence level the speed differences for all data sets are in the [-6.2; 6.3] interval, so ±6.5 %. At 15 knots, which is aproximately the fastest that vessels sail in the observed case area, this is equal to an accuracy of ±1.0 knots.

Table 5.5 The 95% confidence intervals in percentages for the speed difference between two average tracks of one vessel size class.

Size Class (*1,000 dwt)	Incoming	Outgoing
< 10	[-6.2; -0.2]	[-1.1; 2.5]
10-40	[-3.1; 5.5]	[-4.8; 3.8]
40-70	[-4.7; 4.9]	[-5.6; 1.2]
70-100	[-5.4; 0.6]	[-2.2; 6.3]
> 100	[-6.1; 4.9]	[-3.4; 0.5]

5.2.3 Conclusions

The accuracy of the average path that is calculated is at least ±30 meters. The accuracy of the vessel speed is ±6.5 %. Both values are low enough to conclude that enough data is available to make a reliable analysis of the vessel path and vessel speed. The derived accuracies should however be kept in mind when evaluating those two characteristics.

13 1 knot = 1 nautical mile per hour = 1.852 kilometer per hour = 0.514 meters per second.

5.3 The influence of vessel size

To investigate the influence of vessel size, the average tracks of the different size classes are compared with each other. As well the average path that vessels take as the accompanying speed is investigated. This comparison is again done by calculating the mean and standard deviation of the differences between the two average vessel paths and vessel speeds at the different grid points (see Figure 5.1). The goal is to see if there are significant differences between the size classes and, if there are not, which size classes can be brought together.

In Figure 5.3 the average path for outgoing vessels from the smallest (<10,000 dwt) and the largest (>100,000 dwt) size class are plotted. It can be observed that the differences between the two trajectories increase rapidly when the vessels have left the protected port area (Part A). Outside the (northern) breakwater the waterway is much wider and the smaller vessels (with a smaller depth) are less restricted and deviate to the north. Inside the protected port area there are also differences between the two tracks, but these are smaller and less suitable for a visual inspection. An example is in the Beerkanaal, where the smallest vessels sail more to the east. Next to this, these vessels take a sharper curve into the Beerkanaal, when they are leaving the Amazonehaven.

The above described differences make it clear that for a detailed description of the differences it is needed to split the trajectory between the North Sea and the Amazonehaven in several parts. It is especially worthwhile to look separately at the parts outside (Part A) and inside the protection of the breakwater.

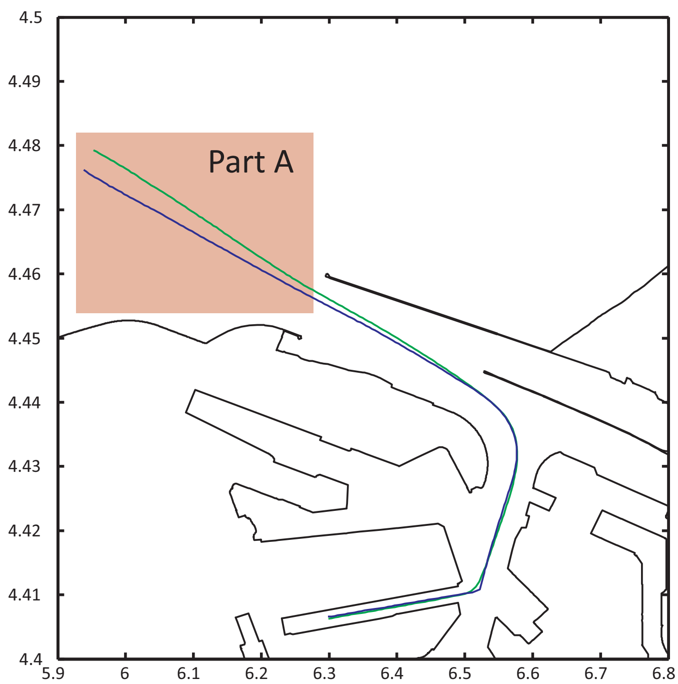


Figure 5.3 Average path for outgoing vessels, size classes <10,000 dwt (green) and >100,000 dwt (blue)

5.3.1 Influence on the average path

To be able to draw valid conclusions, a quantative analysis of the differences is made. The results, the differences between the size classes for both incoming and outgoing vessels, are summarised in Table 5.6 and Table 5.7

Table 5.6 Comparison of the average tracks from different vessel size classes, for incoming vessels. A positive value for the mean indicates that the size class on that row sails more to the starboard side of the vessel class in the column.

Size Class (*1,000 dwt)	10-40		40-70		70-100		> 100	
	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)
< 10	16	11	75	47	84	66	93	77
10-40			59	39	68	59	77	70
40-70					9	27	18	39
70-100							9	14

Table 5.7 Comparison of the average tracks from different vessel size classes, for outgoing vessels. A positive value for the mean indicates that the size class on that row sails more to the starboard side of the vessel class in the column.

Size Class (*1,000 dwt)	10-40		40-70		70-100		> 100	
	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)	Mean (m)	St Dev (m)
< 10	39	41	62	56	83	92	103	114
10-40			23	19	44	53	65	75
40-70					21	37	41	61
70-100							20	26

It can be seen that all mean differences have a positive value. This means that the size class on the row sails to the starboard side of the corresponding class in the column (which is the largest of the two compared classes). To see whether the size classes differ significantly from each other, the accuracy determined in the previous section is used: ±30 meters. To compare the differences with this accuracy, the 95% confidence intervals are calculated (Table 5.8).

It can be seen that all confidence intervals are outside the [-30; 30] accuracy interval. Only the combination of <10,000 dwt and 10,000-40,000 dwt and the combination of 70,000-100,000 dwt and >100,000 dwt, both for incoming vessels, come close to the accuracy interval. So when looking at the whole trajectory, it can be concluded that all size classes differ significantly from each other concerning the path they choose.

Table 5.8 95% confidence intervals in meters for the difference between the average trajectories of two vessel size classes

Size Class	10-40		40-70		70-100		> 100	
(*1000 dwt)	In	Out	In	Out	In	Out	In	Out
< 10	[1; 39]	[-19; 120]	[4; 153]	[-8; 164]	[-5; 251]	[-26; 251]	[1; 245]	[-14; 251]
10-40			[-1; 121]	[-19; 55]	[-8; 219]	[-42; 150]	[-5; 251]	[-31; 244]
40-70					[-19; 103]	[-21; 103]	[-22; 137]	[-11; 192]
70-100							[-10; 44]	[-5; 92]

As said before, the majority of the differences is found in the part of the trajectory outside the protection of the ports breakwater (Part A). It is therefore worthwhile to investigate the differences that occur within the protected port area. This is done by again calculating 95% confidence intervals, now leaving out the part outside the protection of the breakwater (Table 5.9).

Table 5.9 95% confidence intervals in meters for the difference between the average trajectories of two vessel size classes, for the trajectory within the port's breakwater

Size Class	10-40		40-70		70-100		> 100	
(*1000 dwt)	In	Out	In	Out	In	Out	In	Out
< 10	[0; 39]	[-20; 37]	[2; 116]	[-14; 74]	[-7; 104]	[-34; 89]	[-4; 97]	[-24; 88]
10-40			[-1; 82]	[-27; 38]	[-10; 69]	[-47; 53]	[-7; 79]	[-37; 49]
40-70					[-21; 9]	[-22; 17]	[-23; 15]	[-11; 16]
70-100							[-10; 14]	[-6; 22]

Table 5.9 shows that the combinations of the three highest vessel size classes are inside the accuracy interval. The combination of the size classes <10,000 dwt and 10,000-40,000 dwt also gives a small interval, but this is outside the determined accuracy limits. Therefore the conclusion is drawn that the vessel size classes 40,000-70,000 dwt, 70,000-100,000 dwt and >100,000 dwt do not differ from each other significantly. So, when evaluating the path that vessels take, they can be brought together. It should however be kept in mind that this is only valid for the area inside the port's northern breakwater. Outside the protection of the port, every size class should be investigated individually.

5.3.2 Influence on the average speed along the path

Also the average speed is investigated for the combinations of different size classes. This is done in the same manner as for the trajectories above. Again the mean and standard deviation of the differences are calculated. The differences are again reflected in percentages, to obtain the relative deviation of the vessel speed. Table 5.10 and Table 5.11 show the mean and standard deviation for respectively incoming and outgoing vessels.

Table 5.10 Comparison of the average speed from different vessel size classes, for incoming vessels. A positive value for the mean indicates that the size class on that row sails faster than the other vessel class in the column.

Size Class (*1,000 dwt)	10-40		40-70		70-100		> 100	
	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)
< 10	3.3	6	25.6	10.6	29	8.9	26.9	10.6
10-40			23.3	7.6	26.7	5.8	24.7	7.2
40-70					4.2	3.9	1.6	3.5
70-100							-2.8	4.5

Table 5.11 Comparison of the average speed from different vessel size classes, for outgoing vessels. A positive value for the mean indicates that the size class on that row sails faster than the other vessel class in the column

Size Class (*1,000 dwt)	10-40		40-70		70-100		> 100	
	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)	Mean (%)	St Dev (%)
< 10	5.4	12.1	20.8	14.5	28.5	12.7	21.2	18.6
10-40			16.7	7.2	24.6	7.6	17.8	11.2
40-70					9.6	4.1	1.6	6.4
70-100							-9	8.8

It can be seen that for incoming vessels the three largest size classes have a good resemblance (Mean < 5%). Also the two smallest size classes differ not too much. For outgoing vessels the equality is less, but the means of the mentioned size class comparisons are still within 10% of each other. These differences seem however too large to state that there is no significant speed difference. To proof this point, the 95% confidence intervals are derived. Table 5.12 clearly indicates that no confidence interval is within the predefined accuracy interval of ±6.5 %.

Table 5.12 95% confidence intervals in percentages for the difference between the speeds of two vessel size classes.

Size Class (*1000 dwt)	10-40		40-70		70-100		> 100	
	In	Out	In	Out	In	Out	In	Out
< 10	[-4; 11]	[-5; 32]	[12; 40]	[5; 48]	[17; 41]	[14; 54]	[11; 42]	[0; 54]
10-40			[11; 35]	[8; 34]	[15; 36]	[13; 44]	[14; 36]	[5; 42]
40-70					[-3; 14]	[-5; 16]	[-5; 12]	[-6; 15]
70-100							[-13; 8]	[-18; 17]

Figure 5.4 shows an example of the speed development along the trajectory for two size classes: 70,000-100,000 dwt and >100,000 dwt, outgoing vessels. From this figure it becomes clear that there indeed is a significant speed difference between the size classes. It is obvious that the differences do **not** largely occur outside the protected port area, as with the average path. There is a continuous, significant speed differ-

ence. This is also found for the other combinations of size classes. Therefore a splitting of the trajectory into different parts (e.g. inside and outside the port's breakwater) will not lead to a hugely improved resemblence.

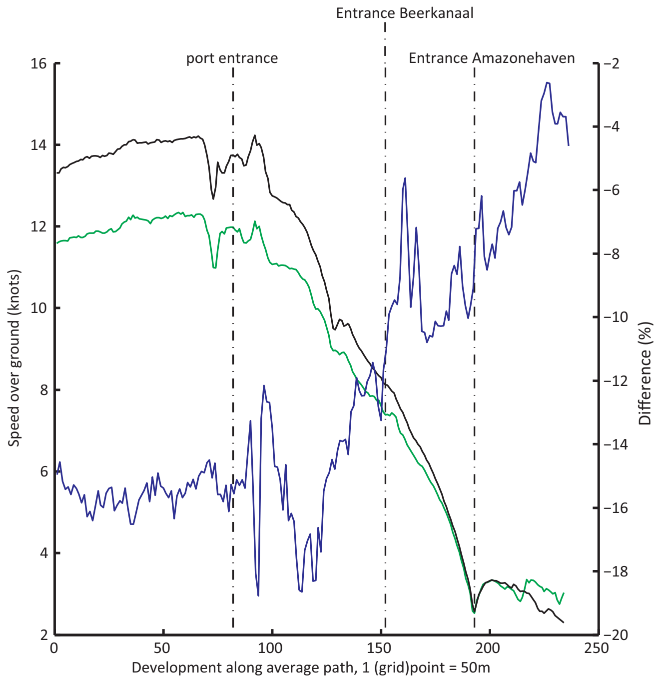


Figure 5.4 Speed development and the relative difference between the tracks (blue). Size class 70,000-100,000 dwt (green) and size class >100,000 dwt (black)

Next to the differences, Figure 5.4 shows some interesting agreements in the speed development. Altough the speed is definitely different, the shape of the two lines is very similar. Most striking is the speed dip close to the port entrance. This dip is present in the graphs of all size classes, but only for outgoing vessels. This is because at this location pilots leave the vessel, by a pilot boat that comes alongside. For this manoeuvre, the vessels have to reduce speed during a short time interval.

Also interesting is the strong reduction in speed at the entrance of the Amazonehaven. This has to do with the fact that these vessels have to make a turn towards the Beerkanaal, after they have left the Amazonehaven. This is especially true for larger vessels, that cannot make this turn when they are sailing too fast. Therefore, the smaller vessel size classes show this dip too, but for them the speed reduction is much less. Incoming vessels also show this speed reduction, but less sharp than the outgoing vessels do.

5.3.3 Conclusions

The vessel size definitely has an influence on as well the chosen path as the vessel speed. Concerning the average path the following conclusions can be drawn. First, the smaller vessels sail to the starboard side of the larger vessel on average. In practice, this means that they sail more close to the shore. In a bend, smaller vessels take a shorter path than the larger vessels, as they make a sharper curve (smaller radius). The three largest size classes show a very good resemblence, when looking at their average path inside the port's breakwater. Outside the breakwater there is however a significant difference. The other size classes behave significantly different in both areas.

The differences between the size classes in vessel speed are larger than the differences found for the average path. No combination of size classes has a resemblence that is within the accuracy interval. Although the three largest size classes show these significant difference, they have a relatively good agreement with each other, compared to the other size classes. In general it can be said that vessel speed decreased when the vessel size increases. An exception to this is size class 70,000-100,000 dwt, which has a lower average speed than size class >100,000 dwt. The most probable reason for this is that vessels from size class >100,000 dwt do use more tugs, which increases their flexibility to alter for example their speed. This makes it possible for them to navigate with a larger speed inside the port area[14].

Although the average paths of some vessel size classes have a very good resemblence, no size classes are brought together into one group. This is because the vessel speeds are significantly different for all size classes. Besides this, the average paths outside the protection of the port's breakwater are also very different from each other.

5.4 Vessel and vessel speed distribution

Next to the average path vessels take, it is important to derive insight into the deviation from this path. In Figure 5.5 a grid has been laid over the determined case area. The dimensions of a grid cell are 25 X 25 meters (0.5 X gridsize). The colors of the plotted points indicate how many vessels has send an AIS message when they where inside that specific grid area. The data used in this figure is from size class 70,000-100,000 dwt, for incoming vessels.

It can already be seen from this picture that most vessels choose approximately the same path, but that there is also a deviation from this path. This deviation is sometimes very large, for example outside the port. On other location the distribution over the waterway is relatively narrow, which is for example the case in the Maasmond. In the Beerkanaal, there is clearly 1 path most vessels take, but some vessels choose a completely different, more westwards, route. This figure makes it clear that it is needed to investigate the distribution over the waterway in different cross sections. In this way, a more detailed insight in the different vessel paths can be obtained.

14 This practical explanation of the results found is derived from an interview with Ben van Scherpenzeel (Port of Rotterdam). Other practical interpretations of the theoretical results found in this thesis are concluded from this interview as well.

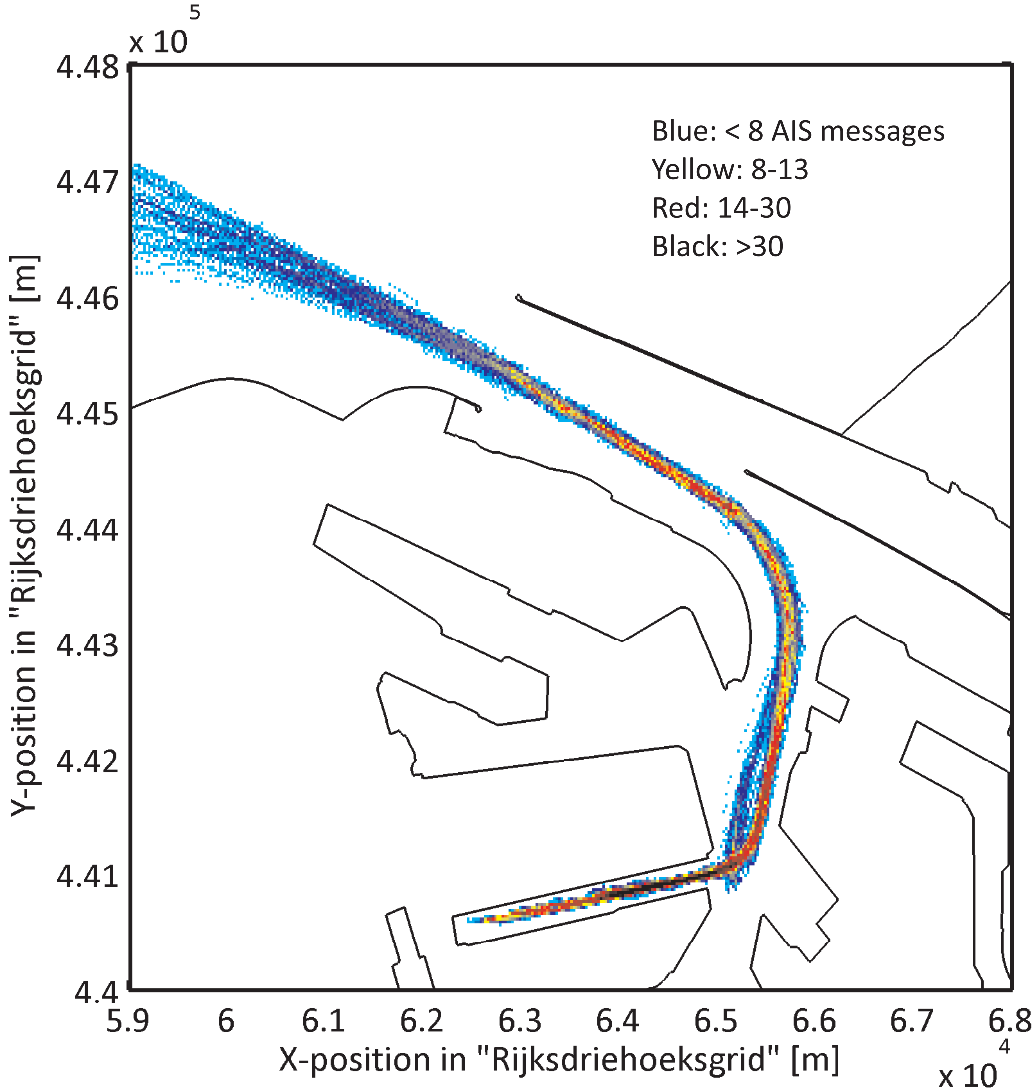


Figure 5.5 Overview of all AIS messages sent from specific areas.
Size class 70,000-100,000, ingoing vessels

At every grid point (each 50 meters) a distribution over the cross section over the waterway is calculated from the available data points. For 4 locations on the incoming and outgoing trajectories the distributions are elaborated further. The locations where this is done are indicated in Figure 5.6

Location 1 is chosen, because it gives more insight into the behaviour of vessels just outside the port. Influences of for example their destination (e.g. Hamburg, Antwerp) might be visible in this cross section. Location 2 shows how the vessels behave in a relatively wide waterway (e.g. how do they prepare before taking the bend into the Beerkanaal). The other locations are chosen because they give insight in how vessels behave in a bend (location 3) and more close to their destination (location 4).

Next to the path that vessels take, also the variance in the vessel speed is important. Therefore the distribution of the vessel speed is also investigated for the cross sections indicated in Figure 5.6. This is done in two parts. First, the distribution of the vessel speed in a certain cross section is determined. Hereafter, this is linked to the spatial distribution by calculating the distribution of the average vessel speed **over** a cross section.

Figure 5.6 Cross sections on the vessel trajectories, which are used to obtain more insight into the spatial vessel distribution and the distribution of the vessel speed. Source: Google Earth

5.4.1 Spatial vessel distribution on cross-sections

Figure 5.7 shows an example of a spatial distribution, derived from the empirical data at a certain cross section. On the X-axis, a value of zero correspondents to the calculated value for the average track. This figure shows therefore the deviation from the average. A positive value for X means that the vessel sails more to the starboard side.

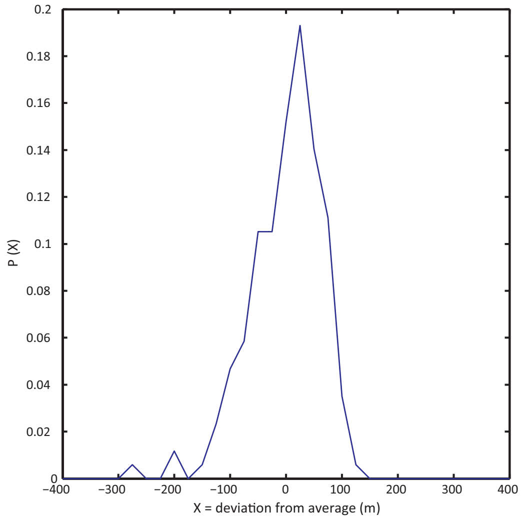


Figure 5.7 Spatial distribution on location 3 (see Figure 5.6), Size class 10,000-40,000; In-coming.

By visual inspecting the different distributions, it seems a normal distribution function would make a good fit. To obtain (besides the visual inspection) a second indication how the data is distributed, the skewness and kurtosis are calculated. The skewness is a measure of the asymmetry of the distribution of the empirical data. A normal distribution is symmetrical; therefore the skewness of this distribution is 0. Values between -1 and 1 indicate that the data are approximately normal distributed. The kurtosis gives an indication of the peakedness of a distribution function. A normal distribution has a kurtosis of 3. In this thesis the kurtosis is corrected by subtracting 3, because in this way values around 0 are to be expected for a normal distribution. This is also known as the excess kurtosis. Equation (5.2) and (5.3) show the formulas for the skewness and kurtosis (Groenveld, 2001).

$$\text{Skewness} = \frac{\sum_{i=1}^{n} (x_i - \mu)^3 * p(x_i)}{[\sum_{i=1}^{n} (x_i - \mu)^3 * p(x_i)]^{3/2}} \tag{5.2}$$

$$\text{Excess kurtosis} = \frac{\sum_{i=1}^{n} (x_i - \mu)^4 * p(x_i)}{[\sum_{i=1}^{n} (x_i - \mu)^2 * p(x_i)]^2} - 3 \tag{5.3}$$

where n=number of datapoints

The skewness and excess kurtosis are calculated for the different datasets at all locations. The results are summarized in Table 5.13 and Table 5.14 respectively.

Table 5.13 Skewness for the different datasets at locations 1 to 4.

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	-0.16	-0.5	-0.64	-0.17	-0.24	-0.26	-0.21	-0.07	0.09	0.02
2	-0.1	-0.44	-0.36	-0.46	0.01	-0.78	-0.05	-0.07	-0.28	0.08
3	-1.24	-0.02	-0.63	0.52	0.09	0.04	-0.17	0.21	0.02	-0.14
4	-0.24	-0.73	-0.07	-0.49	1.06	-0.91	0.32	-0.58	0.94	-0.4

Table 5.14 Excess kurtosis for the different datasets at locations 1 to 4.

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	-0.43	0.12	-0.09	-0.48	-0.5	-0.62	-0.72	-0.79	-0.51	-0.68
2	-0.06	-0.17	0.05	-0.03	-0.4	1.81	-0.36	-0.86	-0.71	-0.98
3	3.07	-0.57	0.44	-0.13	-0.69	-0.4	-0.21	0.28	-0.62	-0.37
4	0.09	0.17	-0.54	-0.12	0.8	1.17	0.06	2.57	0.72	0.75

It can be seen that the skewness is, except for 2 values, always inside the [-1; 1] - interval. This means that, based on the skewness, it can be concluded that the distributions are indeed approximately normal distributed. It is remarkable to see that the skewness for most datasets has a negative value. This means that they have a tail to the left side of the distribution. In practice, this tail is towards the port side of the vessels. This means that there are often some vessels that deviate more to the middle of the channel, whereas the deviation towards the shore is more strictly bounded. From a practical point of view this seems a logical conclusion.

The excess kurtosis is for most datasets around 0. There are however some noticeable low and high values. Most eye-catching is the value of 3.07 for size class <10,000 dwt; incoming at location 3. Figure 5.8 (left) shows the graph of this distribution. This makes it clear that this high value is caused by a relative small peak at the left side of the distribution. Due to the very small standard deviation of this distribution, this peak has a big influence on the excess kurtosis. (which is the comparison between the 4th moment relative to the mean and the 4th power of the standard deviation). This also explains the other values larger than 1. In practice, this small peak is caused by 1 or 2 vessels that sail along this path. The fact that such a small amount of vessels have accidentally sailed at this location is no reason to reject the assumed normal distribution.

Values around and lower than -1 are found as well. These data sets have an excess kurtosis that indicates they are mainly uniform distributed (the excess kurtosis for a uniform distribution is -1.2). Most close to this are the outgoing vessels from size class >100,000 at location 2, with an excess kurtosis of -0.98. Figure 5.8 (right) shows this distribution, which makes it clear that indeed a uniform distributed might be a better fit for this data set at this specific location. By far most data sets do however indicate that a normal distribution is expected to give a good fit. It is therefore tried to do so.

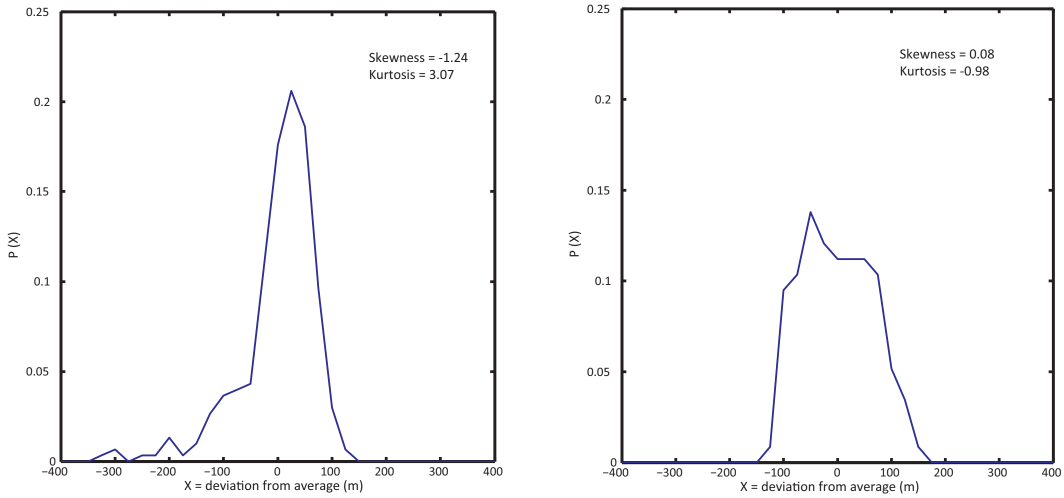


Figure 5.8 Spatial distribution for the vessel size class <10,000; incoming at location 3 (left) and >100,000; outgoing at location 2 (right)

The normal distribution that is used to fit the observed distribution functions is a free truncated normal distribution. It is described by three parameters: the mean (μ), the variance (σ^2) and a scaling parameter (A). The fact that it is truncated means that the distribution is bounded below and above. Normally, a normal distribution is not bounded and values on the X-axis can go to (minus) infinity. In practice, vessels will not deviate that much from their path, because then they are grounded. Of course this might (very rarely) happen in reality, but in such cases other mechanisms than a statistical deviation from the average path will be leading. This is therefore not taken into account in the normal distributions that describe the vessels trajectories.

Figure 5.9 and shows the fitting of a normal distribution on the four predefined locations. The dataset 10,000 - 40,000; incoming is chosen as an example. The values in the upper right corner of the graphs describe the fitted normal distribution (red dotted line). The R^2 values mentioned indicate the goodness of fit for this distribution. The calculation of this parameter is elaborated below.

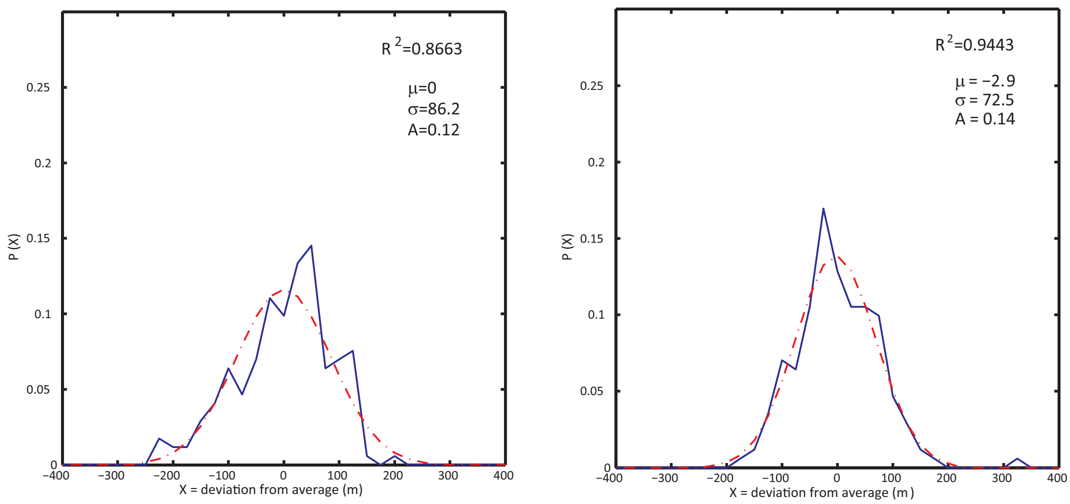


Figure 5.9 The spatial vessel distribution of the vessel size class 10,000-40,000, incoming based on observed values (blue) and the fitted normal distribution (red dotted), on location 1 (left) and location 4 (right).

As said before, the normal distributions are described by three parameters. Next to this, they are bounded by X-values on both sides. Equation (5.4) shows the formula that describes the normal distribution, derived for location 4 (Figure 5.9; right).

$$P_{fit}(X) = A * e^{\frac{-(X-\mu)^2}{2*\sigma^2}}$$

$$\begin{aligned} &X = \text{deviation from the mean in meters} && \quad \textbf{(5.4)} \\ &\text{for } X = [-250;250] \rightarrow \quad \mu = -2.9 \\ &\sigma = 72.5 \\ &A = 0.14 \end{aligned}$$

The skewness and excess kurtosis gave an indication that normal distributions would give a good fit. Now they are derived, the distributions can be tested. Their goodness of fit is first determined by performing a Chi-square test (χ^2). This test determines the degree of agreement between the empirical distribution and the theoretical (normal) distribution. The hypothesis is that there is no significant difference between those distributions. The confidence level (answering the question what is significant) is set on 95%, the same as used previously.

The detailed elaboration of the different χ^2-tests can be found in Appendix E. Table 5.15 shows whether the different data sets and locations pass the χ^2-test (OK) or not (FAIL).

Table 5.15 Results of the χ2-tests for the fitting of the assumed normal distribution to the different data sets.

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
2	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
3	OK	OK	OK	OK	FAIL	OK	OK	OK	OK	OK
4	OK	OK	OK	OK	OK	OK	OK	FAIL	FAIL	OK

Clearly, most distributions have a sufficient fit. There are three data sets that do not pass the χ^2-test. The fails for the datasets 70,000-100,000 dwt;outgoing and >100,000 dwt; incoming at location 4 are not very surprising. The calculated skewness (-0.58 and 0.94) and kurtosis (2.57 and 0.72) for these datasets were already not completely indicating a normal distribution . This is caused by relatively small peaks to the outer limits of the distribution, as explained before. The data set 40,000-70,000 dwt; incoming also fails the χ^2-test at location 3. Figure 5.10 shows the reason for this: a large peak to the right side of the distribution. Such a peak is very unlikely to occur when the vessel distribution is normal distributed. The small peak at the outer left side of the graph is an outlier that is not filtered out by the Matlab code. This outlier does however not influence the outcome of the χ^2-test very much. As almost every data set passes the χ^2-test, it is concluded that the normal distribution is a good approximation of the vessel distribution over a cross section in the waterway.

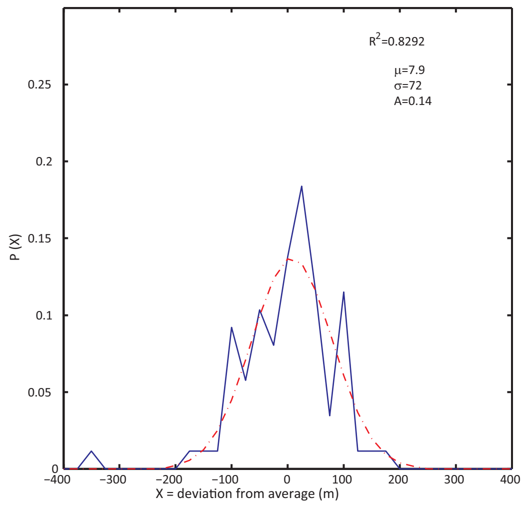


Figure 5.10 The spatial vessel distribution of the vessel size class 40,000-70,000; incoming at location 3

Besides the discussed datasets, it is proven by the χ^2-test-test that every dataset is correctly approximated by its specific normal distribution. Therefore these distributions are used in the following. It is however still interesting to investigate how well the normal distributions fit the empirical data. The χ^2-test-tests have provided an indication for this, but more insight is obtained by calculating the coefficient of determination, R^2. This coefficient depends on the relation between the sum of the squared residuals (SSR) and the sum of the squared errors (SSE). Equation (5.5) shows the calculation of R^2, SSR and SSE.

$$R^2 = \frac{SSR}{SSE + SSR}$$
$$SSR = \sum_{X=1}^{n} (P\,(X) - P(\mu))^2 \tag{5.5}$$
$$SSE = \sum_{X=1}^{n} (P_{fit}(X) - P(X))^2$$

Values of R^2 range from 0 to 1; in which values close to 1 indicate a strong correlation between the two distribution curves. The goodness of fit is therefore dependent on this value. Table 5.16 shows R^2 for all data sets.

Table 5.16 Coefficients of determination (R2) for the spatial vessel distribution

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	0.88	0.85	0.87	0.77	0.83	0.76	0.95	0.76	0.85	0.79
2	0.94	0.85	0.96	0.88	0.97	0.87	0.99	0.91	0.94	0.95
3	0.97	0.82	0.96	0.88	0.83	0.91	0.91	0.86	0.96	0.86
4	0.95	0.96	0.94	0.93	0.94	0.98	0.94	0.97	0.88	0.97

Most datasets have an average value higher than 0.8. For the data sets that did not pass the χ^2-test values above 0.8 are found as well. There are however some interesting patterns that can be observed from the table. Most striking are the lower values that occur for outgoing vessels at location 1 and -to a lesser extent- at location 2 and 3. Figure 5.11 shows the distribution for the size class 70,000 -100,000 dwt; outgoing, at locations 1 (left) and 3 (right). At location 1, the distribution is very wide (σ =123.9 m). Because of this, only a small amount of data points (a few vessels) can already cause a small peak. Next to this, clearly two peaks can be distinguished, both ±100 away from X = 0. This might give an indication that vessels are already adapting their position at the waterway to their destination, towards the South (e.g. Antwerp) or towards the North (e.g. Hamburg).

At location 3, the bend at the entrance of the Beerkanaal, the distribution is much more narrow than at location 1. Another remarkable finding is the fact that the distribution clearly has two peaks. This can be explained by the fact that those vessels have been hindered by vessels coming from the Calandkanaal. Because of this traffic, they had to choose a (less preferable) path more to the innerbend.

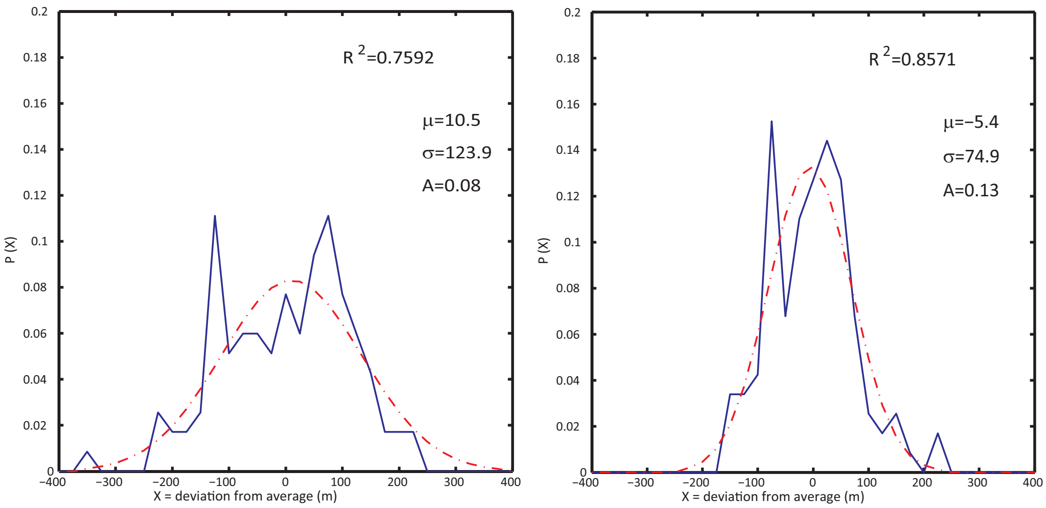
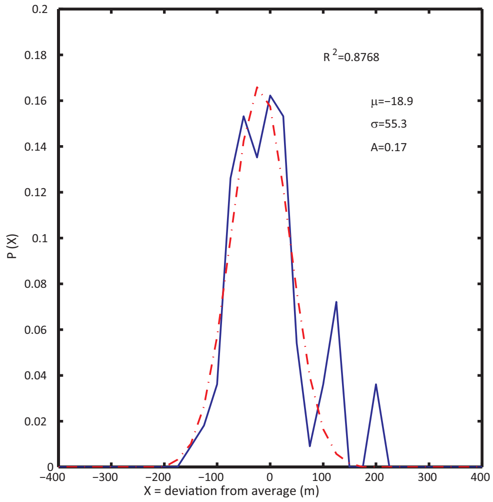


Figure 5.11 The spatial vessel distribution of the vessel size class 70,000-100,000; outgoing at location 1 (left) and 3 (right)

In general, the incoming vessels have a higher R^2 value than outgoing vessels. This is mainly because the outgoing vessels have a wider distribution over the waterway. In practice, they ‘spread out’ more over the waterway depending on for example their destination. There is however one exception to this observation. For the three largest size classes, at location 4 the outgoing vessels are more normally distributed (higher R^2 value) than the incoming vessels.



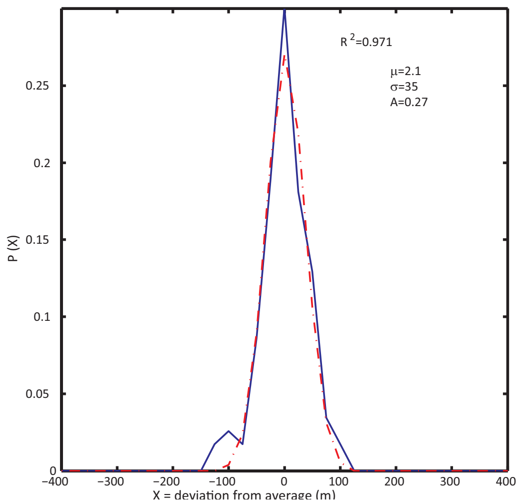


Figure 5.12 The spatial distribution on location 4 for incoming (left) and outgoing (right) vessels from size class >100,000 dwt.

Figure 5.12 shows the distributions at this location for the size class >100,000 dwt, incoming (left) and outgoing (right). The distribution for the incoming vessels clearly shows one peak, but also two smaller peaks to the right side of the distribution. Apparently, a part of the vessels chooses to take another path inside the Beerkanaal. This was already observed from Figure 5.5 on page 43. The presence of these 'preference lanes' is caused by the way the vessels sail into the Amazonehaven. Depending on how they are loaded, vessels have to sail forwards or backwards into the Amazonehaven. When they sail in forwards, what most vessels do, they choose the path closest to the shore (the largest peak in Figure 5.12). This is done because in this way the widest bend can be taken, which is preferred. If they sail in backwards, this is the other way around, as the widest bend is now at the other side of the waterway (see Figure 5.13).

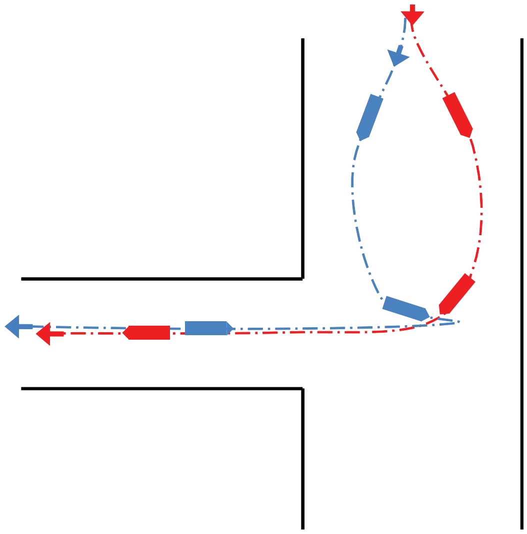


Figure 5.13 The difference in the vessel path when sailing forwards (red) or backwards (blue) into the Amazonehaven.

5.4.2 Vessel speed distribution

Next to the spatial vessel distribution, also the distribution of the vessel speed over the cross section on the 4 predefined locations has been investigated. The accuracy of speed calculations is ±6.5%, which is at a speed of 15 knots equivalent to ±1.0 knot (see section 5.2). The reason for this inaccuracy is the large deviation of the individual vessel speed from the calculated average speed. This large deviation will be investigated more into detail in this section. By calculating the skewness and excess kurtosis, together with performing a χ^2-test it is investigated if the data can again be approximated by normal distributions (see Appendix E).

The skewness and excess kurtosis indicate that a normal distribution is a good indication for almost every dataset. Also the χ^2-test supports this conclusion. To investigate how well a normal distribution matches the data sets, coefficients of determination are calculated. These are shown in Table 5.17.

Table 5.17 Coefficients of determination (R^2) for the vessel speed distribution in locations 1 to 4

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	0.88	0.85	0.87	0.77	0.83	0.76	0.95	0.76	0.85	0.79
2	0.94	0.85	0.96	0.88	0.97	0.87	0.99	0.91	0.94	0.95
3	0.97	0.82	0.96	0.88	0.83	0.91	0.91	0.86	0.96	0.86
4	0.95	0.96	0.94	0.93	0.94	0.98	0.94	0.97	0.88	0.97

It can be seen from the table that all empirical distributions have quite a good fit for a normal distribution. The smallest values are found at location 1, where vessels have more freedom to manoeuvre and to alter their speeds. The highest values for R^2 are found for incoming vessels from the three largest size classes, at locations 3 and 4. At these locations the different vessels speeds have converged more towards each other. This is also shown by Figure 5.14, which show the distribution of the vessel speed in the different cross sections. In the figure also the fitted normal distribution is plotted (discontinuous red line). The three parameters in the right upperside of the figures (μ, σ and A) describe this distribution.

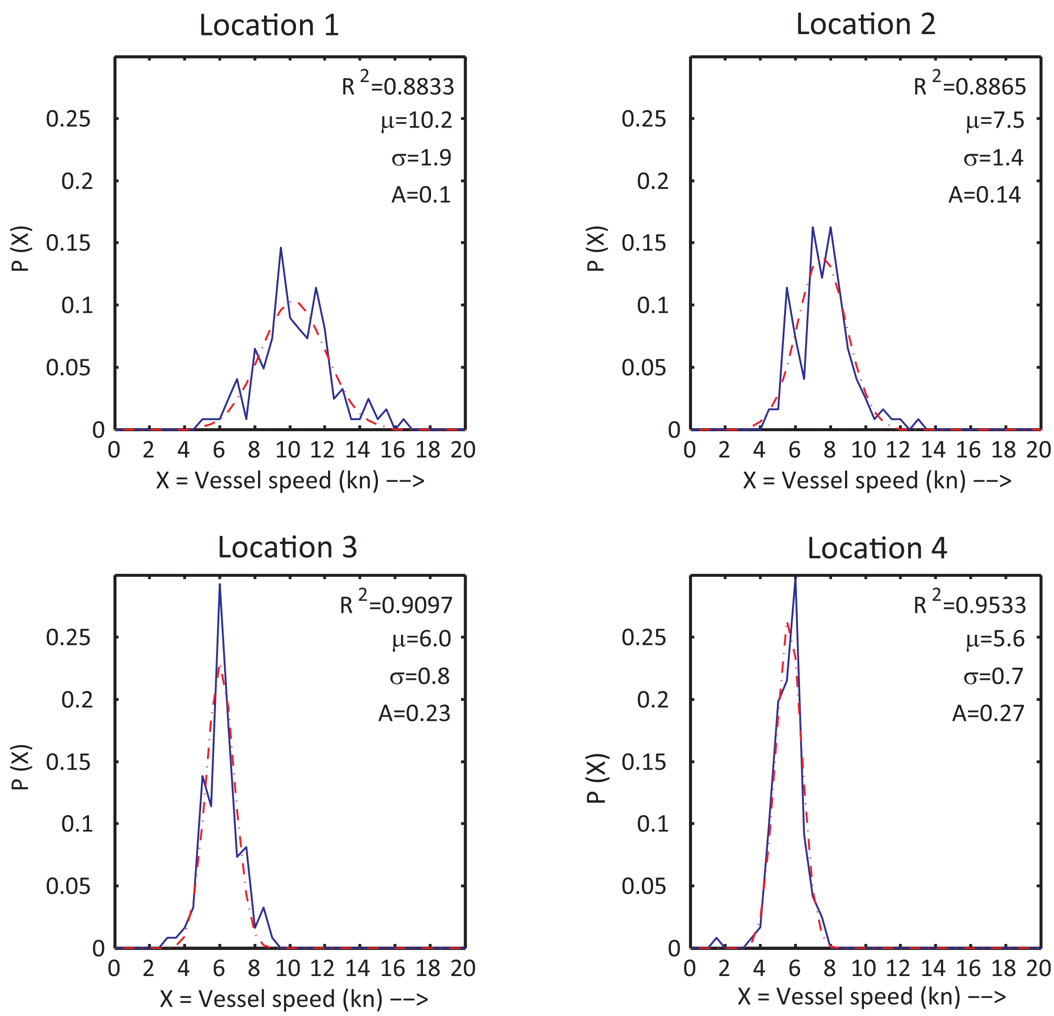


Figure 5.14 Vessel speed distribution on locations 1 to 4, for sizeclass 70,000-100,000 dwt; incoming vessels.

The graphs make clear that the vessel speed has a wide distribution. The width of the speed interval is for the first two locations around 10 knots. It can be seen that this interval decreases when the vessels sails further towards the Amazonehaven. This is also shown by the σ (standard deviation) that develops from 1.9 at location 1 to finally 0.7 at location 4. It can be seen as well that the largest reduction in speed is obtained before location 3, so before the vessel sails into the straight part of the Beerkanaal. The other size classes show the same behaviour, although it must be remarked that for the smaller vessels the deviation (σ) is clearly larger.

Next to the distribution of the vessel speed in a cross section, it is also interesting to obtain insight in the distribution of the vessel speed over a cross section. To do so, graphs are produced that show the average speed on different locations of a cross section. Figure 5.15 gives an example of this, for the cross sections at location 1 to 4, again for incoming vessels from sizeclass 70,000-100,000 dwt.

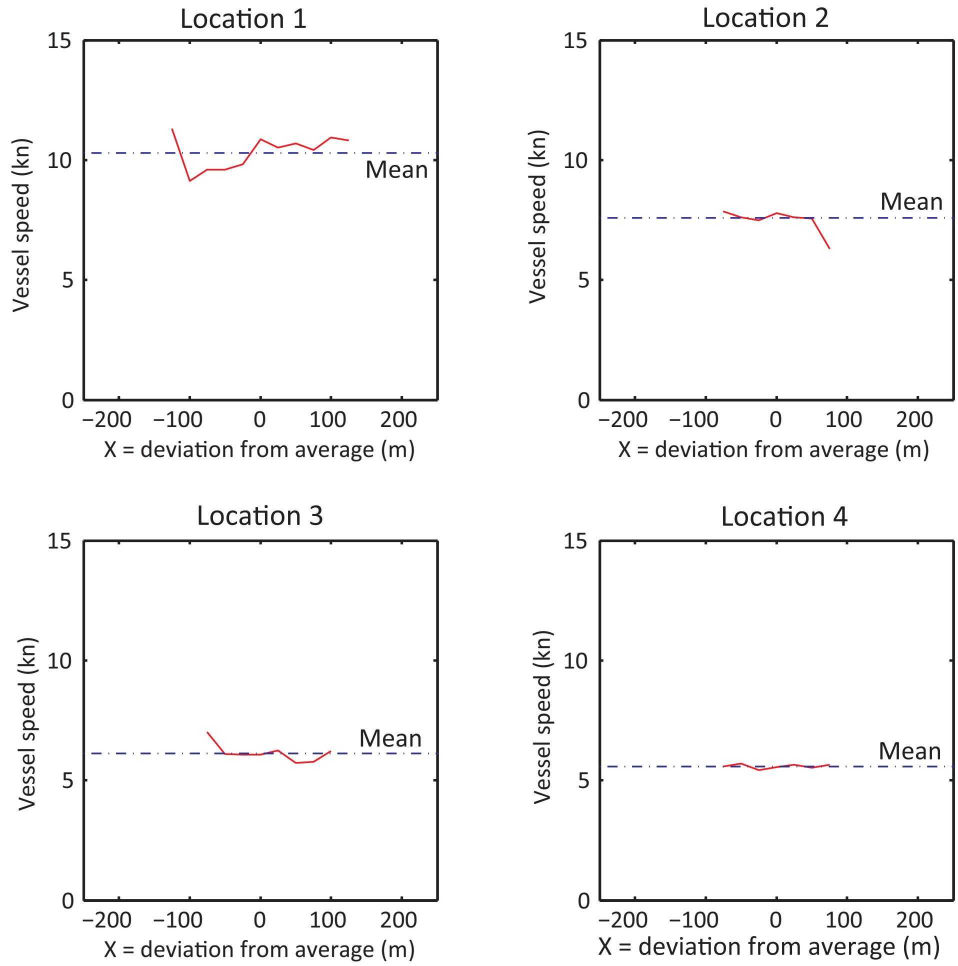


Figure 5.15 Vessel speed distribution over the cross sections at locations 1 to 4, for incoming vessels from size class 70,000-100,000 dwt.

The figure shows that the variance of the vessel speed over these cross sections is not very large. Especially at locations 3 and 4, the vessel speed is clearly independent from the location in the cross sections. For location 2 and -especially- location 1 this image is somewhat more peaky. The irregular behaviour at the outer limits originates from the fact that those points are calculated from a small amount of vessels. This makes those points less accurate and most peaks that occur at the outer limits are therefore not significant. The distributions of the other size classes are investigated as well. Those show a similar pattern as shown in Figure 5.15. For outgoing vessels and for smaller size classes a somewhat more peaky distribution is found sometimes. No proof is however found that the location in the cross section has a significant influence on the vessel speed.

The vessel distributions and vessel speed distributions that are not shown in this chapter can be found in Appendix F.

5.5 Conclusions

In this chapter the average behaviour of vessels, visiting the Amazonehaven, is investigated. The amount of data used makes it possible to draw conclusions regarding average vessel path with an accuracy of ± 30 m. For vessel speed, an accuracy of ± 6.5 % can be achieved. These values are based on a 95 % significance level; this is kept as a treshold value throughout this thesis. The accuracies that are found are accepted as sufficient in this thesis.

It is found that the vessel size clearly influences the average path and speed. As long as the vessels are within the protection of the port's breakwater, the average paths of the three largest size classes have a good resemblence. In the part of the trajctory outside the port's protection, these do however take a significant different path. The vessel speed is different for all 5 size classes.

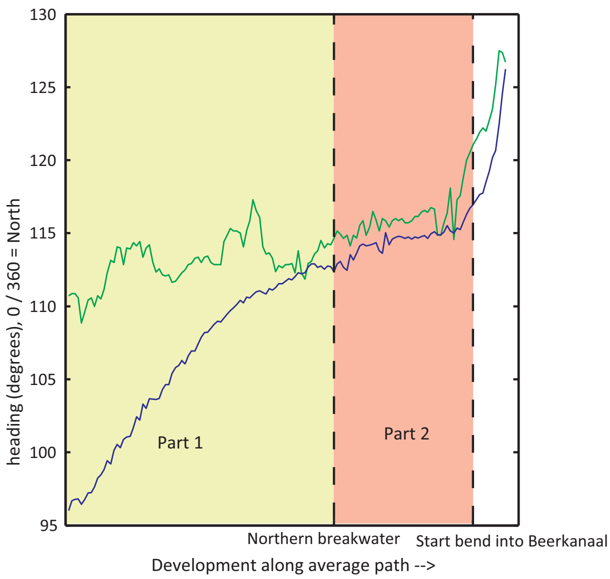
In general, the following can be remarked concerning the influence of vessel size. Larger vessels sail more into the middle of the channel. They also take a larger bend at the entrance of the Beerkanaal. On average, vessels from the largest size class (>100,000 dwt) sail about 100 meters more to the middle than vessels from the smallest size class (<10,000 dwt). This is true for both incoming and outgoing vessels.

The vessel size does also influence the average vessel speed. In general it is true that larger vessels sail slower than smaller vessels. There is one exception to this: vessels from size class 70,000-100,000 sail slower than all other vessels, including the size class >100,000 dwt. The speed difference between both incoming and outgoing vessels from the fastest (and smallest) size class and the slowest size class (70,000-100,000 dwt) is almost 30 %.

The spatial deviation over the waterway is very well approximated by a normal distribution. This is supported by calculating values for the skewness and excess kurtosis of the empirical datasets. A χ^2-test showed as well that the assumed normal distributions are a good approximation. Next to this, R^2 values for the goodness of fit are calculated on 4 different cross sections. These values demonstrate again that the normal distribution is a good fit for the empirical data.

The deviation from the average speed is quite large. In most cross sections the width of the speed distribution can go up to 10 knots, depending on the location and vessel size. The skewness, excess kurtosis, χ^2-test and R^2 values have shown that the vessel speed in a cross section is by a good approximation normally distributed. Also the vessel speed distribution over the cross sections is examined. In these distributions no significant proof is found that the location in the cross section has influence on the vessel speed. It is therefore concluded that the vessel speed is uniform distributed over a cross section.

Chapter 6



External influences

6 External influences

In the previous chapter the average vessel behaviour for different size classes is obtained. This average behaviour is split into the vessel path and the accompanying vessel speed (speed over ground). It is very likely that external circumstances like wind and current have an influence on these characteristics. If this is indeed the case and to what extent, is investigated in this chapter. The factors that are examined are: wind, current and visibility. These are chosen, because the largest influence on the vessel path and speed is expected for these factors. The trajectory between North Sea and the Amazonehaven is, where needed, split into different parts. This makes it possible to draw conclusions regarding the external influence on the vessel behaviour on certain types of waterways. These conclusions are used in chapter 8, for the formulation of generic rules.

6.1 Wind

6.1.1 Split up of the trajectory

For the investigation of the influence of wind, the trajectory between the North Sea and the Amazonehaven is split into two parts. Part 1 ('Maasmond') is between the North Sea and the entrance of the Beerkanaal. Part 2 ('Beerkanaal') is between the entrance of the Beerkanaal and the entrance of the Amazonehaven. The trajectory inside the Amazonehaven is not taken into account, as the manoeuvrability is very limited at this point. It is therefore expected that no significant results shall be found regarding the deviation from the vessel path and vessel speed inside the Amazonehaven.

The Maasmond and Beerkanaal are looked at separately, because the vessel heading is clearly different for these parts (Figure 6.1). This is important, because it means that the wind also works from different directions on the vessels. For example, an incoming vessel that sails in the Maasmond encounters a strong wind from behind. When the vessel enters the Beerkanaal this same wind now comes from his starboard side, through which this wind is likely to have a different influence.

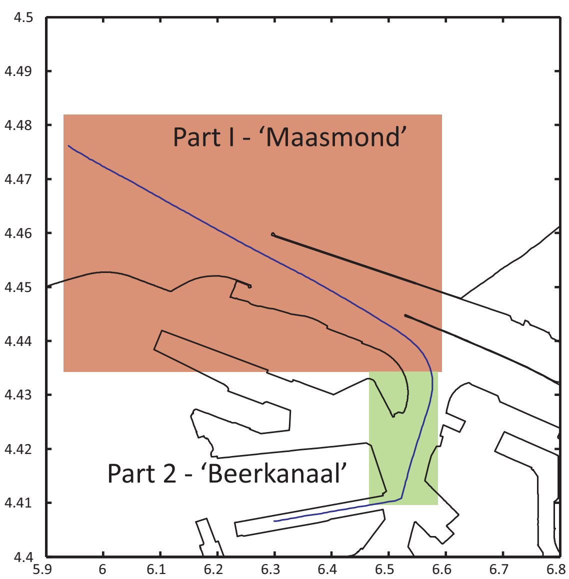


Figure 6.1 Part I and part 2

6.1.2 Wind data

The wind data that is used to map the influence of this external circumstance is obtained from the KNMI[15]. This data set contains the information regarding the wind climate at Hoek van Holland in 2009. Hoek van Holland is seen as a good approximation of the wind climate in the whole case area. Every hour the hourly mean wind speed is known with an accuracy of 1 m/s. Also the mean wind direction is given every hour, with an accuracy of 10 degrees. By coupling the points in time of the individual AIS messages and the wind data set, the wind speed and direction is known for every AIS message.

The influence of wind is examined for different wind directions and wind speeds. The division in wind directions is made, dependend on the vessel heading. For the two trajectories (Maasmond and Beerkanaal) the wind direction is split into four groups: wind from behind, front, port side and starboard side. For the coupling of these groups to the wind data (which is given in degrees), the average heading in the two ports is calculated. Figure 6.2 shows this translation to a specific range of degrees. For incoming and outgoing vessels the same average headings are used, but the range of degrees is exactly the opposite of each other (250º-340º is wind from behind for incoming vessels, but wind from the front for outgoing vessels).

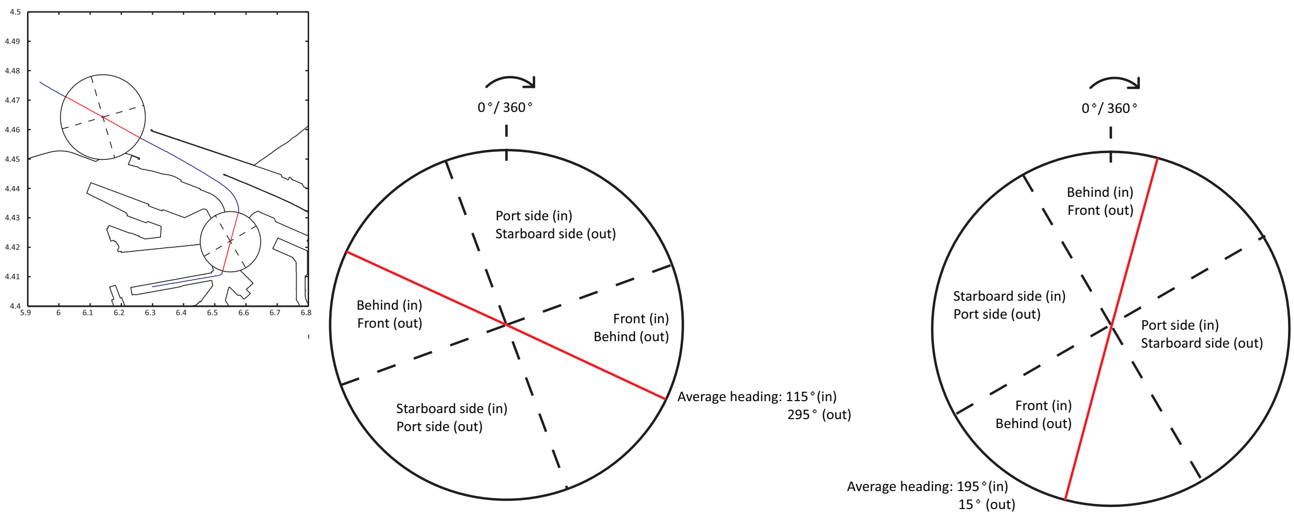


Figure 6.2 Average heading in Maasmond and Beerkanaal

The wind speed is divided into three classes (Table 6.1). By using this division, every wind class has approximately the same amount of tracks. Together with the split up of the wind direction, every vessel size class now is divided into 12 different types of wind influence. It must be remarked that not every of those 12 data sets have the same amount of tracks. This depends very much on the wind direction, as there is for example less frequent wind from the east than from the west.

Table 6.1 Wind speed classes

Wind speed class	Beaufort	Wind speed (m/s)	Wind speed (kn)
I	0 - 3	0 - 5.4	0 - 10
II	4	5.5 - 7.9	11- 15
III	> 5	> 8.0	> 15

15 Royal Netherlands Meteorological institute, the wind data is obtained from their website, www.knmi.nl, at 1 April 2010

6.1.3 Results

For every wind regime and vessel size class, a selection of tracks is obtained. These selections are compared to the average vessel path and vessel speed for that specific size class. This comparison is made for the chosen path as well as the development of the vessel speed along this path. The results are presented in the same way as was done in the previous chapter. An average deviation from the vessel path is calculated. In this, a positive value means that the observed selection sails more to the starboard side of the average path of that specific size class. The speed differences are calculated in percentages. The results are handled separately for the Maasmond and Beerkanaal below.

Maasmond

Figure 6.3 shows the deviation from the average path for the different size classes, when they are subject to crosswind. On the X-axis the cross wind develops from a strong wind from port side to a strong wind from starboard side. The figure clearly shows the quite extensive amount of scatter that is present in the results, mainly because of the natural distribution of vessels over the waterway. The different size classes are also indicated in the figure, to see if significant conclusions concerning the specific classes can be drawn. After a detailed inspection of the figure it is concluded that no significant differences between the size classes can be found. Therefore the size classes are brought together. Also the wind speed is brought together in the three classes derived in the previous section.

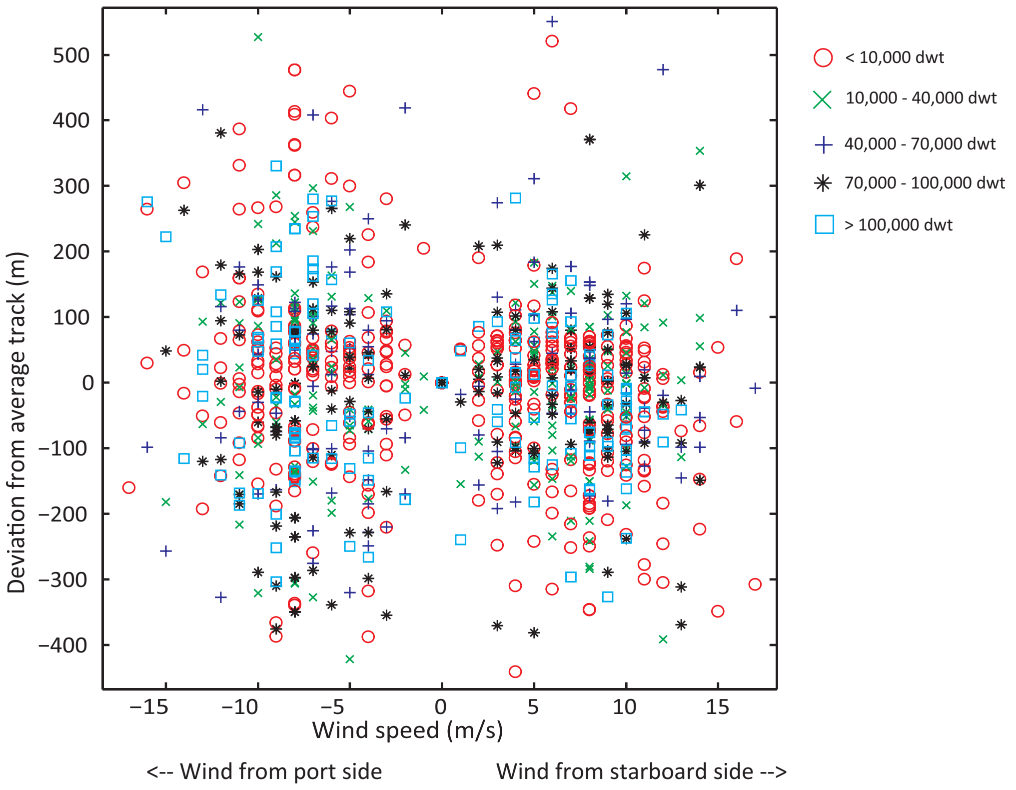


Figure 6.3 Influence of cross wind on the chosen path of individual vessels at the 'Maasmond' trajectory

Figure 6.4 shows a boxplot of the grouped results. The horizontal red line reflects the mean value. The blue box indicates the 25 % and 75 % percentile. The range of results is indicated by the horizontal black line. The red plusses are outliers. Every point that is further away from the mean than approximately 2.7 times the standard deviation is seen as an outlier. This is determined by Matlab. It is obvious from the boxplot that the influence of crosswind is small compared to the natural deviation, which is in the order of hundreds of meters.

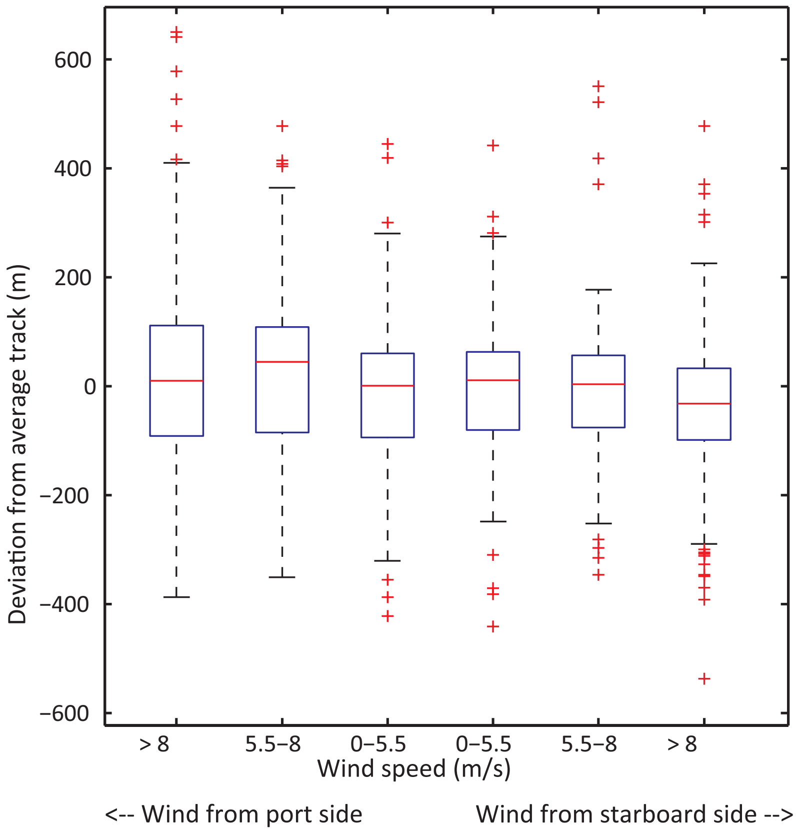


Figure 6.4 Boxplot of the influence of crosswinds in the Maasmond

To obtain a more generic result, a linear function is fit to the mean values derived by the box plot. A linear function is chosen, because this is a simple function and it is statistically difficult to derive a more complex relationship due to the amount of scatter. A visual inspection of the figure supports this conclusion, as a linear function seem to give a reasonable fit. Figure 6.5 shows the linear fit. In chapter 8 this relationship is further elaborated and generalised. In the remainder of this thesis the boxplot and the individual vessel tracks are not elaborated. It is assumed, based on this example that it is correct to do so.

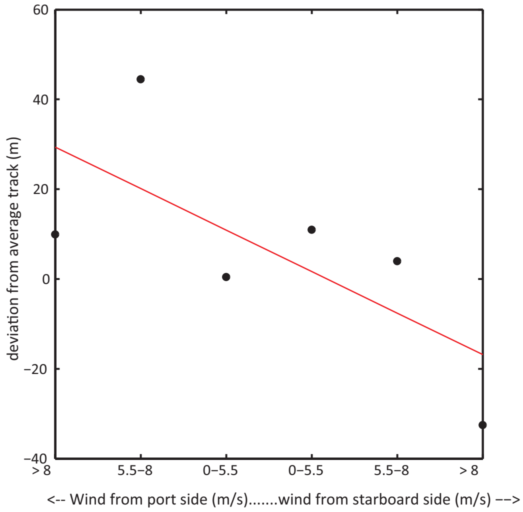


Figure 6.5 Linear relationship regarding the influence of crosswinds in the Maasmond

The vessel speed is affected by crosswinds as well. Figure 6.6 shows the results for the different size classes (left) and their grouped averages (right). The same pattern with a reasonable amount of scatter is present. However, the calculated mean values do not show a linear relationship this time. The vessel speed is clearly smaller at both sides of the graph. In practice this means vessels are likely to sail slower when there is a strong crosswind, regardless if the wind comes from port side or starboard side. The relationship used to describe the calculated mean values, is a second order polynomial.

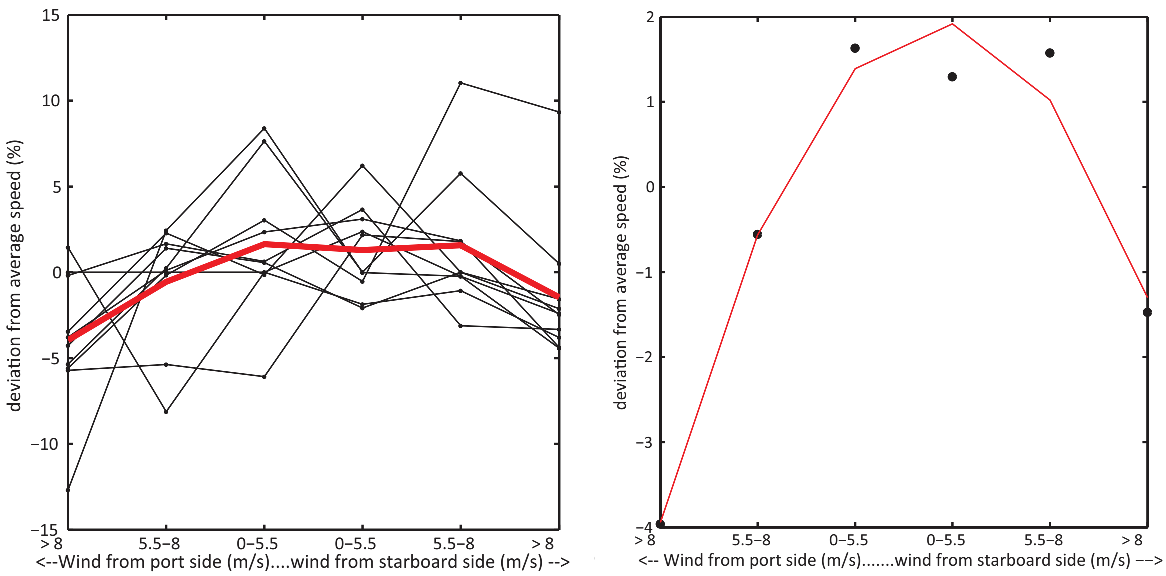


Figure 6.6 The influence of crosswinds on the vessel speed in the Maasmond
The black lines in the left figure represent the results for the different size classes. The red line in the left figure indicates the average, whereas the red lines in the right graph shows the fitted second order polynomial

After investigating the vessel path and vessel speed, it can be concluded that crosswinds definitely have a noticeable influence. For the vessel path this influence is however not very large, especially compared to the natural deviation over the cross section. For large wind speeds the deviation from the average path is in the order of 30 meters. The maximal vessel speed reduction is approximately 4 %. An explanation for both results can be found when looking at the average heading of vessels. Figure 6.7 shows the development of the average heading in the Maasmond for size class >100,000 dwt, for incoming vessels. The blue line is the average for the whole size class. The green line reflects the development of the heading when there is a wind (wind speed > 8 m/s) blowing from starboard side. It can be seen that the vessels obviously have a different heading when they are encountering a strong crosswind.

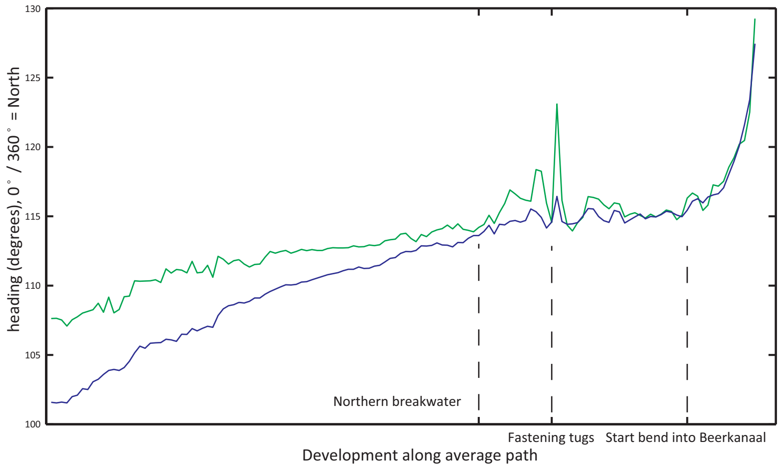


Figure 6.7 Development of the average vessel heading for the whole sizeclass >100,000 dwt and the part of the vessels that encounter strong crosswind from starboard side.

These vessels correct their heading in order to stay on course. If they do not correct their course, the strong crosswind would blow them ‘away’. It can be seen that the heading difference is largest outside the protection of the northern breakwater. When the vessels approach the bend towards the Beerkanaal, the heading difference becomes smaller. This principle is also found for the other size classes, but only for incoming vessels. Outgoing vessels do not, or to a far lesser extent, adapt their heading to the wind circumstances. Interesting peaks in heading are found at locations where tugs fasten. The fastening of tugs sometimes disturbs the transmitting of AIS messages, leading in this case to some peaks in the vessel heading.

The fact that vessels do adapt their heading to keep on course explains why there is not a lot of deviation from the average path. Besides this, it does also explain why the vessel speed decreases if the crosswind speed increases. Because the vessels correct their heading, they are using a part of their engine to counterweight the windforce. So, they are not using their full power to sail ahead; thereby reducing the vessel speed. Another result of the adapted heading is the fact that the path width increases. This can also have an influence on the interaction with other vessels, as the vessel uses more space. This issue is not handled in this study, but it is worthwhile to analyse it in a future study.

Also the influence of wind coming from behind or from the front of the vessel (‘parallel wind’) is investigated. This is done in the same way as the crosswind handled above. Figure 6.8 shows the final results, in which a linear relationship is found and fitted. The wind influence is however much lower than found for the crosswinds. The fact that wind from behind leads to a higher speed feels very logical. The deviation from the average path that is found is however very low (maximal 11 meters) and the linear relationship does not fit well. It is therefore difficult to draw significant conclusions concerning the influence of this wind type on the vessel path.

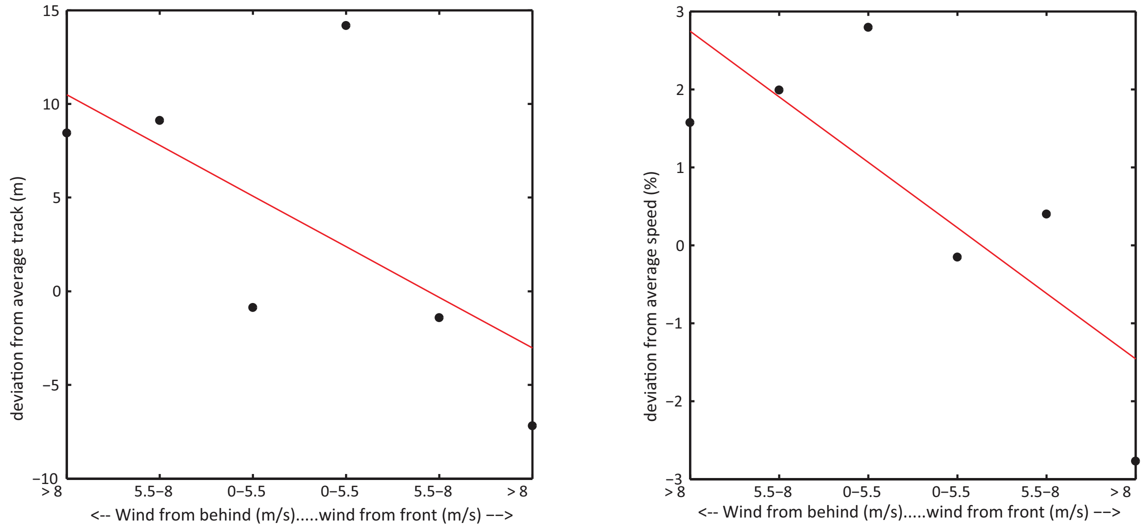


Figure 6.8 The influence of parallel wind on the chosen path and vessel speed in the Maasmond.

Beerkanaal

In the Beerkanaal the influence of wind is investigated in the same way as for the Maasmond. Figure 6.9 shows the influence of crosswinds at this location. It can be seen that the influence on the vessel path is the same as found for the Maasmond. Wind coming from starboard side blows the vessels more towards port side and the other way around. The differences are however much lower (< 10 meters). The linear relationship seems to fit both graphs in a sufficient manner. The influence on the vessel speed is different from the results found for the Maasmond. When the wind blows more from starboard side, the vessel speed seems to decrease. The linear relationship does not give a good fit for the vessel speed and it is also impossible to fit other simple relationships.

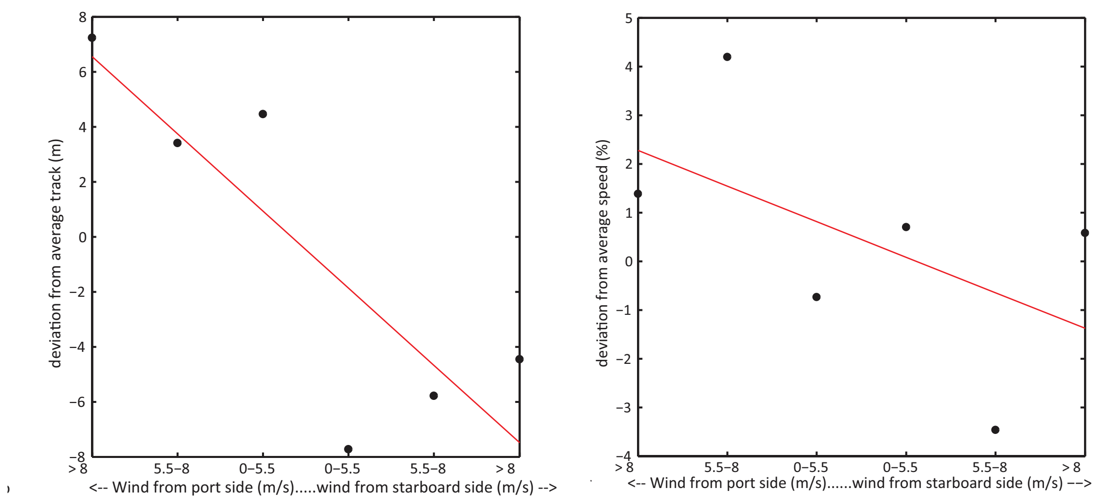


Figure 6.9 The influence of crosswinds on the vessel path and vessel speed in the Beerkanaal.

The influence of parallel wind is investigated for the Beerkanaal as well (see Figure 6.10). As was also found in the Maasmond, this type of wind does not have a lot of influence on chosen vessel path. It is as well not possible to find a good and simple relationship.

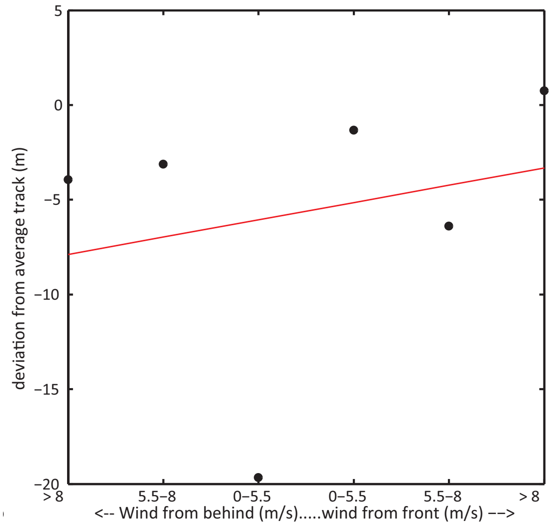
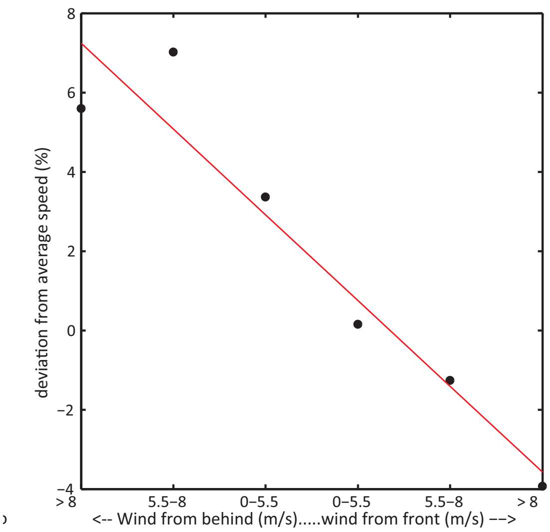


Figure 6.10 The influence of wind from behind and from the front of the vessel on the vessel path in the Beerkanaal.

The influence on the vessel speed is another story, as at this location there is a difference between incoming and outgoing vessels. Figure 6.11 shows the influence of the parallel wind on the incoming (left) and outgoing (right) vessels. Clearly the incoming vessels follow a linear relationship, where a strong wind from behind leads to a higher vessel speed and a strong headwind causes a lower vessel speed. For outgoing vessels the relationship is more complex; in the figure a second order polynomial is tried to fit. This seems to give a good approximation. This is an interesting result, because it is similar to the influence found at the Maasmond, but now for parallel wind instead of crosswind.



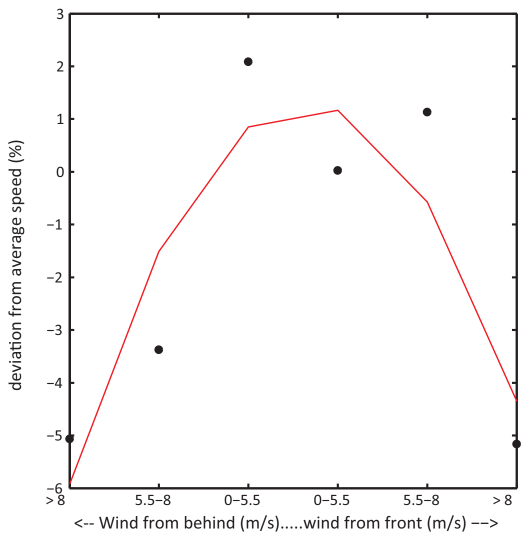


Figure 6.11 The influence of parallel wind on the vessel speed in the Beerkanaal for incoming (left) and outgoing (right) vessels.

6.1.4 Conclusions

The wind circumstances definitely have an influence on the vessel speed and vessel path. The deviation from the average vessel path is not very large, mainly because the vessels correct their heading when they are encountering a strong cross wind. This is concluded by comparing the heading of those vessels with the average heading. Strong crosswinds also cause a decreased vessel speed, as vessels use a part of their engine power to compensate for the windforce. More inside the port area, at the Beerkanaal, the influence of crosswinds is clearly less than at the Maasmond.

Wind coming from behind and from the front of the vessel, parallel wind, hardly influences the vessel path, but does influence the vessel speed. Generally, headwind causes a decrease in vessel speed and a stronger wind from behind the vessel leads to a higher vessel speed. Exception to this are the outgoing vessels in the Beerkanaal. These vessels show a decrease in vessel speed, when the wind is stronger, regardless the direction of the parallel wind.

6.2 Current

6.2.1 Currents in the case study area

For the wind influence, it was assumed that the wind only varies in time. This implied that within the examined case area, the wind speed and wind direction were assumed to be constant over the total area, for a certain moment in time. For current this is not true, as the current varies in time **and** in space, both horizontally and vertically. The horizontal variation in space depends mainly on the ports nautical infrastructure. The vertical variation in space depends for a large part on the interaction between the river (Nieuwe Waterweg) and the tide.

These two factors (river discharge and tide) are the driving factors of the currents that occur in the case study area, resulting in different directions for the current on different depths. This might be explained by the following. Where the salt sea water and the fresh river water meet each other, the first one ‘dives’ under the layer of river water. This is because salt water is heavier than fresh water. Because of this principle there are moments in time where the top layer of the water and the layers beneath have opposite current directions. When in all layers the current direction is approximately equal, there can still be huge differences in current velocity.

6.2.2 Current data

From the Port of Rotterdam, data is obtained regarding the expected curent velocities and directions at three differents depths. This information is known for 10 important locations along the case trajectory, for normative tidal cycles and river discharges (indicated with red dots in Figure 6.12. These 10 locations are grouped, by looking at similarities in their current regimes. By doing so, the horizontal variation in space is taken into account. Finally, 5 different trajectories are pointed out where a similar regime is present (see Figure 6.12). In part 5, the Amazonehaven, the current influence is not further investigated, as the current velocities are very low at this location.

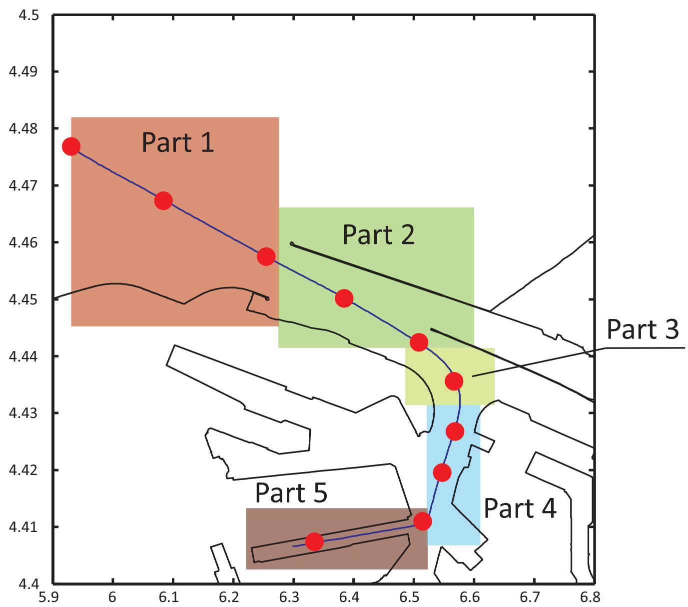


Figure 6.12 Overview of the different current regimes in the case area. The red dots indicate the points where current data is available

From the Servicedesk Data (Rijkswaterstaat) the water levels at the case location are obtained over 2009. By coupling these water levels to the normative current information, the current velocity and direction is known at every chosen location, for the three different dephts. After this, selections are made from vessels that have sailed through the case area while encountering different current velocities and directions. Which layers (depths) are chosen to be taken into account for this depends on the vessel size.

The current direction is split up into 4 categories, the same as used for the wind influence: current from behind, front, port side and starboard side. The current velocity is split into three classes (see Table 6.2). These classes are chosen, because now every size class has about the same amount of vessel tracks. The amount of vessel tracks in one selection depends of course very much on the current direction. Hardly any cross current can for example be found in part 2.

Table 6.2 Current velocity classes

Class	Current velocity (m/s)	Current velocity (kn)
I	< 0.3	< 0.6
II	0.3 - 0.5	0.6 -1.0
III	> 0.5	> 1.0

6.2.3 Results

The results are given in the same way as for the wind influence. Figure 6.13 shows the results for the area outside the protection of the northern breakwater the influence of cross current on the vessel path and the vessel speed. The influence on the vessel path is very clear and in line with the findings for the influence of crosswind. The influence on the vessel speed gives a more scattered image. The best simple fit is given by a second order polynomial, but it is obvious that this fit is far from perfect.

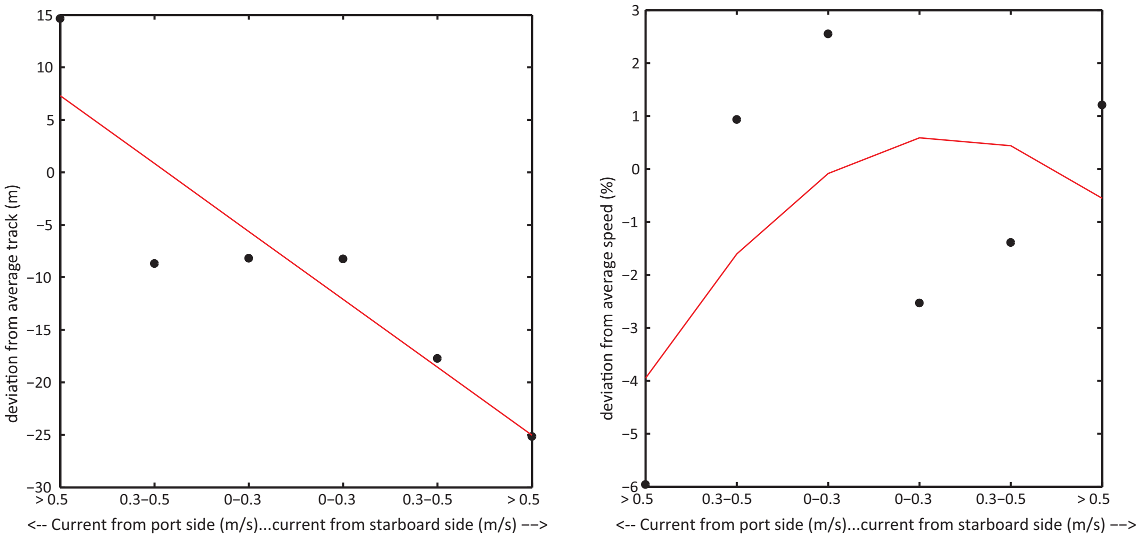


Figure 6.13 The influence of cross current on the vessel path (left) and speed (right) in part 1.

Although the deviation from the average path clearly has a downgoing trend, the absolute deviation is not very large, about 25 meters maximal. Again this can be explained by the fact that vessel adapt their heading to stay on course. This was already found when investigating the influence of wind, but also during high cross current velocities the vessel heading is significantly different from the average heading. Figure 6.14 shows an example of this, for the size class 40,000 - 70,000 dwt.

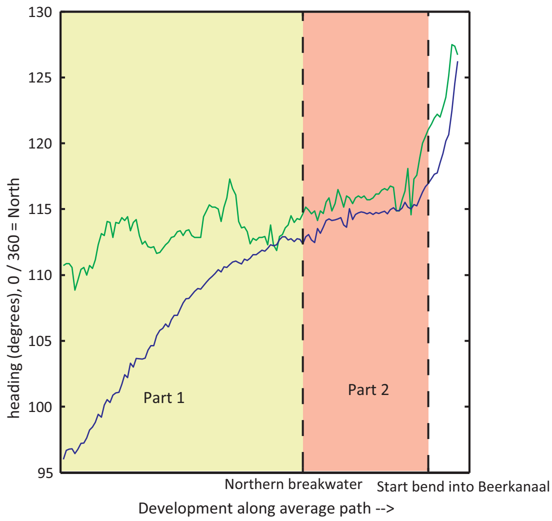


Figure 6.14 Development of the vessel heading under influence of a strong cross current (green) compared to the average heading (blue), both for vessels of size class 40,000-70,000 dwt

The influence of the current that flows parallel to the vessel is shown in Figure 6.15. Both graphs do not have a perfect fit for a linear relationship, but clearly show a trend. The negative values for the deviation from the average path (left figure) indicate that vessels sail more to port side when they experience a strong current from behind. In practice this means that they are sailing more to the middle of the waterway. The vessel speed decreases when the countercurrent increases.

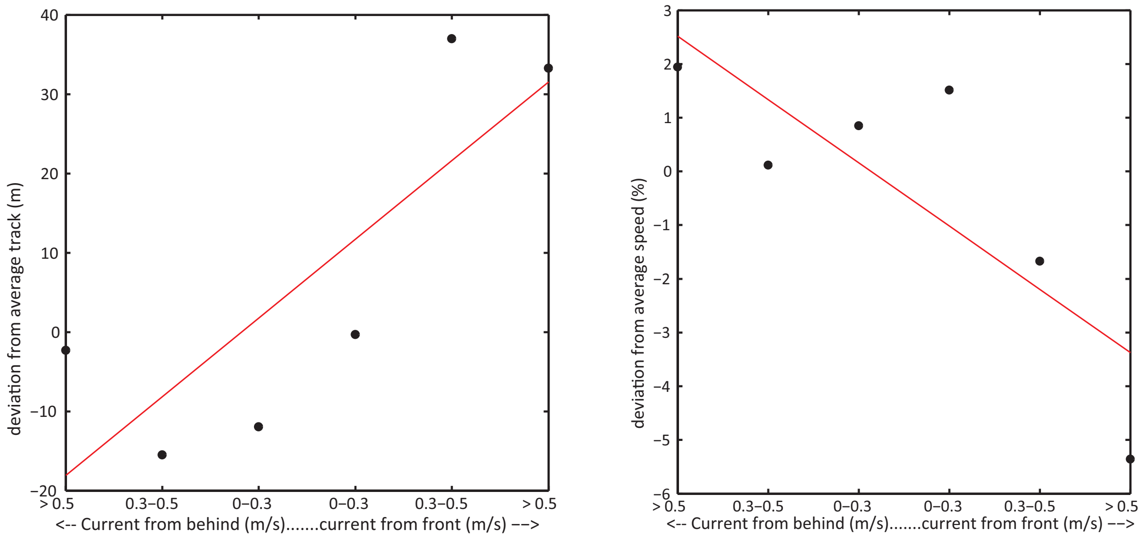


Figure 6.15 The influence of parallel current on the vessel path (left) and speed (right) in part 1

In part 2 only parallel currents are present due to the fact that at this location the waterway is closed at both sides. The influence of this current on the vessel path and vessel speed is similar to the influence found in part 1, but smaller (see Figure 6.16).

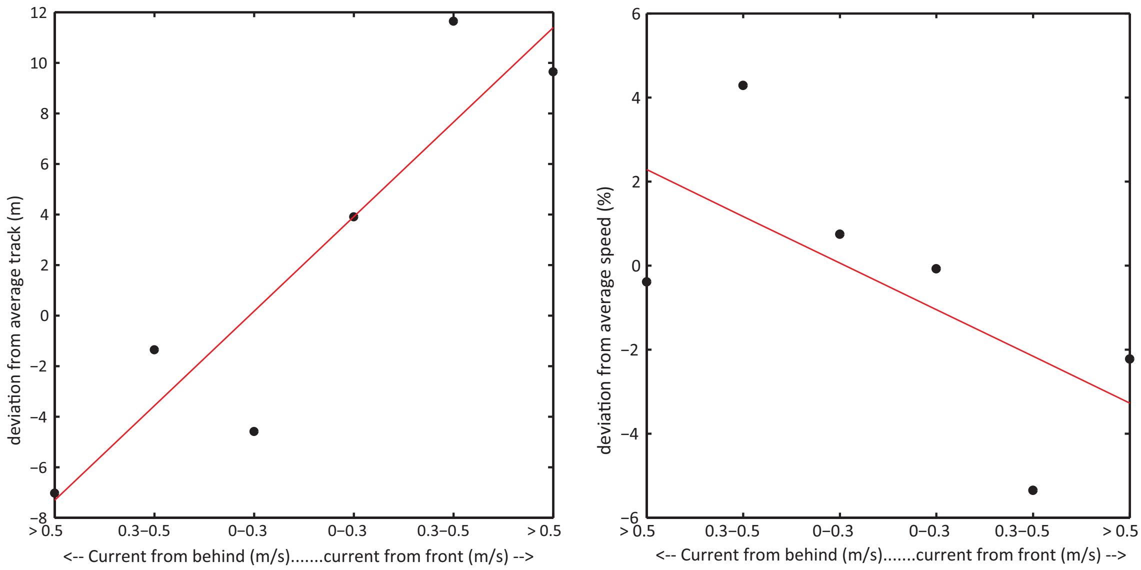


Figure 6.16 The influence of parallel current on the vessel path (left) and speed (right) in part 2

In part 3, the bend at the entrance of the Beerkanaal, and part 4 (Beerkanaal) the current velocities are much lower. Also the influence of the current on the vessel path and speed decreases. For part 3, no significant influences are found. In the Beerkanaal (part 4) there is some influence of parallel current, mainly regarding the vessel path. Figure 6.17 shows this result, which is quite similar to the finding in part 1 and 2. There is no significant influence found on the vessel speed at this location. The cross currents are hardly present in the Beerkanaal; therefore no influence of these current directions is found.

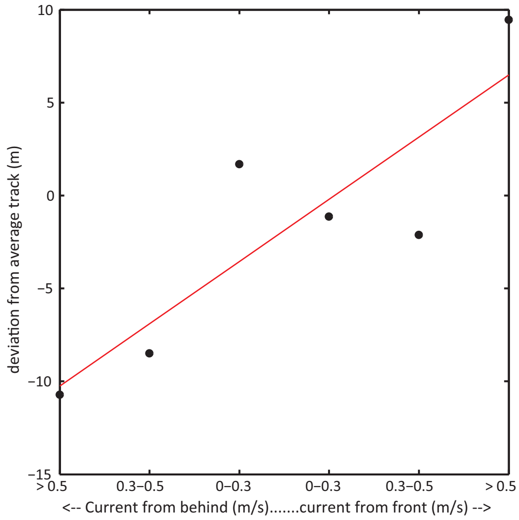


Figure 6.17 The influence of parallel current on the vessel path in part 4 (Beerkanaal)

6.2.4 Conclusions

It is very complex to analyse the influence of the current on the vessel path and vessel speed. This is because the current is hugely affected by the local infrastructure, especially in a port area. In this case also the interaction between the river and the sea is important: this leads to a large deviation in current velocity and direction over the water depth. By splitting up the examined case area and by using several simplifications it is however possible to obtain some good results.

The influence of cross currents could only be observed in part 1, outside the norhern breakwater. At the other locations cross currents are hardly present, due to the local infrastructure. In part 1 the influence of the cross current is similar to the influence of the wind. There is a deviation from the vessel path found. This deviation is not very large, because vessels adapt their heading in order to stay on course. The influence of the cross current on the vessel speed is less clear.

Current coming from behind or the front of a vessel, parallel current, has an influence as well. A strong current from behind makes vessels sail more to the middle of the waterway. A strong head current makes them sail more towards the shore. The vessel speed is also affected: a strong current from behind increases the vessel speed and the other way around. These findings are supported by the results for part 1, part 2 and part 3. In part 4, the Beerkanaal, only the conclusions regarding the vessel path are found.

6.3 Visibility

6.3.1 Visibility data

Visibility data for 2009 are obtained from the KNMI. The investigation of the influence of visibility is more straightforward than for wind and current. Visibility does only vary in time and it has no direction in which it works. The values for visibility are defined by the KNMI as the ‘horizontal visibility at the time of observation’. This visibility is known as the ‘meteorologic visibility’ and is defined as the largest distance at which a black object can be seen and recognised. The interval between the observations is one hour.

The visibility is not split into different classes, as is done with the wind and current. This is because by far, most vessels meet clear visibility conditions. Only when the visibility becomes very low, there is a noticeable influence. This is why there are are only two classes made: bad visibility and sufficient visibility. Bad visibility means that the meteorologic visibility is lower than 2 kilometers. By comparing the moments in time, the AIS messages from the vessels and the visibility data are coupled.

6.3.2 Results

For the determination of the influence on the average path, the case area is again split into two parts: the Maasmond and the Beerkanaal. For the calculation of the deviation from the average speed no split up of the case area is used. Vessels that enter or leave the port with sufficient visibility do not deviate from both the average path and average speed. For vessels that encounter a decreased visibility an influence is present; it is tried to find a relationship between the vessel size and this influence.

In the Maasmond it is not possible to find a clear relationship between the vessel size and the influence on the vessel path. There is however a clear difference between incoming and outgoing vessels. Incoming vessels do not significantly deviate from the average path during times of low visibility. Contrary to this, outgoing vessels do have a deviation to starboard side (the shore), in the order of 50 meters.

In the Beerkanaal the influence of the vessel size is more obvious (see Figure 6.18). There is no difference between incoming and outgoing vessels. The linear trendline fits quite good and a downgoing trend can be observed. In practice, this means that larger vessels sail more to the middle of the channel under low visibility circumstances than smaller vessels.

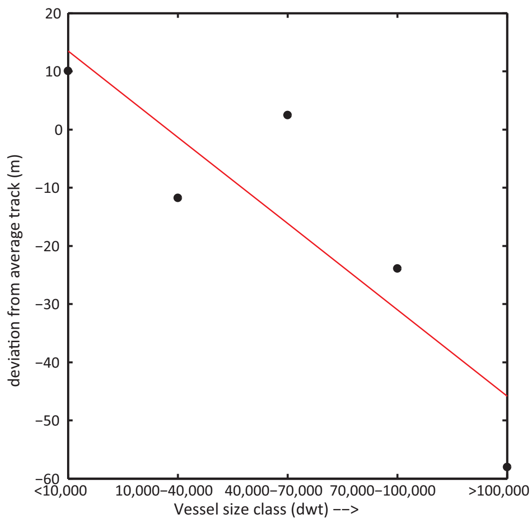


Figure 6.18 The influence of low visibility on the deviation from the average path in the Beerkanaal.

For the influence of low visibility on the vessel speed no significant differences between incoming and outgoing vessels are found. In this case a division can be made in small and large vessels. The small vessels, containing the size classes <10,000 dwt, 10,000-40,000 dwt and 40,000-70,000 dwt are clearly hampered by a low visibility. These vessels decrease their speed, on average, with 6 %. The larger vessels (size classes 70,000-100,000 dwt and >100,000 dwt) have no significant speed difference.

6.3.3 Conclusion

It is difficult to find a very clear relationship for the influence of low visibility. Most important finding is that vessels sail in the Beerkanaal more to the middle of the waterway, when the vessel size increases in case low visibility. Good relationships for the deviations from the average path in the Maasmond and from the average speed are not found. There are however average values obtained that give some insight in this vessel behaviour.

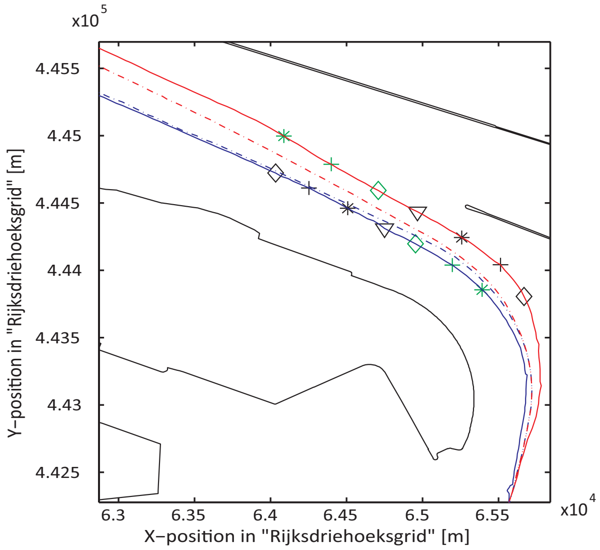
6.4 Conclusions

For all three external circumstances influences on the vessel path and vessel speed are found. The largest deviations from the vessel path are found for crosswind and cross current in the Maasmond, outside the protection of the Northern breakwater. These deviations are limited, because vessels adapt their heading to stay on course. In this way they prevent from being blown or 'flowed' away by the wind or current. A second large deviation is found in the Beerkanaal, in times of low visibility. Especially larger vessels sail more to the middle of the waterway in these circumstances.

Also for the deviation from the average speed the influence of wind and current is quite similar. High crosswind and cross current velocities lead to a lower vessel speed. This result is most visible for wind, but also the current influence shows this pattern. Large wind and current velocities from behind lead to a higher vessel speed, where wind and current from the front cause a decreased speed.

Except for the visibility, no significant differences between the size classes are found. This is mainly due to a lack of data when splitting up one size class into several selections. In some of these selections, there are not a lot of vessel tracks available. This is caused by the lack of occurance of a external influence, for example wind from the east or cross current in the Beerkanaal. Also when the examined external influence does occur frequent, the amount of data is mostly too small to draw significant conclusions for only one size class.

Chapter 7



Interaction

7 Interaction

One of the research questions is to investigate the influence of vessel-vessel interaction in a statistical way. Due to time considerations the statistical analysis of this interaction is not performed. Some research on the influence of interaction is however performed, mainly to show how individual cases can be found and analysed. For this examination the similar case study area is used.

7.1 Interaction in the case study area

Vessel-vessel interaction takes place when a vessel deviates from its normal path, speed or heading, because of the presence of another vessel. Sometimes the vessels react on each other in an early stage; these situations are difficult to track down. Other interaction situations are more obvious and are also more easily found. In the track that vessels sail between the North Sea and the Amazonehaven, there are several places where interaction is likely to occur. For example in the bend at the entrance of the Beerkanaal or in the Beerkanaal itself. A more detailed description of the path and its interesting locations, together with some traffic images, has been given in section 4.2.

The first step is to identify interaction situations. There are mainly two ways to do so, based on the calculation principles used in this thesis. Both methods investigate different types of vessels that are involved in the interaction. The first way (Method I) is based on the interaction between two container vessels that both visit the Amazonehaven. This analysis uses CPA (Closest Point of Approach) and TCPA (Time to Closest Point of Approach) characteristics. The second way (Method II) investigates the interaction between a vessel that visits the Amazonehaven and a vessel that likely does not (thus, this second vessel is not analysed in the case study). This analysis makes use of the calculated 'outliers', vessels that clearly deviate from the average path or speed.

In the case study area several types of interaction are present. These are connected to the types of encounters vessels can experience: head-on, crossing or overtaking. All of these types of interaction will be present, and should be looked at, when investigating the influence of interaction.

7.2 Method I

Of all vessels that are analysed in the case study, also data are known concerning the CPA and TCPA. The CPA is the smallest distance that vessels will have to each other, if they keep their heading and speed constant. The TCPA is the time until this moment is reached (see Figure 7.1). In practice these two parameters give an indication about the possible closest distance to other vessels and the time that is left to adapt course and speed, if this distance is too small.

As an output of ShowRoute, the CPA and TCPA can be obtained for every combination of two vessels that are relatively close to each other. A very small CPA and TCPA indicate that two vessels are close to each other; therefore vessel-vessel interaction is expected. To find some of these interaction situations, lower limits are set for the CPA and TCPA. For the CPA this limit is set at 0.05 nautical mile, roughly 100 meters. The limit for the TCPA is set at 5 minutes. It is also worthwhile to reduce the CPA and TCPA even more. In this case, only a few interaction situation will be found, but these are probably very helpfull in the analysis of situations where a collision was narrowly avoided (near misses).

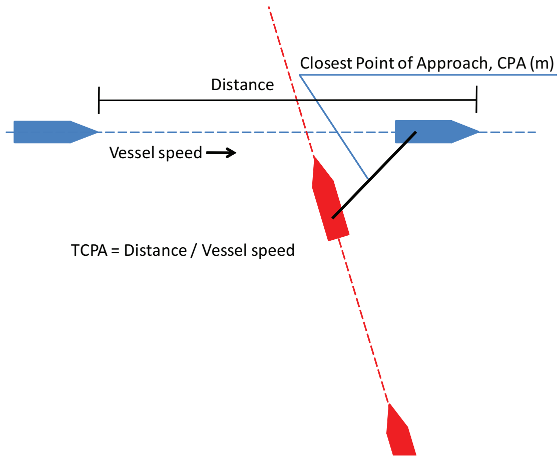


Figure 7.1 Explanation CPA and TCPA

The selection that is obtained by these limits consists of several vessel tracks. Figure 7.2 shows the combination of two of these interacting tracks around the entrance of the Beerkanaal. The blue line shows the individual track of an incoming vessel, from the size class 70,000-100,000 dwt. The red line indicates the track of an outgoing vessel, also from size class 70,000-100,000 dwt. The discontinuous lines show the average paths for this sizeclass, incoming (blue) and outgoing (red). The markers indicate similar moments in time, the triangle indicates therefore the position of the vessels when they are the closest to each other.

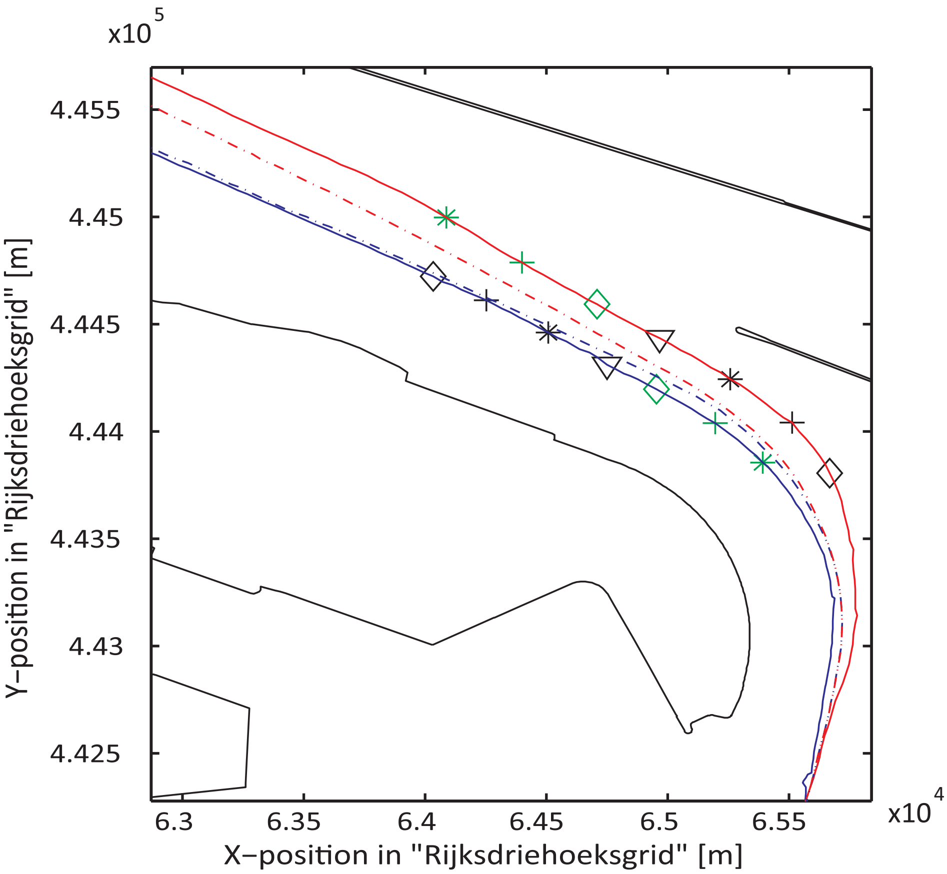


Figure 7.2 An example of interaction shortly before the entrance of the Beerkanaal

A few things can be concluded from this example. First of all, it is obvious that there is an interaction between the vessels, because both deviate clearly from their original path. This is not a very strange conclusion, when looking at the dimensions of the vessels. Both are large container vessels of the size class 70,000-100,000 dwt. They have to pass each other in a rather narrow waterway. This conclusion is based on the deviation from the average path. Before its path is disturbed by the outgoing vessel, the incoming vessel sails quite close (a little bit to the south) to the average path of its size class. At a certain moment it deviates quite strong to the shore; after it has taken the bend into the Beerkanaal it returns at the average track. The outgoing vessel undergoes about the same. At first instance, it almost exactly follows the average path. In the bend it deviates strongly to the starboard side of the average path. Contrary to the incoming vessel, it does not come back at the path after the interaction. So in its case, the interaction has a structural effect.

The interaction situation has now been described qualitatively. To obtain statistical equations concerning the vessel behaviour during an interaction situation, it is also important to do quantitative analyses. In this analysis, a few questions should be answered. First, at what distance in space and time do the interaction manoeuvres start. When this is known, it is important to investigate what the behaviour exactly includes. This can be described by an adjustment of the vessel speed (knots / minute) and vessel heading (degrees per minute). It should also be derived at what moment (for example a distance between the two vessels involved) these adjustments are seen as being sufficient. Finally, the question should be answered how vessels behave after the interaction situation has passed.

In this example the following results are found. The incoming vessel starts with his divergent behaviour when the distance between the two vessels is about 1000 meters. At this point the time to closest point of approach is 1.5 minute. The outgoing vessel already starts deviating from his path when the distance between the vessels is approximately 4 kilometers. The actions that are undertaken by the incoming vessel can be quantified by looking at Figure 7.3. On the X-axis of this figure the area in which the interaction takes place is shown; this can be compared to the X-axis of Figure 7.2. Regarding the vessel speed two conclusions can be drawn. First, the vessel sails faster than the average of its size class. This deviation (± 1 knot) can however be explained by the natural spread in vessel speed.

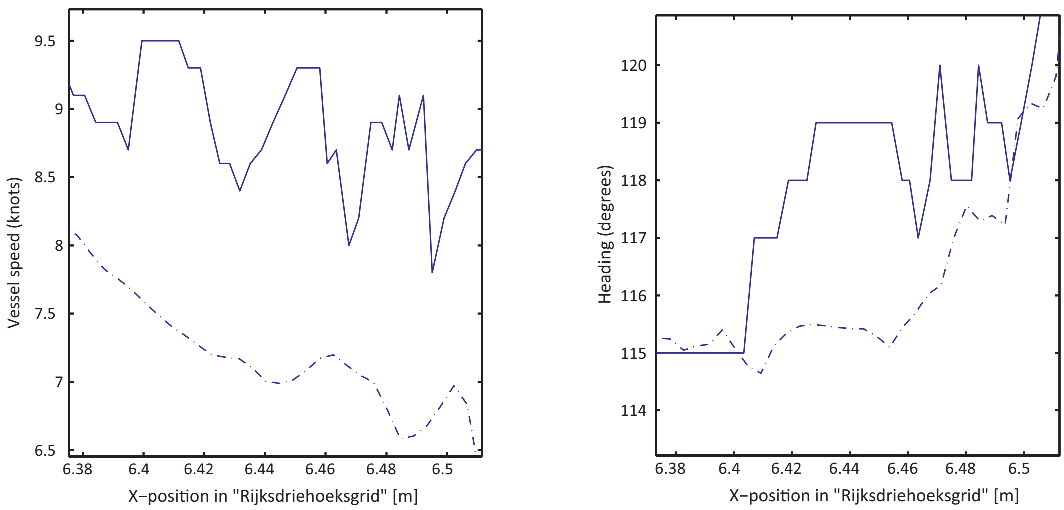


Figure 7.3 Development of the vessel speed (left) and vessel heading (right) compared to the average of the sizeclass 70,000-100,000 dwt (discontinuous line).

The graph on the right, the heading, gives a good indication how the vessel deviates from his path. Clearly around X=64,000 m the vessel heading quickly increases and after about 250 meters, the heading has risen with 4 degrees from 115 degrees to 119 degrees. This means that the ratio of the heading adjustment is about 1 degree per 60 meters. With a vessel speed of 9 knots this implies approximately 4 degrees per minute. In the figure it can be seen that after 600 meters (X = 65,000 m.) the heading is again almost the same as the average heading. At that moment, the distance between the vessels is 300 meters.

After the vessels have passed each other, the interaction is over. The results of the interaction are however still present. About 2 kilometers after the vessels have passed each other, the incoming vessel is back around the average track. The outgoing vessel does not converge towards the average track anymore.

Another remark can be made. The incoming vessel, that takes the inner bend into the Beerkanaal deviates less from its original path than the outgoing vessel. Both vessels sail before the interaction along the average path of their size class, by approximation. The maximal deviation from this average path is for the incoming vessel 100 meters, for the outgoing vessel 200 meters. This has very likely to do with the space that is available for the vessels. The incoming vessel is in the inner bend and sails already quite close to the side of the waterway, whereas the outgoing vessel has some ‘reserve’ space left at his starboard side.

7.3 Method II

As explained in the first section of this chapter, the method II interaction situations are derived by calculating outliers. These outliers have been found during the calculation of the average vessel behaviour in chapter 5. During this calculation some vessels were found that had such a different vessel path or vessel speed, that these were called outliers. The idea is that the large deviations of these vessels originate from the fact that they had to alter course or speed because of a vessel-vessel interaction.

The CPA and TCPA data is only known for the vessel tracks that were investigated in the case study. If the outliers indeed had interaction, this will very likely not be with another investigated vessel. This is because these vessels are only a very small part of the total amount of vessels that sail through the case area. So, in first instance there is no information concerning the vessels that possibly had interaction with the determined outliers. To obtain this information, the total traffic image around an outlier is played in ShowRoute (see Figure 7.4).

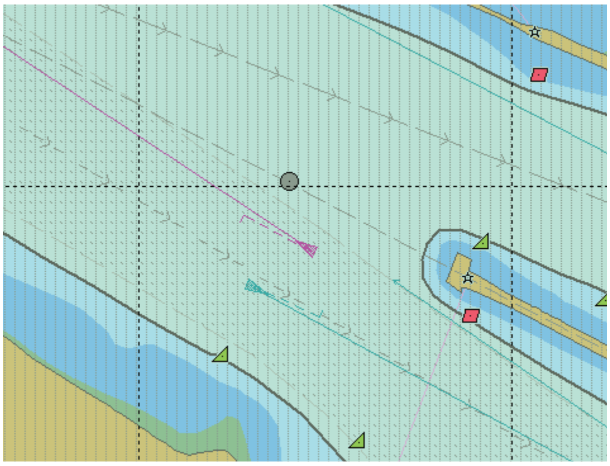


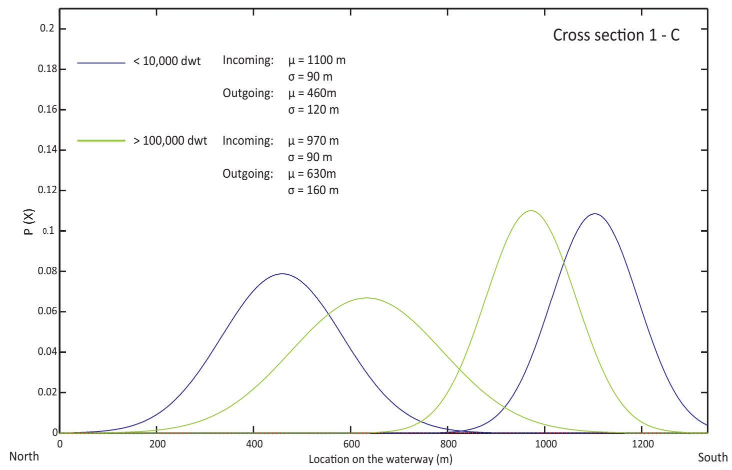
Figure 7.4 Example of the interaction of an outliers (purple triangle) with another vessel, after plotting the whole traffic image.

This gives two options. The first option is to see whether there have been vessels present that sailed close to the outliers. Secondly, if interaction situations are indeed found, the information of interacting vessels can be obtained. These can then be used to produce the same numbers and figures as in method I, from which a quantative analysis can be performed.

7.4 Conclusion

The example shows that it is possible to do a quantitative analysis concerning vessel behaviour in an interaction situation. The data derived here are however only valid for this specific situation. For the derivation of statistical equations, it is needed to observe and analyse many more of these situations. Different types of interaction should be investigated as well. This would also make it possible to include the vessel speed in the analysis. Due to the large natural spread in vessel speed it is difficult to draw conclusions based on a small number of situations.

Chapter 8



Generic rules

8 Generic rules

In this chapter the vessel behaviour analysed in the case study is transformed into generally applicable rules. In this way the vessel behaviour in other waterways and ports can be described, based on the findings of the case study. To generalise the result of the case study, the first issue to be handled is the mapping of the nautical infrastructure. The infrastructure is different at every location. The track of the case study is split in several parts in section 8.1. After dealing with the infrastructure, the average vessel behaviour is generalised (section 8.2) and the external influences are included (section 8.3).

8.1 Defining waterways

The track in the case area is split into 5 different parts, which were also used for the examination of the influence of current (see Figure 8.1). In this section the different parts are generalised to specific types of waterways. It is tried to find outer boundaries for every part, thereby finding the width of the characterised waterway. In this way it is possible to describe the vessel's position in relation to its position on the waterway.

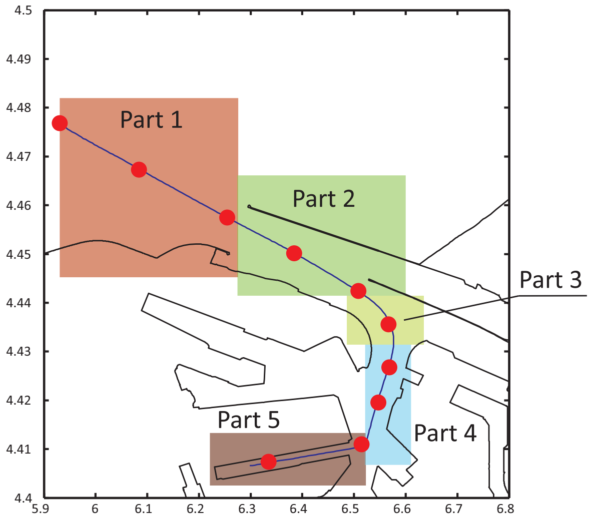


Figure 8.1 Overview of the different current regimes in the case area.

8.1.1 Part 1 - Outside the northern breakwater

In this part the width of the waterway is not really defined by an acceptable depth. The fact that vessels want to enter or leave the port of Rotterdam, and therefore converge towards the entrance of the port, is normative. Therefore the width of the waterway is defined by taking a certain angle from the entrance of the port. This angle has been determined by looking at the 98% contours from the incoming and outgoing vessels. In port areas where these contourlines are not available, this angle should be determined by investigating the depth profiles, navigational aids present (e.g. buoys), the origin, destination, expected type and size of the vessels that visit that port. When there are similarities found with this case study area, than contourlines of this case study can be used to give a first insight in the angle of the line. Size class <10,000 dwt is chosen for this, as these vessels use the widest space and therefore have the normative contourlines. Figure 8.2 shows these contours (red) and the average path (green dotted, incoming and outgoing). The blue line shows the definition of the width of the waterway.

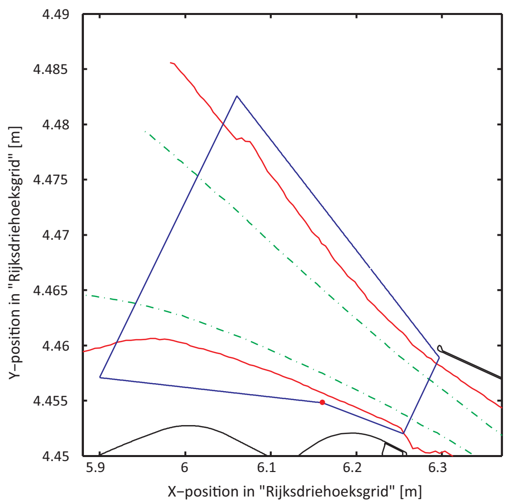


Figure 8.2 Overview of the simplified waterway (blue) in part 1. Also indicated are the average path (green dash dotted), the 98% contours (red) and the buoys (red).

By using the 98% contours, it is inevitable that some vessels will sail outside the determined limits. Other vessels will sail very close to these limits. These outer limits should therefore not seen as a strict border. Vessel do not run aground if they go outside. The limits represent the most likely area to contain vessel tracks, while there are no nautical infrastructure restrictions.

8.1.2 Part 2 - 'Maasmond'

The waterway in part 2 is clearly indicated by buoys. By drawing straight lines between those buoys, it is possible to obtain the width of the waterway. This width is decreasing, as all vessels converge towards the entrance of the Beerkanaal. Figure 8.3 shows an overview of the buoys (red dots) and the determined waterway. At some locations, the 98% contour lines are not straight, but quite 'peaky'. This is probably because of errors in disturbed AIS messages, caused by the fact that tugs fasten to the cargo vessels at that location.

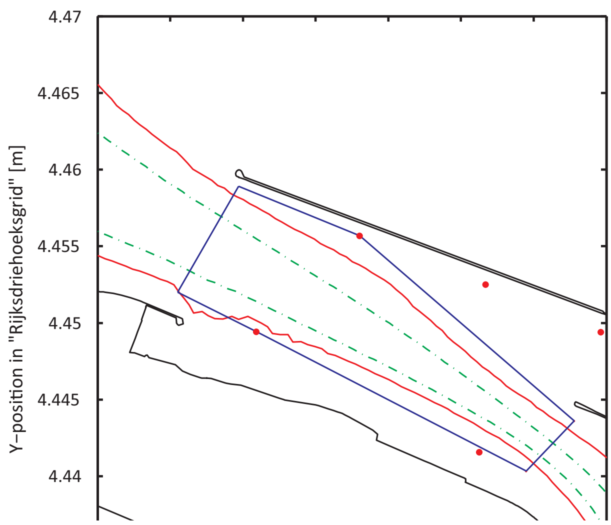


Figure 8.3 Overview of the simplified waterway in part 2.

8.1.3 Part 3 - Bend at entrance Beerkanaal

Also this part is distinguished as separate part, as this is completely different from the relatively straight waterways in the Maasmond and Beerkanaal. In the inner bend as well as the outer bend, buoys are present that show the outer limits of the waterway (see Figure 8.4). The limits in the outer bend are 'cut of', these limits do not exist in reality, because this is the entrance to another waterway, the Calandkanaal. In this case use is made of a buoy to predict the limits of the waterway in the outer bend. In other port areas, these navigational aids could be used as well. When these are not present, the 98% contour lines give a good indication. Another option is to investigate and set the outer bend to a certain distance from the inner bend.

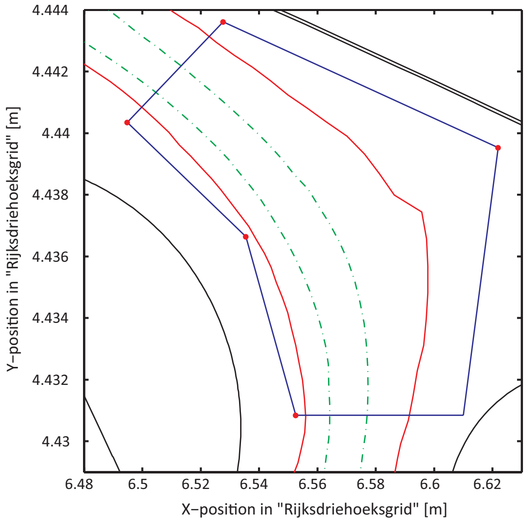


Figure 8.4 Overview of the simplified waterway in part 3.

8.1.4 Part 4 - the Beerkanaal

The schematisation of the waterway in the Beerkanaal is shown in Figure 8.5. The width is approximately constant for the whole segment. Only at the entrance of the Amazonehaven, the width decreases. Use is made of existing buoys, shore contourlines and 98% vessel path contours to determine the outer limits of the waterway. This part is quite similar to part 2, the main difference is the fact that the vessel now approach their goal, the Amazonehaven, which influences their behaviour (e.g. sailing in backwards).

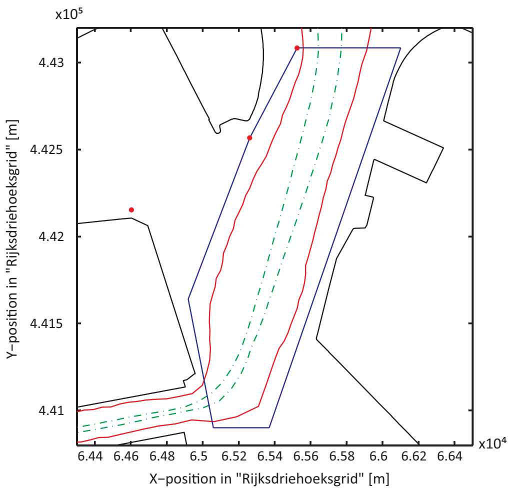


Figure 8.5 Overview of the simplified waterway in part 4.

8.2 Average behaviour

With the total trajectory schematised into different parts, it is possible to obtain the vessel location with respect to the waterway. The distribution of vessels over a cross section in the waterway is handled, as well as the distribution over a cross section of the vessel speed. To obtain a sufficient insight, these generalised distributions are derived for several cross sections in every part. The shape and size of most of these distributions was already found in chapter 5, but here they are coupled to the simplified nautical infrastructure.

8.2.1 Part 1 - Outside the northern breakwater

In this section an example will be given how the distributions of both location and vessel speed are derived. For the other cross sections in this and in the other parts, this approach remains the same. In part 1, 4 different cross sections are investigated (see Figure 8.6). As an example Cross section 1-C is elaborated below.

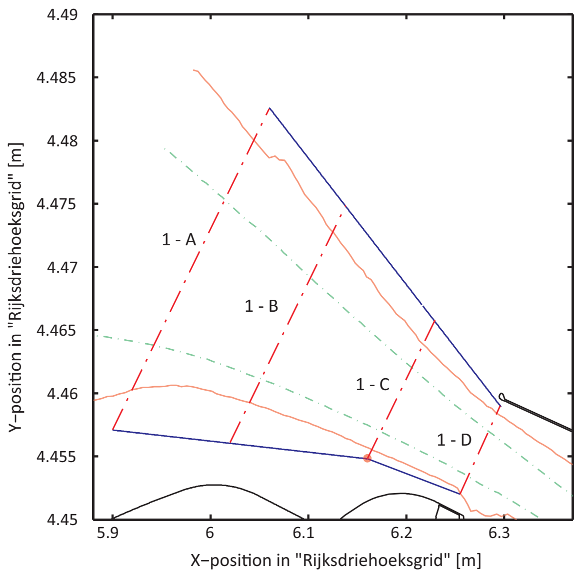


Figure 8.6 The cross sections that are investigated in part 1.

At cross section 1-C, the deviation over the waterway is investigated, for both incoming and outgoing vessels from size classes <10,000 dwt and >100,000 dwt. The normal distributions are based on the real vessel tracks, as explained in chapter 5. Figure 8.7 shows these distributions. Several characteristics are important in the derivation of generic rules. First, the width of the waterway. This can be seen on the X-axis (0 is on the port side of the incoming vessels) and is at this location equal to 1300 m. Next, the mean and standard deviation of the distributions. It can immediately be seen that the largest size class sail more to the middle of the channel. This results in a substantial overlap between the incoming and outgoing vessel distribution for this size class. The smallest size class sails more to the outer limits and has almost no overlap.

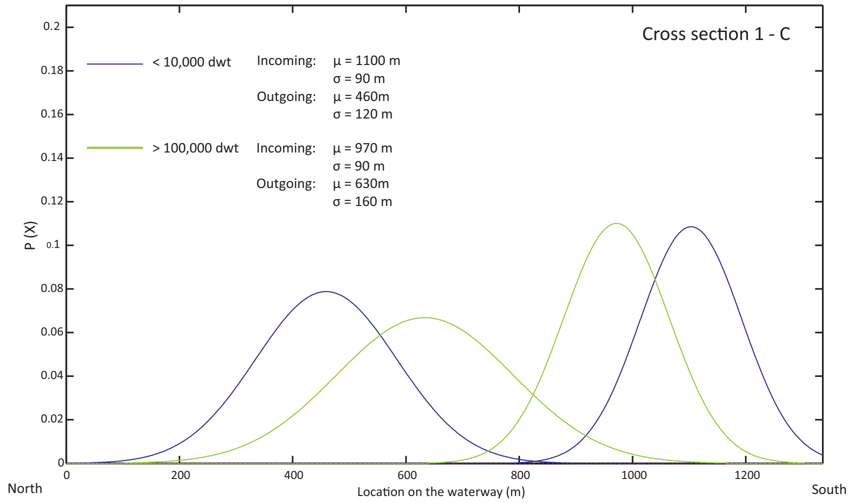


Figure 8.7 Distribution over the waterway at cross section 1-C

From the results shown in the figure, it is possible to formulate rules regarding the probable position of a vessel on the waterway in this cross section, depending on its size class. Next to the vessel distribution over the cross section, also the vessel speed distribution should be examined. This is also based on the results from chapter 5. Figure 8.8 shows the normalised speed distributions in cross section 1-C for the smallest and largest size class, for incoming vessels. The distributions are truncated in such a way that their total width is about 14 knots. Most striking is the fact that the smallest vessels sail about 2 knots faster than the largest vessels. For the vessel speed the mean and standard deviation give enough information to formulate generalised rules.

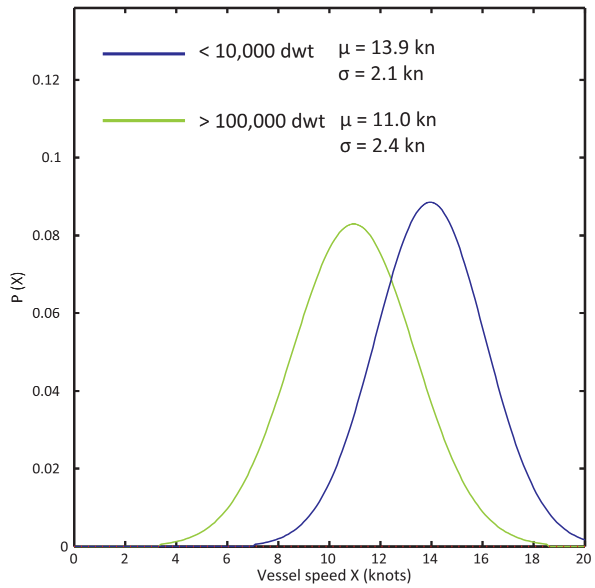


Figure 8.8 The speed distribution for incoming vessels at cross section 1-C

The example shows that now enough information is available to calculate the probability that a vessel, from a certain size, sails at a specific location in the cross section, with a specific speed. Figure 8.7 and Figure 8.8 also offer information concerning for example the overlap between incoming and outgoing vessels. All cross sections will be handled in the same way as the example above. The results are presented in tables, in which the most important characterics (mean, standard deviation, width of the waterway) can be found.

These tables can be found in Appendix G; an example is given below for cross section 1-C, Table 8.1.

Table 8.1 Characteristics of the different size classes in cross section 1-C

Width of the waterway (B): 1300 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean (μ)	St Dev(σ)	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	1100	90	13.9	2.1	460	120	14.7	2.1
10,000-40,000	1080	100	14.6	2.4	520	130	15.0	2.1
40,0000-70,000	1000	90	11.1	1.5	560	120	13.6	2.3
70,000-100,000	980	90	10.6	1.8	600	140	12.0	2.4
>100,000	970	90	11.0	2.4	630	160	14.3	2.0
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.85	0.07	0.96	1.11	0.35	0.09	1.06	0.95
10,000-40,000	0.83	0.08	0.97	1.14	0.40	0.10	1.02	0.84
40,0000-70,000	0.77	0.07	0.93	0.65	0.43	0.09	1.03	0.92
70,000-100,000	0.75	0.07	0.92	0.82	0.46	0.11	1.04	1.26
>100,000	0.75	0.07	0.87	0.89	0.48	0.12	1.05	0.87

In the second part of Table 8.1 a generalisation is made to respectively the width of the waterway and the 'starting' vessel speed characteristics. The width of the waterway that is used is indicated at the top of the table. The 'starting' vessel speed characteristics used, are the mean (μ_{V0}) and standard deviation (σ_{V0}) of the vessel speed in cross section 1-A (see Table 8.2). By dividing the mean and standard deviation of the vessel speed with the original mean and standard deviation, insight into the development of the vessel speed is obtained.

Table 8.2 Vessel speed characteristics of the different size classes in cross section 1-A

Width of the waterway: 3000 meters				
	Incoming		Outgoing	
Size class (dwt)	Speed distr. (kn)		Speed distr. (kn)	
	μ_{V0}	σ_{V0}	μ_{V0}	σ_{V0}
<10,000	14.5	1.9	13.9	2.2
10,000-40,000	15.1	2.1	14.7	2.5
40,0000-70,000	11.9	2.3	13.2	2.5
70,000-100,000	11.5	2.2	11.5	1.9
>100,000	12.6	2.7	13.6	2.3

8.3 External influences

The external circumstances do not change the shape of the normal distributions that are found for the spatial and speed distributions. This is because the investigation of the external influences in chapter 6 did not include the **individual** deviation from the average path and speed. This was not possible, because there was not enough data in most selections to obtain significant results. In most cases, no differences between size classes are found. There is one exception to this, the influence of visibility on the vessel speed.

The above mentioned means that the external circumstances mainly cause a shift of the normal distributions. The size of the shift depends on the external influence itself. In chapter 6 already, mostly linear, relationships were found. They have to be transformed to obtain a more general insight in the external influence. Figure 8.9 shows what is meant by this transformation. The left figure is the original influence, as found in chapter 6. The right figure shows the generalised influence, in which the X-axis is no longer divided in 6 size classes. The values on the Y-axis seem larger, but this is because the results are extrapolated. With this relationship it is possible to adapt the spatial vessel distribution to the current that is present at a certain moment in time.

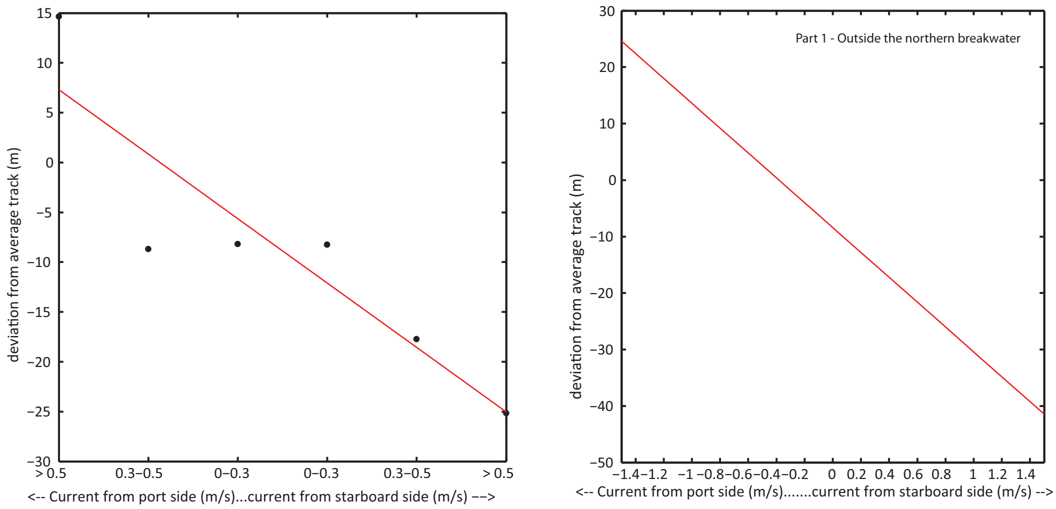


Figure 8.9 The influence of cross current on the vessel path at part 1.

The influence of the cross current at part 1 is an example of how the influences are generalised. The other influences and locations are elaborated in the same way. These graphs can be found in Appendix G.

8.4 Implementation in maritime models

In Section 3.5, the characteristics of four maritime models were discussed, concerning the possibility to implement the results of this thesis. For the description of the models, the following issues were mentioned:

Type 1 - Nautical infrastructure
    Describe lateral vessel distribution over a cross section over the waterway.
    Describe the vessel speed distribution over and in a cross section over the waterway.
Type 2 - Vessel related characteristics
    Distinguish between static characterics as vessel size and vessel type.
    Distinguish between dynamic characteristics, for example vessel destination.
Type 3 - External circumstances
    Take external influences like wind, current and visibility into account.
Type 4 - Interaction with other vessels
    Ability to include deviation from the predefined path and speed because of interaction with other vessels.

Now the results of the case study are known, these types can be elaborated a bit further. Type 1, the nautical infrastructure, is described in detail in the case study. Results have been obtained concerning the vessel and vessel speed distribution over the waterway, dependent on the type and width of the specific waterway. Type 2, the vessel characteristics are treated partly, as only the influence of vessel size and destination (to some extent) are treated. Results for the destination are obtained to some extent, as the sailing direction of vessels (incoming or outgoing) has been taken into account.

External circumstances do not change the size and shape of the vessel distributions, but shift them to portside or starboard side. The vessel-vessel interaction, type 4, is not elaborated statistically. Although examples are given how to find and analyse these situations, no statistical results are available.

The first maritime model handled in chapter 3 was SAMSON. This model is able to include the results from the case study concerning the type 1, type 2 and type 3 characteristics. The main disadvantage of SAMSON is the inability to simulate the nautical traffic. This characteristic is however mainly needed for the modelling of interaction. Because no interaction results are found, this is not a large drawback for the implementation of the available case results. However, if a future study would obtain more insight in the process of vessel-vessel interaction, simulating nautical traffic is preferable.

For HarbourSim, the most serious drawbacks were the (speed) distribution over the waterway. Because several results are found for this distribution over the waterway, the model should be adjusted largely to be able to implement this. Also the interaction is very limited in HarbourSim, but since interaction results have not been determined, this is no problem at the moment. Again, future studies might change this.

MARTRAM was found to meet most of the criteria mentioned. The model simulates the nautical traffic and there is a distribution over the waterway, also for vessel speed. The distributions used should be adapted to the results found in the case study. If this is done, it can also handle the influence of the external circumstances. MARTRAM also simulates interaction, but only in very limited way (vessels can only reduce speed). If later on interaction results are found, MARTRAM should be extended to cope with this, but at the moment the model keeps up with the criteria.

The fourth model that was investigated, Dymitri, simulates nautical traffic in most detail. It runs on behavioural rules, that are based on the simulation of the human brain. This makes it difficult to implement the results that are found in the case study. The results that are found (mainly distributions and factors that influence these distributions) are not linked to behavioural rules. In other words, Dymitri is not based on certain distributions over the waterway, but on the decisions of individual vessels. Contrary to this, results of future interaction research can be implemented more easily in the model. This is because these results will be more like behavioural rules, as they are closer to the (case specific) nature of the interaction process.

8.5 Conclusions

The results of the case study have been used to derive generic rules regarding the vessel path and vessel speed inside a port area. For this, the total trajectory between North Sea and Amazonehaven is split into different characteristic waterways. It is not always possible to assign real, physical outer limits. This is because sometimes the physical restrictions, like depth, are not normative. This is for example the case outside the breakwater, when vessels converge towards the port entrance.

The vessel path and speed are described by normal distributions, obtained in chapter 5. Visual representations of these distributions quickly give insight into differences between size classes and between incoming and outgoing vessels from one size class. The external influences are generalised and, in most cases, cause a horizontal shift of the spatial and speed distribution for every size class.

The generic rules, that are derived from the case study, can be implemented most easily in a model like MARTRAM. A model like SAMSON does not simulate nautical traffic, because this is not the purpose of the model. This is especially difficult in the light of a possibly increased future insight in the interaction process, whereas nowadays SAMSON would be sufficiently able to implement the results of the case study. HarbourSim does not allow deviation from the average path, an important result of the case study. Dymitri simulates the nautical traffic in great detail, but the approach of the model is different than what follows from the results from the case study.

Chapter 9

Conclusions & recommendations

9 Conclusions & recommendations

9.1 Conclusions

After performing the AIS analysis and formulating generic results, final conclusions can be drawn. They are split up in such a way that the separate research questions are answered and, finally, the problem definition of the research is handled.

AIS and maritime models

This research question was divided into the possibilities and limitations of AIS, characteristics of maritime models and the use of AIS in maritime modelling. Next to the main functions of AIS, being collision avoidance and navigational aid, the system is also used in maritime modelling. Until now, AIS data are mainly used to determine the nautical traffic input (e.g. inter arrival time) and the behaviour of nautical traffic at a larger scale (e.g. insight into the traffic network). Not much use is made of the possibility to obtain insight into individual vessel behaviour, something what is done in this thesis. In doing so, it is possible to deal with the human factor in maritime models. Problems that exist when using AIS data in these maritime models are caused by the fact that some AIS data contain errors and therefore are not completely reliable.

AIS data analysis

This research question was divided into the influences of vessel size, external influences and interaction on the vessel path and vessel speed. This study has shown the possibilities to describe the individual vessel behaviour in the port of Rotterdam area statistically, by using an analysis of AIS data. In this thesis the behaviour in a specific case area is investigated, but it is also possible to do so for the other areas in the port of Rotterdam. The investigated factors vessel size, wind, current and visibility all have a significant influence on the vessel path and speed. No conclusions regarding the interaction can be made, as no statistical analysis of the vessel-vessel interaction has been performed.

Generic rules

This reserach question was divided into the transfer from specific to generic rules and the possibility to implement them in maritime models. With the approach used in this thesis, it is possible to obtain generic rules that describe the vessel path and vessel speed in a port area. To do so, the case study area is split into several characteristic waterway segments and the location specific results are generalised to their specific segments. Currently existing maritime models are not able to directly implement the generic rules found, but with a small number of adjustments it is possible for some of them to do so.

Finally, it can be concluded that by using an analysis of AIS data, clearly more insight is obtained in the detailed individual vessel behaviour. This understanding of the behaviour can be formulated in generic rules. These rules can be implemented in maritime models, which improves the simulation of the individual vessel path and vessel speed.

9.2 Recommendations

This thesis has shown that it is possible to obtain insight in vessel behaviour by using AIS data. One of the main final goals of the thesis is to use this insight to obtain generic rules, which can be implemented in a maritime model. Some rules are derived in this thesis, but there are several issues where further research is needed.

First of all, only container vessels are investigated in the case study. Other types of vessels will have different behaviour, as they have other dimensions. For example dry bulk vessels, that have a larger depth and a smaller height. This makes them, theoretically, more sensitive to the influence of currents and less sensitive to wind. This same depth could also restrict them more to the middle of the waterway, where a larger water depth could be expected.

Rules concerning the influences of external circumstances are obtained in this thesis. Additional research would however be very beneficial for the insight into these and other external influences. First, only wind, current and visibility are examined, as these were expected to be the most important in the case study. The visibility data in the case study depended mainly on the presence of weather influences like fog and rain. The question if a vessel sailed by daylight or not, is not taken into account. This is an interesting issue, as vessels might behave differently if they sail by night (despite good lighting in the port area). The influence of waves is also a possible subject of future research, but it is of minor importance when looking at a port area; therefore this is not a first necessity.

For the external influences, there is no relationship found between the different size classes (except for visibility). It might be the case that there is no clear relationship, but it is more likely that -to some extent- a relationship exist. There is however a lot of data needed before this can be shown statistically, as the influence of the external circumstances on the vessel path and speed is small compared to the natural deviation from the average. Another characteristic that should be looked at more closely is the path width, as cross currents and cross winds cause a larger path width. More research is therefore worthwhile. This research should not have a case area between the sea and a terminal, but should focus on a specific waterway segment. Every vessel that sails through this segment should be analysed; in this way enough data could be obtained.

The generic rules that are obtained in this thesis describe the vessel path and vessel speed by using distributions over different cross sections. A maritime model should be able to use these distributions to simulate nautical traffic. At the moment, no research is done on the relation of the vessel's position between two successive cross sections. A maritime model needs this information before it can simulate individual vessels.

No statistical results of vessel-vessel interaction are obtained in the case study. This is the next step in obtaining insight in the vessel behaviour in port areas. An example has already shown that it is possible to track down interaction situations and how they can be analysed. To obtain statistical valid results however many more situations should be elaborated.

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Appendices

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Appendix A

Safety at sea

Appendix A Safety at sea

A.1 History of maritime transport[1 2]

Already thousands of years ago sea transport was important in trade. In these ancient times this trade was mainly on a regional or national scale. People were not able to sail across big waters, like the Atlantic Ocean. Lack of knowledge of the sea and all its external factors made sailing on open sea a very dangerous activity. Somewhat later, in Roman times, vessels stayed most of the time quite close to the coast, but this was not a guarantee for safe navigation. In bad weather wind and currents could still destroy a ship and also piracy was extensively present.

From the Middle Ages until the 18th century the shipping industry developed, but safety at sea stayed low. In the 19th century the loss of cargo and life by shipwreck was still enormous. Only during the winter of 1820 over 2,000 ships were lost in the North Sea, causing the death of 20,000 people. The problems were internationally recognised and in 1840 the first navigation rules, dealing with the lighting of ships, were applied. In the next decades mainly England and France formulated more guidelines and rules to aid navigational safety.

The internationalisation of the shipping industry persevered in the 20th century. It became clear that the shipping business needed general agreements, to improve safety and ensure fair competition. The Berlin convention of November 1906 gave rise to the first rules on wireless telegraphy. In 1910 conventions on collision and lifesaving and assistance were signed. However, a disaster was needed to accelerate the developments on the field of standards setting.

A.2 SOLAS[3 4]

On 14 April 1912 the RMS Titanic sank near Newfoundland. No one had expected the world's newest and largest passenger vessel to sink. Next to the fact that so many –sometimes rich and famous- people died, this led to the question whether individual countries could set their own safety standards. A conference was held in London which led to the first International Convention for the Safety of Life at Sea (SOLAS). This was one of the first treaties that focussed on the protection of human life instead of property.

Treaties like SOLAS were important, but also very dependent on the dedication and enthusiasm of the different governments. In the first part of the 20th century these governments were mainly occupied by the two world wars. However between these wars, in 1929, a newer version of the SOLAS was accepted. After the Second World War the internationalisation of the shipping business increased rapidly. Key development was the founding of the Inter-Governmental Maritime Consultative Organization (IMCO).

1 The UN Atlas of the Oceans, www.oceansatlas.org, accessed: 27/10/2009

2 The history of safety at sea, Philippe Boisson, the UN Atlas of the Oceans, http://www.oceansatlas.com/unatlas/issues/safety/transport_telecomm/history_safety/history_safety.htm, accessed: 27/10/2009

3 IMO's 50th anniversary: shipping and the oceans, Overview of shipping and navigation history, World Maritime Day 1998, International Maritime Organization, http://www.imo.org/About/contents.asp?topic_id=320&doc_id=886&header=false, accessed: 27/10/2009

4 International convention for the safety of life at sea (SOLAS), 1974, International Maritime Organization, International Maritime Organization, http://www.imo.org/Conventions/contents.asp?topic_id=257&doc_id=647, accessed: 27/10/2009

The IMCO was established in Geneva in 1948. The first official meeting of the new organisation was held in 1959. In 1982 the name was changed in how we know it nowadays: the International Maritime Organization, IMO. The IMO is a specialised agency of the United Nations; her headquarter is located in London. The main goal for IMO is 'to develop and maintain a comprehensive regulatory framework for shipping and its remit today includes safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping'. [5]

To reach the above described main purpose, international conventions have been set up. It is IMO his task to maintain and update these conventions as well as set up new ones if needed. Three types of treaties are distinguished. First there are conventions which aim to prevent accidents. Second, treaties prescribe what to do if an accident happens. Third, there are conventions that establish compensation and liability regimes. The SOLAS convention is a convention of the first type: to prevent accidents. Other key treaties of this type are MARPOL (International Convention for the Prevention of Pollution from Ships) and STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers)[6].

The SOLAS convention was one of the first tasks of IMO. It came into force in 1965. The idea was to keep the convention up to date by adjusting and expanding it with amendments. The procedures to do so appeared to be very slow; therefore a fifth convention was set up in 1974, in which the amendment process was made quicker.

The SOLAS convention currently consists of 12 chapters. In December 2000 a number of amendments was adopted. One of the revised chapters of the convention was chapter V: 'Safety of Navigation'. This brought in new mandatory requirements concerning the use of voyage data recorders (VDR's) and automatic identification systems (AIS). A time scheme was introduced to clarify which vessels should be equipped with these items at what time.

According to the new chapter V in SOLAS the AIS is "designed to be capable of providing information about the ship to other ships and to coastal authorities automatically". In the December 2000 amendment these vessels were required to install the AIS depending on their size between between July 2005 and July 2007. The implementation of the AIS was further accelerated by a new amendment adopted in December 2002. In this amendment, all vessels between 300 and 50,000 gross tonnage were obliged to be fitted with AIS on 31 December 2004 at the latest.

5 International Maritime Organization, Introduction to IMO, http://www.imo.org/About/mainframe.asp?topic_id=3, accessed: 31/1/2010

6 International Maritime Organization, Conventions, http://www.imo.org/Conventions/mainframe.asp?topic_id=148, accessed: 27/10/2009

Appendix B

Data in an AIS message

Appendix B Data in an AIS message

Table B.1 Data in an AIS message

Static information	**Sent every 6 minutes and on request of a competent authority**
MMSI	Maritime Mobile service Identity. Set during installation.
Call sign	Set during installation
Name	Ship's name
IMO number	International Maritime Organization number
Length and beam	Set during installation or if changed
Location of position fixing antenna	Set during installation or may be changed for bi-directional vessels or those fitted with multiple position fix antennae.

Dynamic information	**Sent every 3-10 seconds, dependent on speed and course alteration**
Ship's position with accuracy indication and integrity status	Automatically updated from the position sensor connected to the AIS.
Position Time stamp in UTC	Automatically updated from ship's main position sensor connected to AIS. (e.g. GPS)
Course over ground (COG)	Automatically updated from ship's main position sensor connected to the AIS, provided that sensor calculates COG. (This information might not be available)
Speed over ground (SOG)	Automatically updated from the position sensor connected to the AIS, provided that the sensor calculates SOG (This information might not be available).
Heading	Automatically updated from the ship's heading sensor connected to the AIS.
Navigational status	Navigational status information has to be manually entered by the officer on watch (OOW) and changed, as necessary, for example: underway by engines, restricted in ability to manoeuvre (RIATM), aground, at anchor, moored, engaged in fishing, not under command (NUC), constrained by draught and underway by sail. In practice, since all these relate to the COLREGS, any change that is needed could be undertaken at the same time that the lights or shapes were changed.
Rate of turn (ROT)	Automatically updated from the ship's ROT sensor or derived from the gyrocompass. (This information might not be available).

Voyage related information	Sent Every 6 minutes, when data is amended or on request
Ship's draught	To be manually entered at the start of the voyage using the maximum draft for the voyage and amended as required; e.g. after de-ballasting prior to port entry.
Hazardous cargo (type)	As required by competent authority. To be manually entered at the start of the voyage confirming whether or not hazardous cargo is being carried, namely: - Dangerous Goods (DG) - Harmful Substances (HS) - Marine Pollutants (MP) - Indications of quantities are not required.
Destination and ETA	At Master's discretion. To be manually entered at the start of the voyage and kept up to date as necessary.

Appendix C

Applications and possibilities of AIS

Appendix C Applications and possibilities of AIS

This appendix shortly describes how AIS is or can be used by coastal authorities and VTSs or in search and rescue operations.

C.1 Aiding coastal authorities

AIS offers a good opportunity for coastal authorities to monitor the vessels sailing through the coastal waters of a nation. A larger range and more information (e.g. type of cargo and destination) can be obtained than with radar; this leads to a good overview of maritime activity. In this way they can keep control of for example hazardous cargo. A disadvantage of AIS is the fact that AIS messages are sent by the vessels themselves (compared to radar, where the signal is reflected by the vessels). Although most vessels are not likely to do so, it is possible to transmit incorrect messages on purpose.

Shore side established AIS stations can simply monitor, but also actively request data from passing vessels (ship-shore). These stations can also transmit information to vessels (shore-ship), for example tides and weather forecasts.

C.2 Vessel Traffic Services

In most busy ports and waterways a VTS exists to keep control of the nautical traffic. These services use radar to map the traffic. Identification is done by radio and radar information. VTS use AIS messages for additional information and as backup when radar is not working sufficient. AIS data is used increasingly, but radar still is the main source of information for VTS operators[1]. There are mainly two reasons for this. First, the technical reliability of the signal is not always very high. This is for example the case under container cranes and when tugs are fastening to the vessel. The second reason that AIS is not fully relied on by VTS operators is due to errors and inaccuracies in the AIS messages.

Most of these errors occur in the static data of a message. Theoretically, it is possible to identify vessels quickly and correctly with AIS, which can be very useful, especially in crowded waterways. The vessel name in AIS messages does sometimes not exactly match with the name in the port its database. This makes it difficult to use the AIS data for identifying vessels. Therefore nowadays identification is, at least for the port of Rotterdam, still done manually, with help from radar and radio. This is done by determining the location from where a radio signal is transmitted (radar direction finder, see Figure C.1 (left). When the target is identified on the radar, a vessel name can be placed manually.

1 Information derived from a visit to the VTS Hoek van Holland, port of Rotterdam, Netherlands

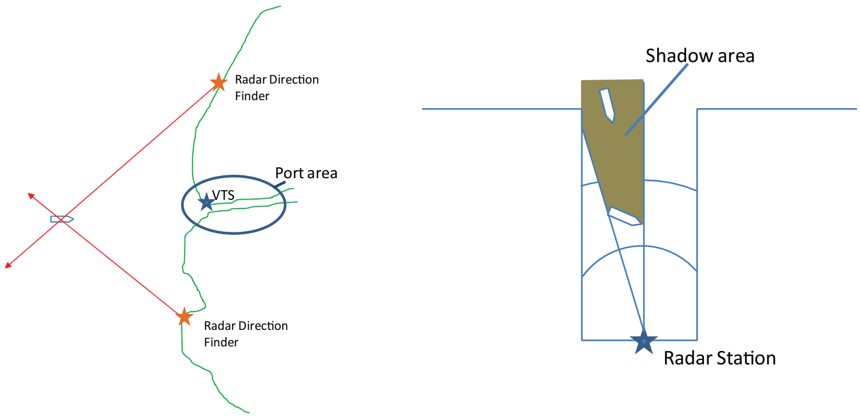

Figure C.1 The principle of a radar direction finder (left) and Radar waves blocked by another vessel (right)

VTSs can also use AIS data to map the traffic situation inside and around the port area. Advantage of AIS over radar is that the position of the vessels is much more precise. Next to this, AIS detection is not limited by obstacles like other vessels or landmass (e.g. around corners), see Figure C.1 (right). Disadvantage of AIS is the occurrence of a lot of errors in the data, which makes it difficult to rely on. Furthermore, not all vessels sailing in or through the port are equipped with AIS (e.g. fishing, recreational and inland shipping vessels).

C.3 Search and rescue

During a marine search and rescue operation it is important to know the position and navigational status of all ships in vicinity of the ship or person in distress. With AIS, this information is available for the vessels. Also Search and Rescue (SAR) aircraft can transmit their position by AIS. Lately a new tool is developed to locate persons in distress: the AIS-SART (Figure C.2). This device transmits AIS messages containing the actual position of the person[2] .

Figure C.2 AIS SART, as developed by Jotron AS.

2 International Maritime Organization, IMO, http://www.imo.org/includes/blastDataOnly.asp/data_id%3D20463/246%2883%29.pdf, accessed: 24/12/2009

Appendix D

Matlab model for the AIS analysis

Appendix D Matlab model for the AIS analysis

The matlab model used for the analysis of AIS data transforms in several steps the available rough AIS messages into data concerning the vessel behaviour of a specified selection of vessels. In this appendix, first the converting from rough AIS messages towards a number of ready to use vessel tracks is handled. Hereafter it is shown how different selections can be made from these vessel tracks. Finally, the selected vessel tracks are analysed.

D.1 Transformation rough AIS data

Some adjustments have to be made before the AIS messages that are obtained as output from ShowRoute can be used in the AIS analysis. The vessel's position is given in longitude and latitude coordinates. Disadvantage of these coordinates, is that they are measured in degrees, minutes and seconds. There is also the difficulty that one degree in lateral direction is a different distance than one degree in longitudinal direction. This makes it very difficult to compare them and because the results concerning the vessel behaviour should be obtained in meters, it is decided to recalculate the coordinates. They are transformed to coordinates in the 'Rijksdriehoeksstelsel' (RD). This national grid is used as a basis for geographical indications and files, like Geographic Information Systems. Also the port of Rotterdams infrastructure is expressed in RD coordinates. So, to evaluate a vessels position compared to the ports infrastructure it is needed to recalculate the geographical coordinates to RD coordinates. The Matlab code that is used to do so is presented below:

```
function [A0] = transform_to_RD(A0)
disp('Transform to RD...')
Latitude = A0(:,1);
Longitude = A0(:,2);
dF = 0.36 * (Latitude - 52.15517440);
dL = 0.36 * (Longitude - 5.38720621);
for i=1:size(A0)
A0(i,2)= 155000+(190094.945 * dL(i)) + (-11832.228 * dF(i) * dL(i)) + (-144.221 * dF(i)^2 * dL(i)) + (-32.391 * dL(i)^3) +
(-0.705 * dF(i)) + (-2.340 * dF(i)^3 * dL(i)) + (-0.608 * dF(i) * dL(i)^3) + (-0.008 * dL(i)^2) + (0.148 * dF(i)^2 * dL(i)^3);
A0(i,1) = 463000+(309056.544 * dF(i)) + (3638.893 * dL(i)^2) + (73.077 * dF(i)^2 ) + (-157.984 * dF(i) * dL(i)^2) +
(59.788 * dF(i)^3 ) + (0.433 * dL(i)) + (-6.439 * dF(i)^2 * dL(i)^2) + (-0.032 * dF(i) * dL(i)) + (0.092 * dL(i)^4) + (-0.054 *
dF(i) * dL(i)^4);
end
```

After the transformation towards the RD coordinates, the location of the antenne that transmits the messages on the vessel should be taken into account. This antenna is mostly not situated exactly in the middle of the vessel; it can be at a different place at every vessel. This causes inaccuries when comparing vessel positions with each other. These inaccuraries can be negligible at open sea, but in a port area, they are definitely not. It is therefore needed to adjust the vessel's coordinates by taking into account the position of the antenna in the vessel. This exact position is fortunately include in the AIS message, which makes it possible to do so. The Matlab code below shows how this calculation is done.

```
function [A2] = AntennaLocation(A1)
disp('Antenna Location...')

pf = 0.8;
sf=1 ;

for i=1:size(A1)
        bow(1)  = A1(i,1) + A1(i,8)*cos(A1(i,7)*pi()/180)*sf;
        bow(2) = A1(i,2) + A1(i,8)*sin(A1(i,7)*pi()/180)*sf;
        starfor(1)  = A1(i,1) + A1(i,8)*cos(A1(i,7)*pi()/180)*pf*sf  - A1(i,10)*sin(A1(i,7).*pi./180)*sf;
        starfor(2) = A1(i,2) + A1(i,8)*sin(A1(i,7)*pi./180).*pf.*sf + A1(i,10)*cos(A1(i,7)*pi./180).*sf;
        staraft(1) = A1(i,1) - A1(i,9)*cos(A1(i,7)*pi()/180)*s - A1(i,10)*sin(A1(i,7)*pi./180).*sf;
        staraft(2) = A1(i,2) - A1(i,9)*sin(A1(i,7)*pi./180).*sf + A1(i,10)*cos(A1(i,7)*pi./180).*sf;
        portaft(1) = A1(i,1) - A1(i,9)*cos(A1(i,7)*pi./180).*sf  + A1(i,11)*sin(A1(i,7)*pi./180).*sf;
        portaft(2) = A1(i,2) - A1(i,9)*sin(A1(i,7)*pi./180).*sf  - A1(i,11)*cos(A1(i,7)*pi./180).*sf;
        portfor(1) = A1(i,1) + A1(i,8)*cos(A1(i,7)*pi./180).*pf.*sf  + A1(i,11)*sin(A1(i,7)*pi./180).*sf;
        portfor(2) = A1(i,2) + A1(i,8)*sin(A1(i,7)*pi./180).*pf.*sf - A1(i,11)*cos(A1(i,7)*pi./180).*sf;
        A1(i,1)=(starfor(1)+staraft(1)+portaft(1)+portfor(1))/4;
        A1(i,2)=(starfor(2)+staraft(2)+portaft(2)+portfor(2))/4;
end
```

D.2 Track selection

After the operations mentioned above, a number of tracks is left with which the analysis can be performed. Before any calculations regarding for example the average vessel path can be made, a selection of tracks must be determined. This selection can depend on the vessel size and the direction of the vessel (incoming or outgoing). It is however also possible to include the external circumstances in the selection process. By using a Graphical User Interace (GUI) the selection criteria are filled in, see Figure D.1.

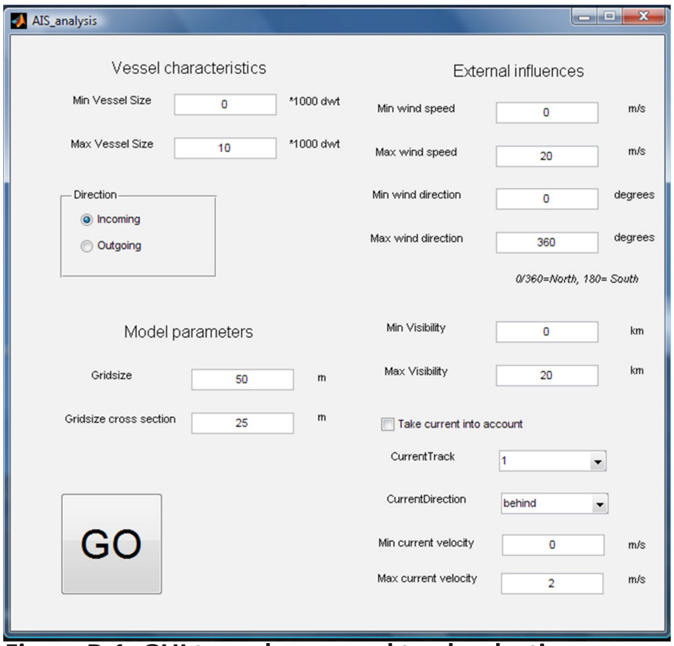

Figure D.1 GUI to make a vessel track selection

After filling in the GUI, the following Matlab code is run.

```
function [A4,f,h,tracks_data,GeenInfo] = route_toewijzing(A2,a,ondergrens,bovengrens,r,LowLim_wind,UpLim_
wind,LowLim_dir,UpLim_dir,LowLim_visibility,UpLim_visibility,Current_track,Current_dir,Current_size_max,Current_
size_min,Cur)
disp('Chosing tracks...')
tf=strcmp(a,'ingaand');
if tf==1
s=200;
t=100;
end
if tf==0
s=100;
t=200;
end

n=1;
k=1;
for i=1:size(A2)-1
  if abs(A2(i+1,3)-A2(i,3))<600
     A2(i,6)=n;
  else
     A2(i,6)=n;
      n=n+1;
     if (and(A2(i,2)<62000,A2(i,1)>444300))
        A2(i,13)=200;
     else
```

```
            A2(i,13)=300;
        end
        if and((A2(i,1)<441500),and(A2(i,1)>440000,and(A2(i,2)<66000,A2(i,2)>62200)))
            A2(i,13)=100;
        end
        if (and(A2(i+1,2)<62000,A2(i+1,1)>444300))
            A2(i+1,13)=200;
        else
            A2(i+1,13)=300;
        end
        if and((A2(i+1,1)<441500),and(A2(i+1,1)>440000,and(A2(i+1,2)<66000,A2(i+1,2)>62200)))
            A2(i+1,13)=100;
        end
        b{1,n}=A2(k+1:i,:);
        k=i;
    end
end

load Input/Grootte
b{1,1}=0;nnn=0;GeenInfo=0;
for i=2:n
    c=size(b{1,i});
    d=b{1,i};
    for x=1:size(Grootte)
        if d(1,5)==Grootte(x,1)
            d(:,12)=Grootte(x,2);
        end
    end
    b{1,i}=d;
    if or(d(1,12)<ondergrens,or(d(1,12)>bovengrens,c(1,1)<10))
        b{1,i}=0;
    end
    if d(1,12)==0;b{1,i}=0;nnn=nnn+1;GeenInfo(nnn)=d(1,5);end
    if or(d(1,14)<LowLim_wind,d(1,14)>UpLim_wind)
        b{1,i}=0;
    end
    if UpLim_dir-LowLim_dir>0
        if or(d(1,15)<LowLim_dir,d(1,15)>UpLim_dir)
            b{1,i}=0;
        end
    else
        if and(d(1,15)<LowLim_dir,d(1,15)>UpLim_dir)
            b{1,i}=0;
        end
    end
    if or(d(1,16)<LowLim_visibility,d(1,16)>UpLim_visibility)
```

```
      b{1,i}=0;
    end
    if or(b{1,i}==0,Cur~=1);else
      [Check] = Current_check(d,Current_track,Current_dir,Current_size_max,Current_size_min);
      if Check(1,1)==0;
        b{1,i}=0;
      end
    end
end

j=1;b{1,1}=0;tracks_data(1,1)=0;
for i=1:n
    c=size(b{1,i});
    d=b{1,i};
    if size(b{1,i})<100;b{1,i}=0;end
    if b{1,i}==0;
    else
    if or(d(1,13)~=s,d(c(1,1),13)~=t)
      b{1,i}=0;
      else
      tracks_data(j,1)=i-1;
      tracks_data(j,2)=d(1,5);
      j=j+1;
      end
    end
end

y=0;f{1,1}(1,1)=0;
for i=1:n
    if b{1,i}==0
    else
      y=y+1;
      f{y,1}=b{1,i};
    end
end
if f{1,1}(1,1)~=0
g=randperm(round(numel(f)));
h=f(g(1:numel(f)*r));

A4=cell2mat(h);
else
    h{1,1}=0;A4(1,1)=0;
end
```

D.3 Analysis selected tracks

The analysis of the selected tracks contains several aspects. First target is to determine the average vessel path and the accompanying average vessel speed. Together with this, also the deviation of the vessels over the different cross sections in the waterway is determined. The same is done for the vessel speed. The Matlab code in which this is done, is presented below.

```
function [Tracks,B1] = bepaling_gem_positie_snelheid_final_v4(a,gridsize,gridsize_verdeling,h)
disp('Calculate average track (1)')
tf=strcmp(a,'ingaand');
if tf==1
route=180;
else route=0;
end
load Input/RefLine

Xstart=59000;
Xeind=68000;
Ystart=440000;
Yeind=450000;
Xtotal=Xeind-Xstart;
Ytotal=Yeind-Ystart;
Xkruis=65500;
Ykruis=4.441*10^5;
Deviation=cell(numel(RefLine(:,1)),3);

n=0;
for xxx=1:numel(RefLine(:,1))
  disp(xxx)
  x=RefLine(xxx,1);
  n=n+1;
  v=0;
  vv=0;
  bb=0;pp=0;bbb=0;

  for iii=1:size(h)
    if xxx==1;Tracks{iii,2}=h{iii,1}(1,6);end
    clear a
    a(:,1)=h{iii,1}(:,1);
    a(:,2)=h{iii,1}(:,2);
    a(:,3)=h{iii,1}(:,4);
    a(:,4)=h{iii,1}(:,7);
    a(:,5)=h{iii,1}(:,6);
    b=a;
    v=0;
```

```
        bb=0;
    for i=1:size(a)
        Bpar=a(i,1)-a(i,2)*tan((RefLine(xxx,3)-90)*pi/180);
        CrossX=(Bpar-RefLine(xxx,4))/(tan((RefLine(xxx,3))*pi/180)-tan((RefLine(xxx,3)-90)*pi/180));
        CrossY=tan((RefLine(xxx,3)-90)*pi/180)*CrossX+Bpar;
        Dist=sqrt((CrossY-a(i,1))^2+(CrossX-a(i,2))^2);
        if or(Dist>gridsize/2,or(abs(RefLine(xxx,1)-a(i,2))>2000,abs(RefLine(xxx,2)-a(i,1))>2000))
            b(i,:)=0;
        else
            v=v+1;
            bb(v,1:5)=a(i,:);
            bb(v,7)=CrossX;bb(v,8)=CrossY;
        end
    end
    vv=vv+1;
    if numel(bb(:,1))~=1;bbb(vv,1:8)=mean(bb(:,1:8));bbb(vv,6)=v;Tracks{iii,1}(xxx,1)=mean(bb(:,8));Tracks{iii,1}(xxx,2)=m
ean(bb(:,7));Tracks{iii,1}(xxx,3)=mean(bb(:,3));
    else
        if bb(1,1)~=0;bbb(vv,1:8)=bb(:,1:8);bbb(vv,6)=v;Tracks{iii,1}(xxx,1)=bb(:,8);Tracks{iii,1}(xxx,2)=bb(:,7);Tracks{iii,1}
(xxx,3)=bb(:,3);
        else
            bb=0;
             for i=1:size(a)
              Bpar=a(i,1)-a(i,2)*tan((RefLine(xxx,3)-90)*pi/180);
              CrossX=(Bpar-RefLine(xxx,4))/(tan((RefLine(xxx,3))*pi/180)-tan((RefLine(xxx,3)-90)*pi/180));
              CrossY=tan((RefLine(xxx,3)-90)*pi/180)*CrossX+Bpar;
              Dist=sqrt((CrossY-a(i,1))^2+(CrossX-a(i,2))^2);
              if or(Dist>gridsize,or(abs(RefLine(xxx,1)-a(i,2))>2000,abs(RefLine(xxx,2)-a(i,1))>2000))
                  b(i,:)=0;
              else
                  v=v+1;
                  bb(v,1:5)=a(i,:);
                  bb(v,7)=CrossX;bb(v,8)=CrossY;
              end
             end
            if numel(bb(:,1))~=1;bbb(vv,1:8)=mean(bb(:,1:8));bbb(vv,6)=v;Tracks{iii,1}(xxx,1)=mean(bb(:,8));Tracks{iii,1}(xxx,
2)=mean(bb(:,7));Tracks{iii,1}(xxx,3)=mean(bb(:,3));
            else if bb(1,1)~=0;bbb(vv,1:8)=bb(:,1:8);bbb(vv,6)=v;Tracks{iii,1}(xxx,1)=bb(:,8);Tracks{iii,1}
(xxx,2)=bb(:,7);Tracks{iii,1}(xxx,3)=bb(:,3);else vv=vv-1;end
            end
        end
    end
  end
    e=bbb;

    if numel(e)~=1;
```

```
    eX=mean(e(:,7));
    eY=mean(e(:,8));
    Deviation{n,2}=eX;Deviation{n,3}=eY;
    Deviation{n,1}(1,:)=-400:gridsize_verdeling:400;
    Deviation{n,1}(2,:)=0;Deviation{n,1}(3,:)=0;
    for eee=1:numel(e(:,1))
       if or(and(e(eee,4)>45,and(e(eee,4)<=135,e(eee,8)<eY)),or(and(e(eee,4)>135,and(e(eee,4)<=225,e(eee,7)<eX)),or(a
nd(e(eee,4)>225,and(e(eee,4)<=315,e(eee,8)>eY)),and(or(e(eee,4)>315,e(eee,4)<=45),e(eee,7)>eX))))
          e(eee,9)=sqrt((e(eee,7)-eX)^2+(e(eee,8)-eY)^2);
          else e(eee,9)=-sqrt((e(eee,7)-eX)^2+(e(eee,8)-eY)^2);
       end
       nnn=0;
       for nnn=1:numel(Deviation{n,1}(1,:))
          if abs(e(eee,9)-Deviation{n,1}(1,nnn))<gridsize_verdeling/2
             Deviation{n,1}(2,nnn)=Deviation{n,1}(2,nnn)+1;
             Deviation{n,1}(3,nnn)=Deviation{n,1}(3,nnn)+e(eee,3);
          end
       end
    end
    Afw2=prctile(e(:,9),2);Afw98=prctile(e(:,9),98);
    f(n,12)=Afw2;f(n,13)=Afw98;
    if route==180;
       Prct2X=eX-Afw2*cos(RefLine(xxx,3)*pi/180);Prct2Y=eY-Afw2*sin(RefLine(xxx,3)*pi/180);
       Prct98X=eX-Afw98*cos(RefLine(xxx,3)*pi/180);Prct98Y=eY-Afw98*sin(RefLine(xxx,3)*pi/180);
    else Prct2X=eX+Afw2*cos(RefLine(xxx,3)*pi/180);Prct2Y=eY+Afw2*sin(RefLine(xxx,3)*pi/180);
       Prct98X=eX+Afw98*cos(RefLine(xxx,3)*pi/180);Prct98Y=eY+Afw98*sin(RefLine(xxx,3)*pi/180);
    end
    f(n,1)=mean(e(:,7));
    f(n,2)=mean(e(:,8));            %average path
    f(n,3)=Prct2X;
    f(n,4)=Prct2Y;
    f(n,5)=Prct98X;
    f(n,6)=Prct98Y;
    f(n,7)=mean(e(:,3));             %average speed
    f(n,8)=prctile(e(:,3),2);
    f(n,9)=prctile(e(:,3),98);
    f(n,10)=vv;
    f(n,11)=mean(e(:,4));
    u{n,1}(:,1)=e(:,3);
    end
end

g=find(f==0);
f(g)=NaN;
B1=f;
```

Appendix E

χ^2 tests, skewness and excess kurtosis

Appendix E χ² tests, skewness and excess kurtosis

This appendix gives the more detailed elaboration of the χ^2 tests that are performed in the case study. Next to this, also the results from the calculation of the skewness and excess kurtosis that are not shown in the main report, are shown here.

E.1 χ² tests

χ^2 tests are performed for as well the vessel distribution as the vessel speed distribution over the waterway (see section 5.4). This test examines the degree of agreement between the empirical distribution and a specific theoretical distribution. Equation (E.1) shows how the value for χ^2 is calculated.

$$\chi^2 = \sum_{1}^{k} \frac{(f_o - f_e)^2}{f_e} \quad \textbf{(E.1)}$$

where

f_o = observed frequency of each class or interval;
f_e = expected frequency for each class or interval predicted by a theoretical distribution;
k = total classes or intervals.

If the value for χ^2 is equal to zero, then the empirical en theoretical distribution have a perfect match. If this is not the case, the size of χ^2 determines the degree of agreement. The hypothesis that is made when performing a χ^2 test, is that no significant difference exists between the compared distributions. If the calculated value for χ^2 is too large, this hypothesis is rejected. Before it can be seen if this is the case, two questions should be answered. First, the degree of freedom of the distributions should be obtained. The degrees of freedom reflect the number of classes in which the two distributions are compared to each other and the number of parameters that is needed to describe the theoretical distribution,equation (E.2)).

$$\theta = k - 1 - m \quad \textbf{(E.2)}$$

where

θ = degrees of freedom;
k = number of classes or intervals;
m = number of parameters needed to calculate the expected frequencies.

After the degrees of freedom are determined, the significance level has to be set. This reflects the confidence level that is used to reject or accept the hypothesis. This level can be set by at different values, depending on for example the nature of the studie. Throughout this thesis a level of 95% is used; this is also done for the χ^2 tests.

When the value for χ^2, the degrees of freedom and the significance level are known, the hypothesis can be tested. This is done by comparing the value found for χ^2 to a value obtained from a Chi-square distribution. This is value from the Chi-square distribution is mostly derived from a table, in which also the degrees of freedom and the significance level are included. Table E.1 shows an example of how a part of this table looks like. It can be seen that the a significance level of 95% combined with 5 degrees of freedom, leads to a value of 11.1.

Table E.1 Example of a part of the Chi-square distribution table

Degrees of freedom	Significance level			
	99.5 %	99 %	95 %	90 %
1	7.88	6.63	3.84	2.71
2	10.6	9.21	5.99	4.61
3	12.84	11.34	7.81	6.25
4	14.96	13.28	9.49	7.78
5	16.7	15.1	11.1	9.2
6	18.5	16.8	12.6	10.6

This value can hereafter be compared to the value found for χ^2. If the value for χ^2 is larger than the value found in the table, their is a significance difference between the two distributions. The hypothesis of no difference is in such a case rejected.

In the thesis, the above described χ^2 test is performed several times. As wel the vessel distributions, as the vessel speed distributions over different cross sections are tested. Table E.2 to Table E.11 show the results for these tests. The column 'χ^2' shows the value that was found for χ^2 and 'Freedom' reflects the degrees of freedom. The column 'χ^2 table' shows the value that was read from the Chi-square distribuion table. The column 'Check' reflects the result of the comparison between the first two: the hypothesis is accepted (OK) or rejected (FAIL).

Table E.2 χ^2 tests performed for the vessel distributions over the cross sections on location 1-4 Size class < 10,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	12.9	19	30.1	OK	16.2	24	36.4	OK
2	8.8	11	19.7	OK	16.3	22	33.9	OK
3	16.6	15	25	OK	14.8	25	37.7	OK
4	7.9	16	26.3	OK	11.6	12	21	OK

Table E.3 χ^2 tests performed for the vessel distributions over the cross sections on location 1-4 Size class 10,000-40,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	18.2	17	27.6	OK	34.2	29	42.6	OK
2	9.7	8	15.5	OK	17.0	16	26.3	OK
3	11.8	12	21	OK	12.4	23	35.2	OK
4	6.2	15	25	OK	15.4	9	16.9	OK

Table E.4 χ^2 tests performed for the vessel distributions over the cross sections on location 1-4 Size class 40,000-70,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	17.4	17	27.6	OK	25.3	20	31.4	OK
2	7.2	6	12.6	OK	20.2	14	23.7	OK
3	28.9	15	25	FAIL	9.7	16	26.3	OK
4	17.2	10	18.3	OK	10.8	8	15.5	OK

Table E.5 χ^2 tests performed for the vessel distributions over the cross sections on location 1-4 Size class 70,000-100,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	7.8	17	27.6	OK	29.7	26	38.9	OK
2	2.5	6	12.6	OK	13.8	15	25	OK
3	12.0	12	21	OK	19.5	15	25	OK
4	16.0	12	21	OK	13.6	6	12.6	FAIL

Table E.6 χ^2 tests performed for the vessel distributions over the cross sections on location 1-4 Size class >100,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	16.5	17	27.6	OK	16.3	27	40.1	OK
2	9.9	9	16.9	OK	16.3	15	25	OK
3	9.9	13	22.4	OK	21.8	15	25	OK
4	23.1	11	19.7	FAIL	8.2	6	12.6	OK

Table E.7 χ^2 tests performed for the vessel speed distributions over the cross sections on location 1-4 Size class <10,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	18.4	17	27.6	OK	7.9	15	25	OK
2	17.7	20	31.4	OK	10.9	12	21	OK
3	10.3	16	26.3	OK	14.5	16	26.3	OK
4	3.8	17	27.6	OK	6.5	13	22.4	OK

Table E.8 χ^2 tests performed for the vessel speed distributions over the cross sections on location 1-4 Size class 10,000-40,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	30.7	20	31.4	OK	22.5	15	25	OK
2	22.2	26	38.9	OK	9.2	13	22.4	OK
3	11.9	19	30.1	OK	18.9	16	26.3	OK
4	7.3	18	28.9	OK	9.7	13	22.4	OK

Table E.9 χ^2 tests performed for the vessel speed distributions over the cross sections on location 1-4 Size class 40,000-70,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	29.7	13	22.4	FAIL	23.8	18	28.9	OK
2	7.7	8	15.5	OK	11.2	15	25	OK
3	8.3	7	14.1	OK	15.5	11	19.7	OK
4	13.7	4	9.49	FAIL	13.1	9	16.9	OK

Table E.10 χ^2 tests performed for the vessel speed distributions over the cross sections on location 1-4 Size class 70,000-100,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	17.4	14	23.7	OK	31.0	18	28.9	FAIL
2	17.8	10	18.3	OK	23.0	16	26.3	OK
3	13.4	6	12.6	FAIL	12.9	12	21	OK
4	2.5	4	9.49	OK	13.1	9	16.9	OK

Table E.11 χ^2 tests performed for the vessel speed distributions over the cross sections on location 1-4 Size class >100,000 dwt.

Location	Incoming				Outgoing			
	χ^2	Freedom	χ^2 table	Check	χ^2	Freedom	χ^2 table	Check
1	13.9	18	28.9	OK	18.4	14	23.7	OK
2	15.3	11	19.7	OK	12.7	11	19.7	OK
3	4.7	5	11.1	OK	6.6	11	19.7	OK
4	9.1	3	7.81	FAIL	8.2	8	15.5	OK

E.2 Skewness and kurtosis

For the vessel distributions over the cross sections at the different locations, the skewness and kurtosis were already given in the main report. For the vessel speed distribution this is however not done. Therefore these two parameters are shown below (Table E.12 and Table E.13).

Table E.12 Skewness for the vessel speed distributions over the cross sections at locations 1 to 4, for the different datasets at locations 1 to 4

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	-0.68	-0.05	-0.63	-0.1	0.2	0.02	0.22	0.33	0.12	-0.28
2	-0.59	-0.12	-0.17	-0.72	0.58	0.47	0.66	0.24	0.12	0.02
3	-0.38	-0.65	0.12	-0.54	-0.43	0.24	0.13	0.16	0.25	0.41
4	-0.36	-0.54	-0.11	-0.21	0.03	-0.17	-0.97	0.44	-0.21	0.22

Table E.13 Excess kurtosis for the vessel speed distributions over the cross sections at locations 1 to 4, for the different datasets at locations 1 to 4

Location	<10,000		10,000-40,000		40,000-70,000		70,000-100,000		>100,000	
	In	Out	In	Out	In	Out	In	Out	In	Out
1	0.33	-0.4	-0.28	-0.48	0.5	-0.79	0.34	-0.33	-0.41	-0.57
2	-0.25	-0.45	-0.65	2.31	0.66	0.69	0.95	-0.62	0.26	-0.63
3	-0.04	0.59	-0.39	0.36	0.9	-0.74	0.5	0.82	0.52	0.18
4	0.18	0.91	-0.35	-0.38	0.73	0.1	3.45	1.03	0.52	0.51

Appendix F

Vessel and vessel speed distributions

Appendix F Vessel and vessel speed distributions

This appendix shows all distributions that are used throughout the case study, to obtain insight in the average vessel behaviour. First, the vessel distributions over the waterway at the four predefined locations is given for every size class. Second, the vessel speed distributions, again at the four specified locations is shown. For both, as well the the empirical as the fitted normal distribution are given. Finally also the speed distribution over the waterway is presented.

F.1 Vessel distribution over the waterway

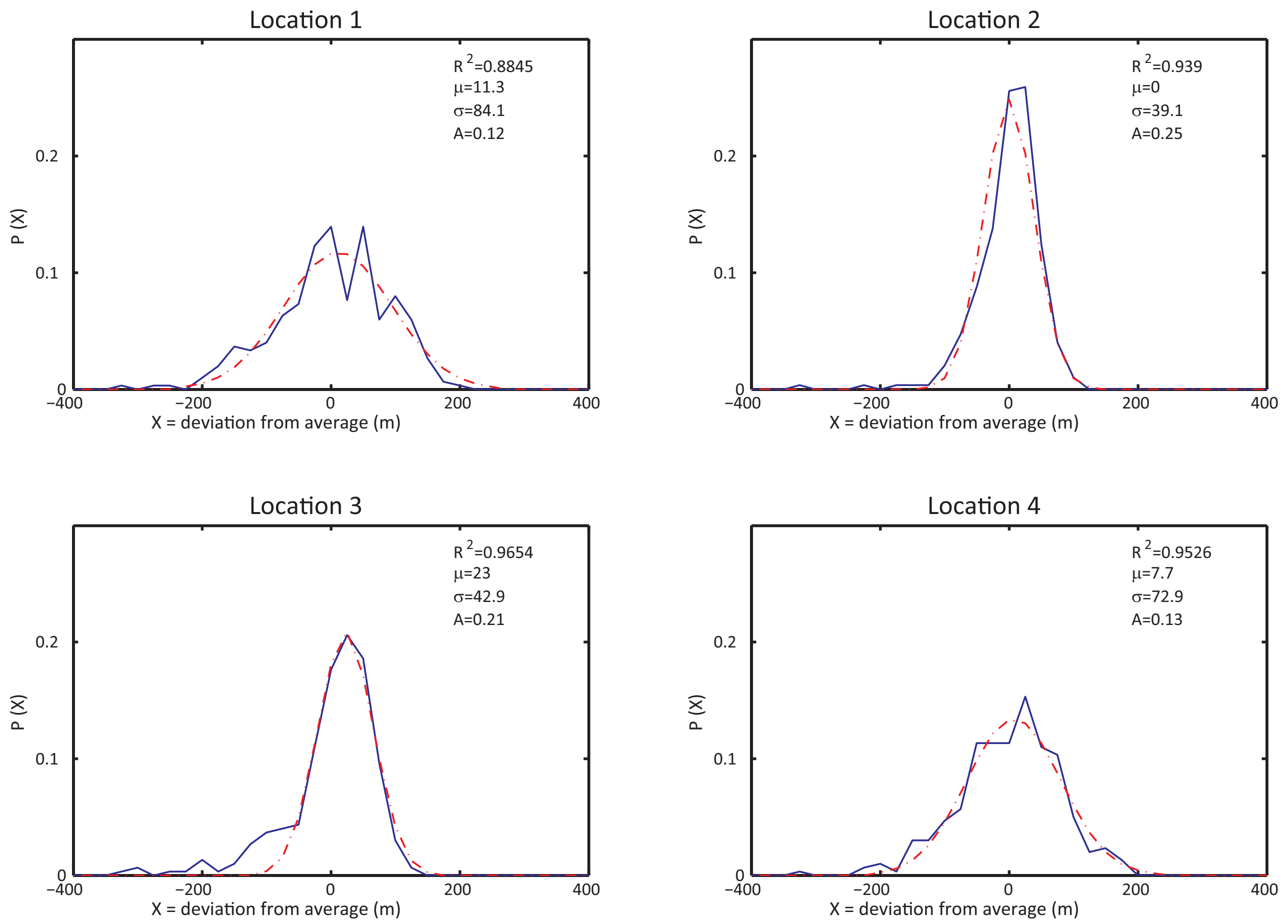

Figure F.1 Vessel distribution over cross sections 1-4 for incoming vessels from sizeclass <10,000 dwt

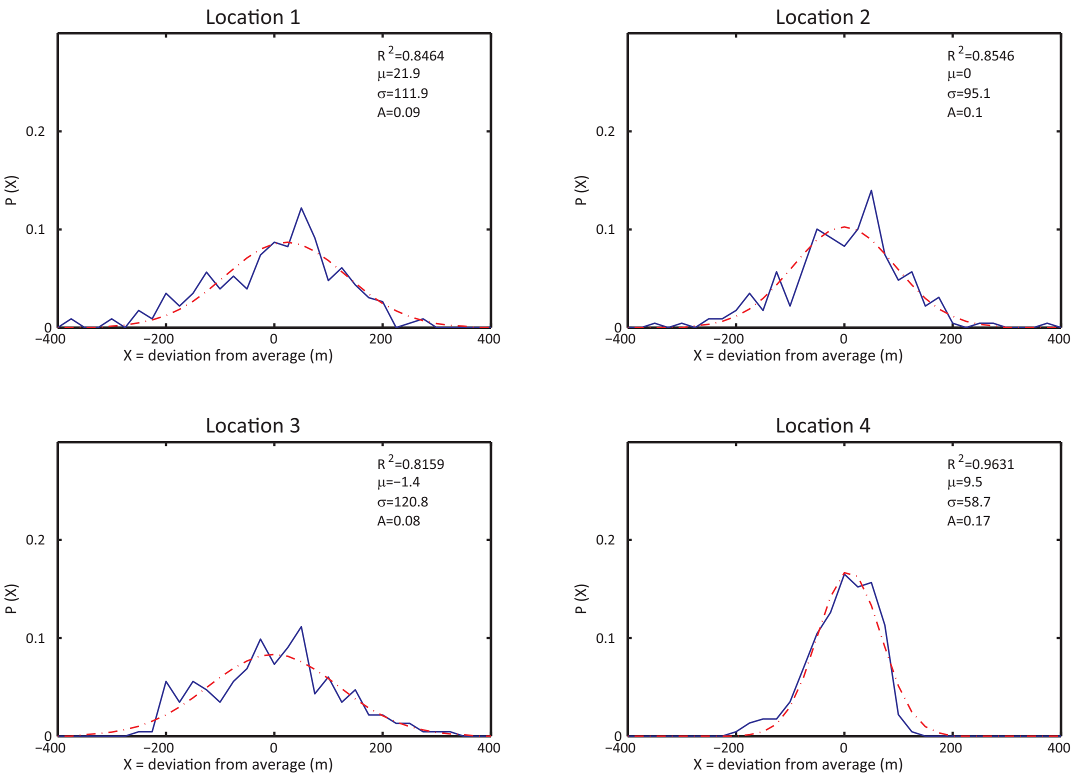

Figure F.2 Vessel distribution over cross sections 1-4 for outgoing vessels from sizeclass <10,000 dwt

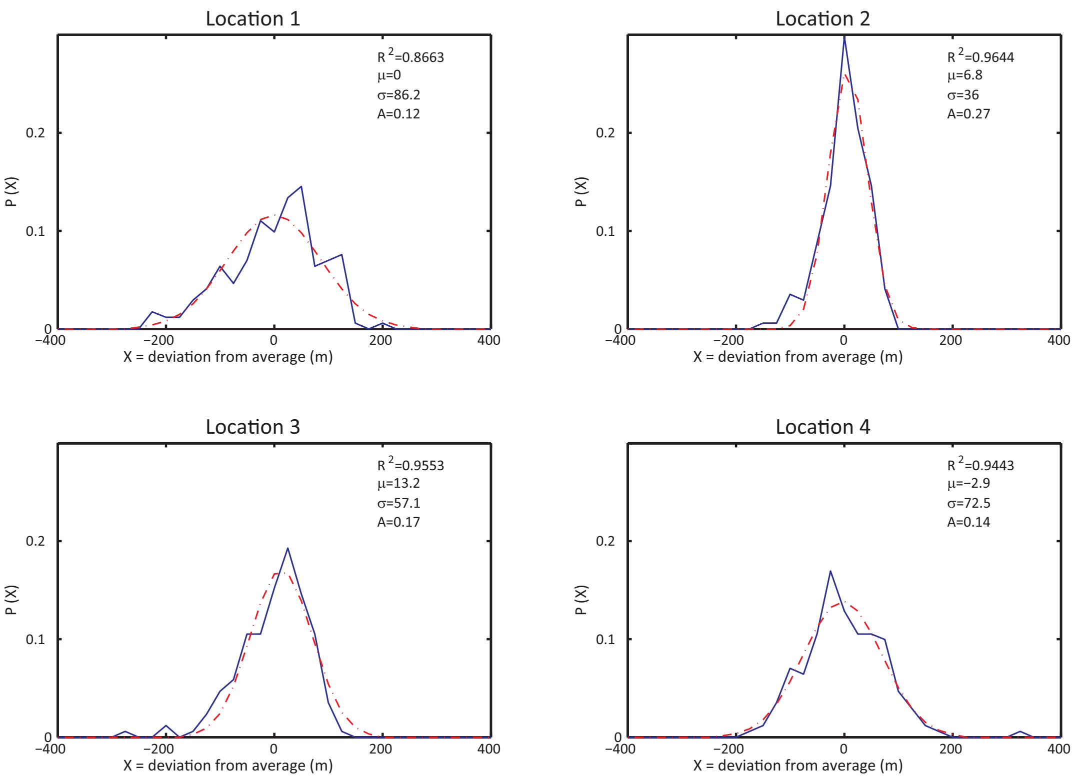

Figure F.3 Vessel distribution over cross sections 1-4 for incoming vessels from sizeclass 10,000-40,000 dwt

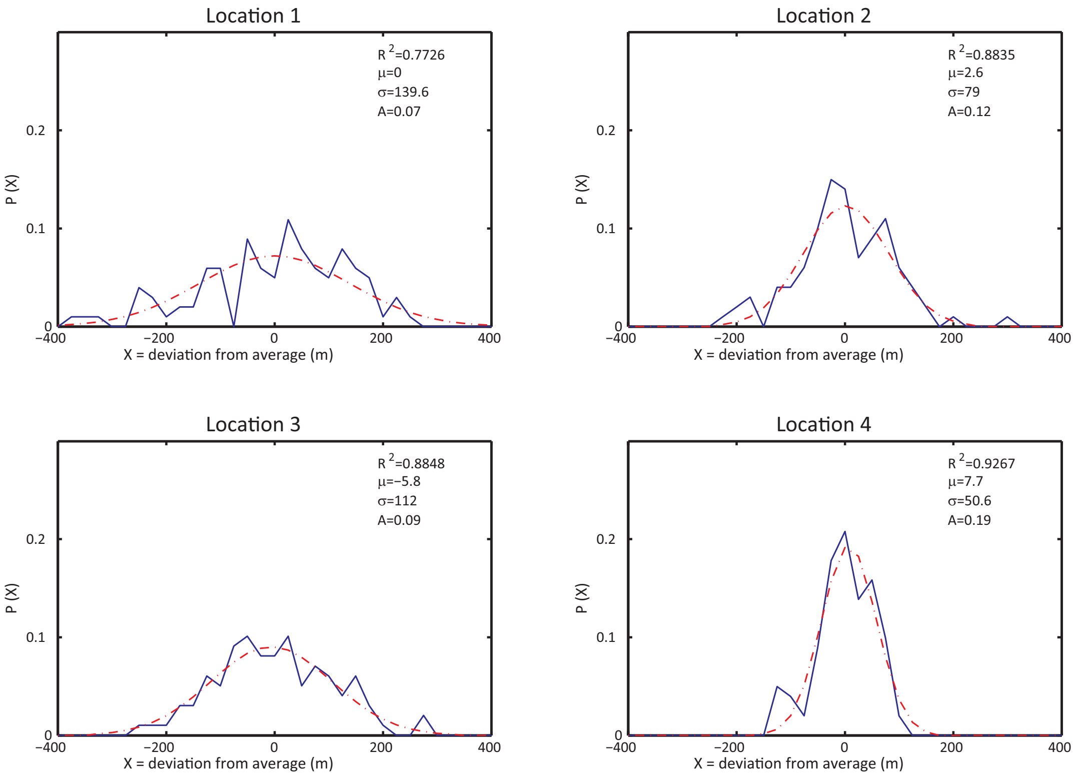

Figure F.4 Vessel distribution over cross sections 1-4 for outgoing vessels from sizeclass 10,000,40,000- dwt

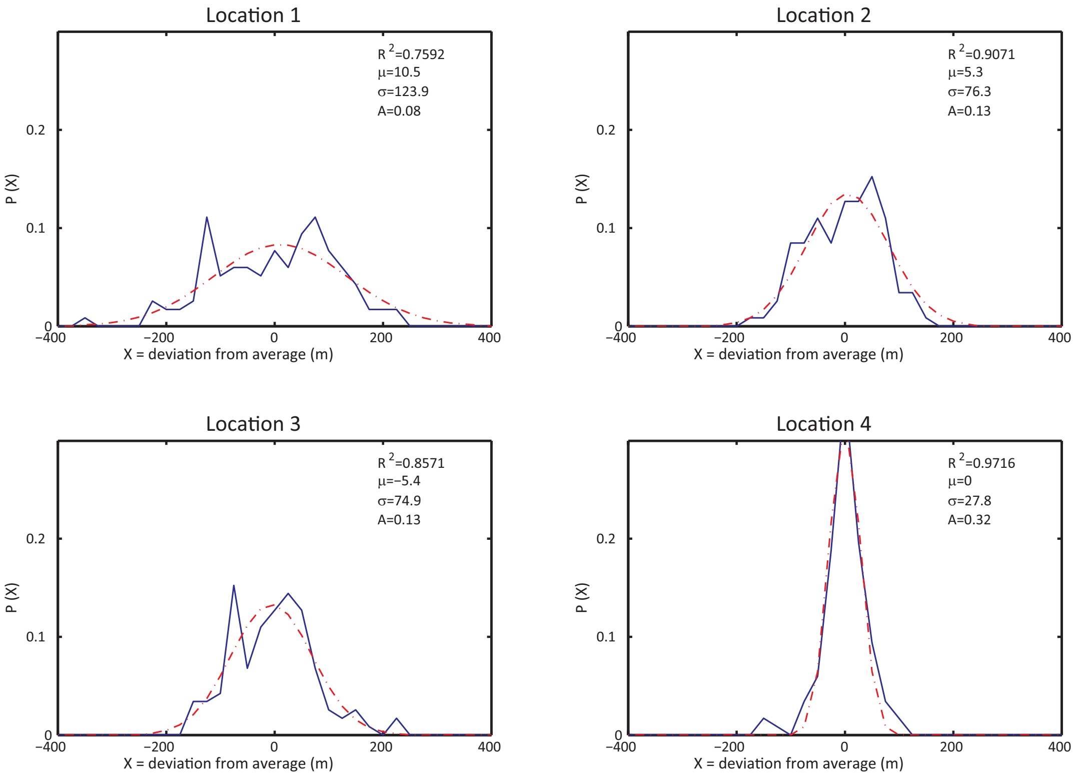

Figure F.5 Vessel distribution over cross sections 1-4 for incoming vessels from sizeclass 40,000-70,000 dwt

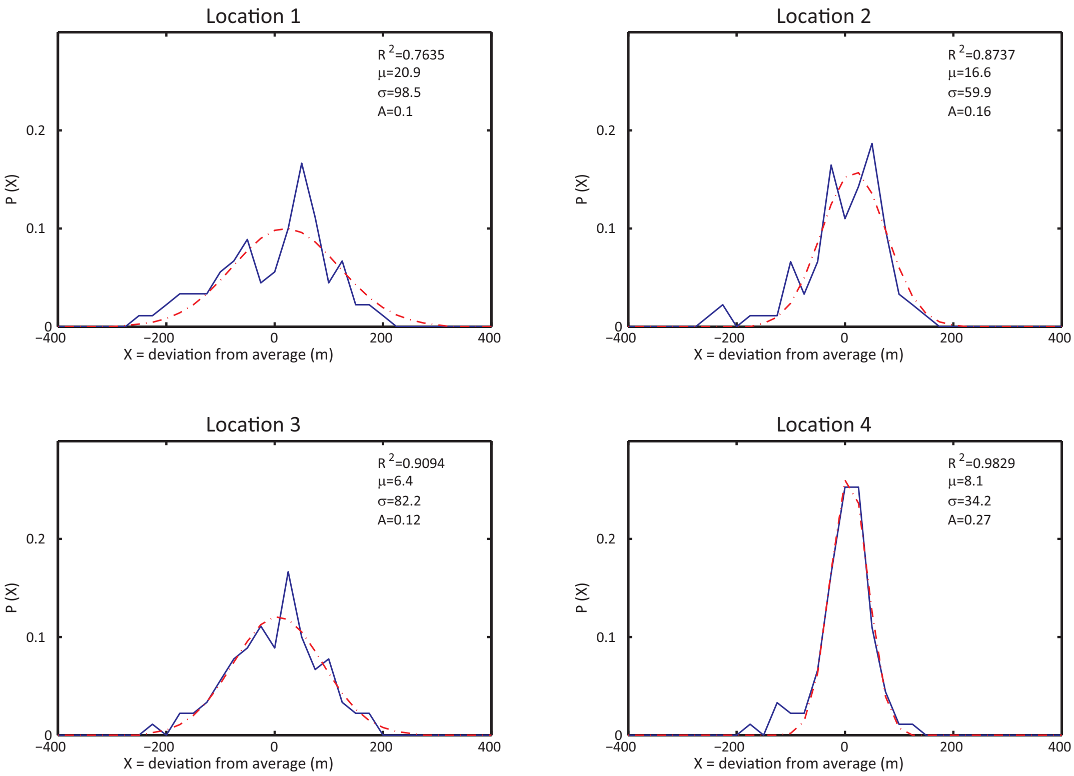

Figure F.6 Vessel distribution over cross sections 1-4 for outgoing vessels from sizeclass 40,000-70,000 dwt

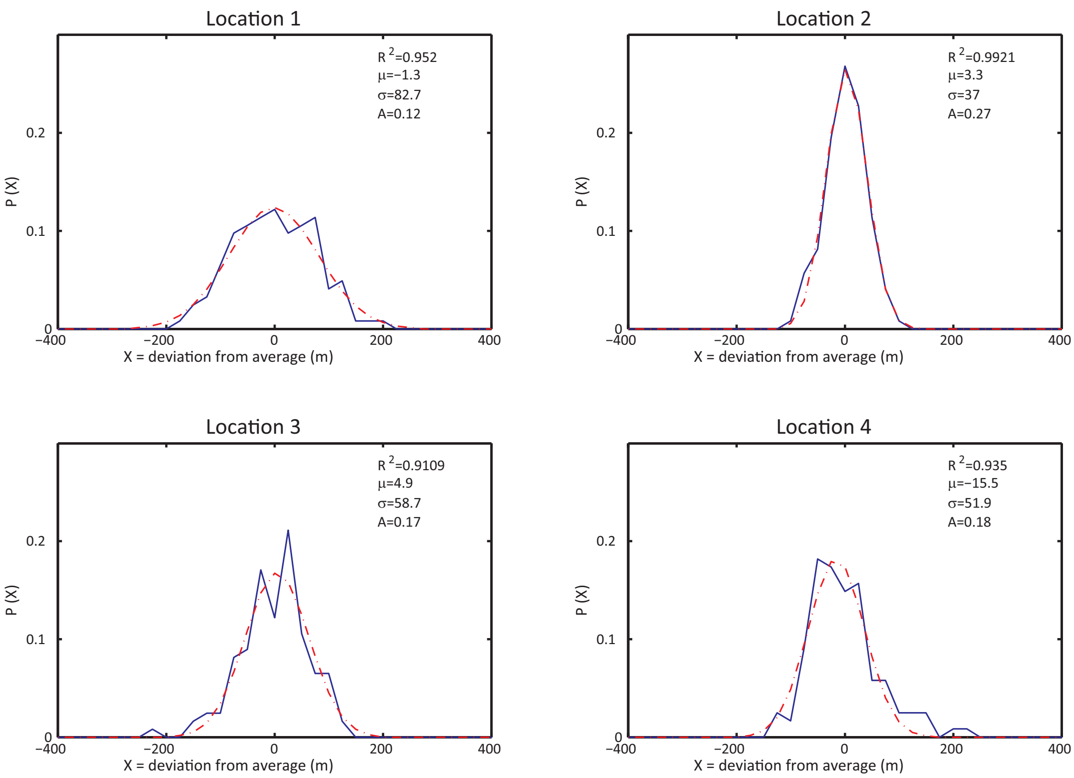

Figure F.7 Vessel distribution over cross sections 1-4 for incoming vessels from sizeclass 70,000-100,000 dwt

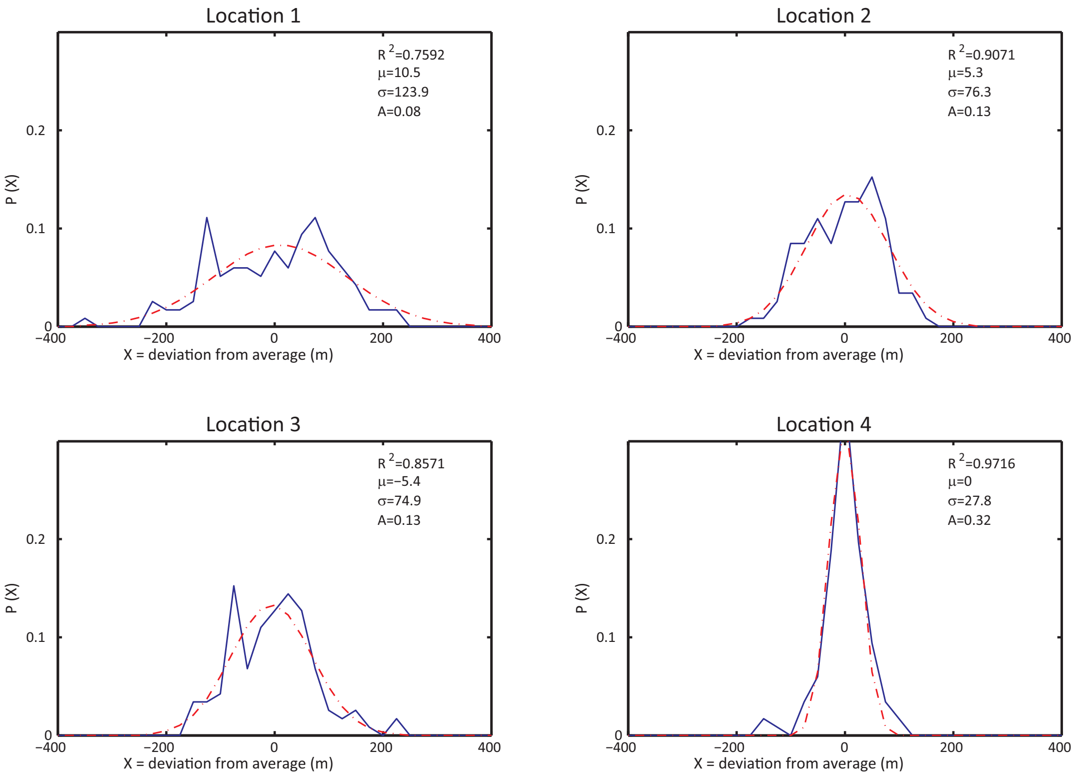

Figure F.8 Vessel distribution over cross sections 1-4 for outgoing vessels from sizeclass 70,000-100,000 dwt

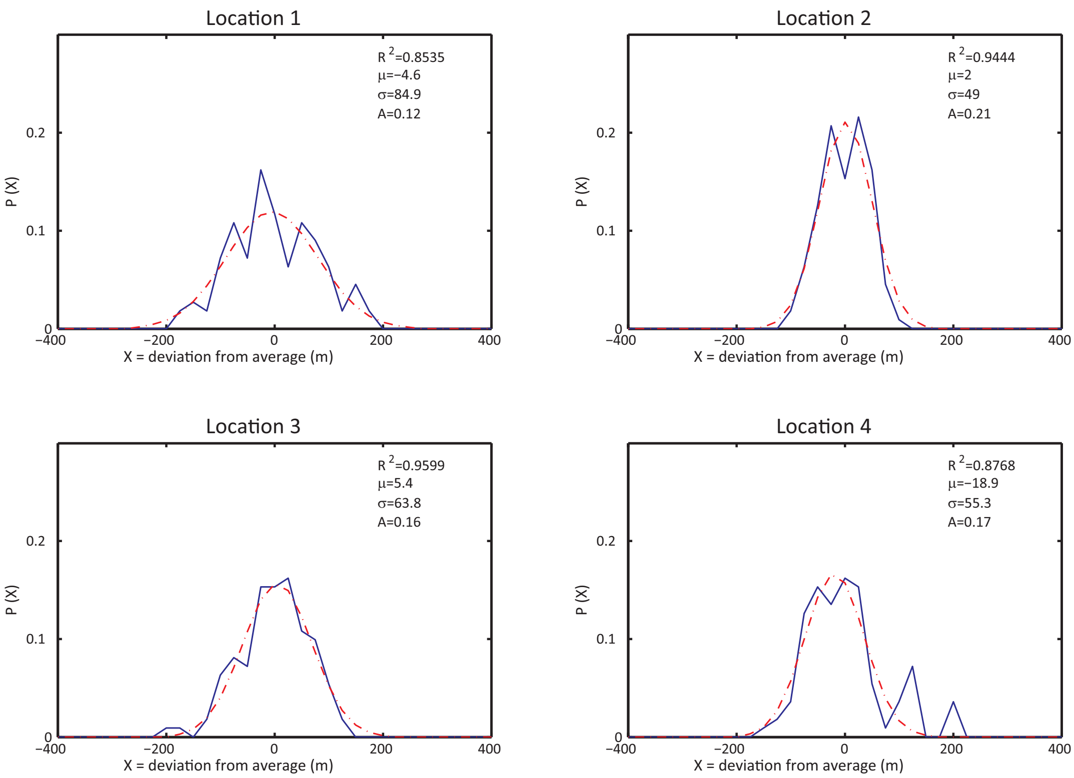

Figure F.9 Vessel distribution over cross sections 1-4 for incoming vessels from sizeclass >100,000 dwt

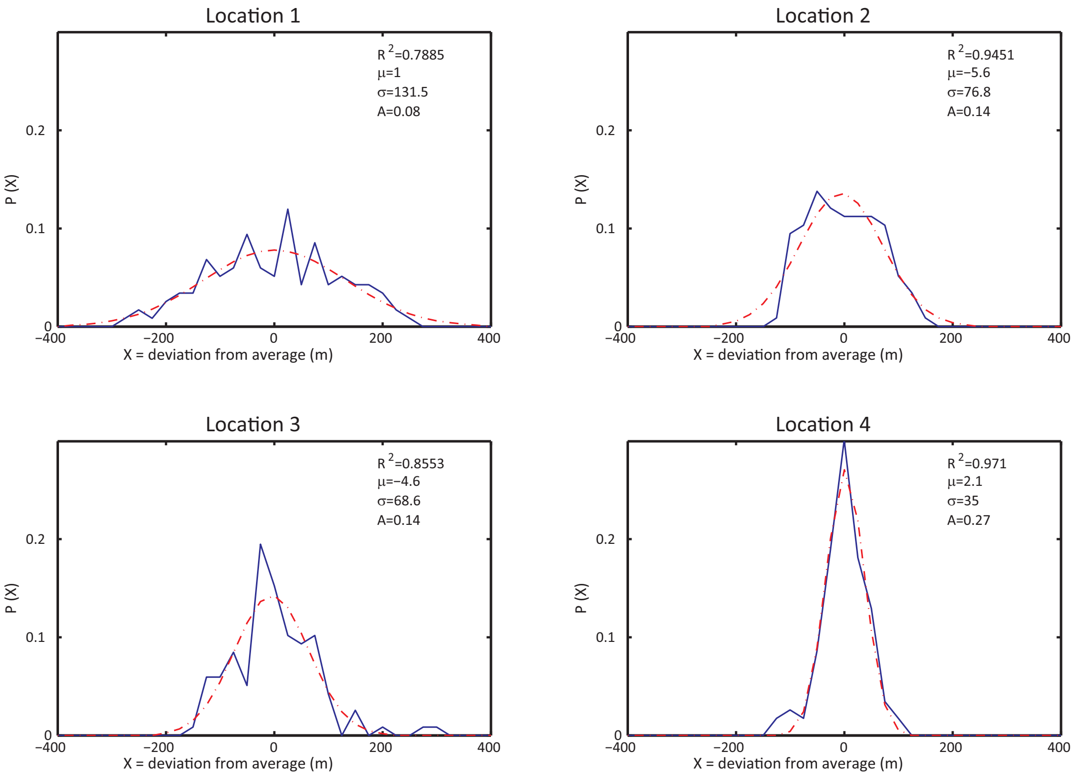

Figure F.10 Vessel distribution over cross sections 1-4 for outgoing vessels from sizeclass >100,000 dwt

F.2 Vessel speed distribution on a location on the waterway

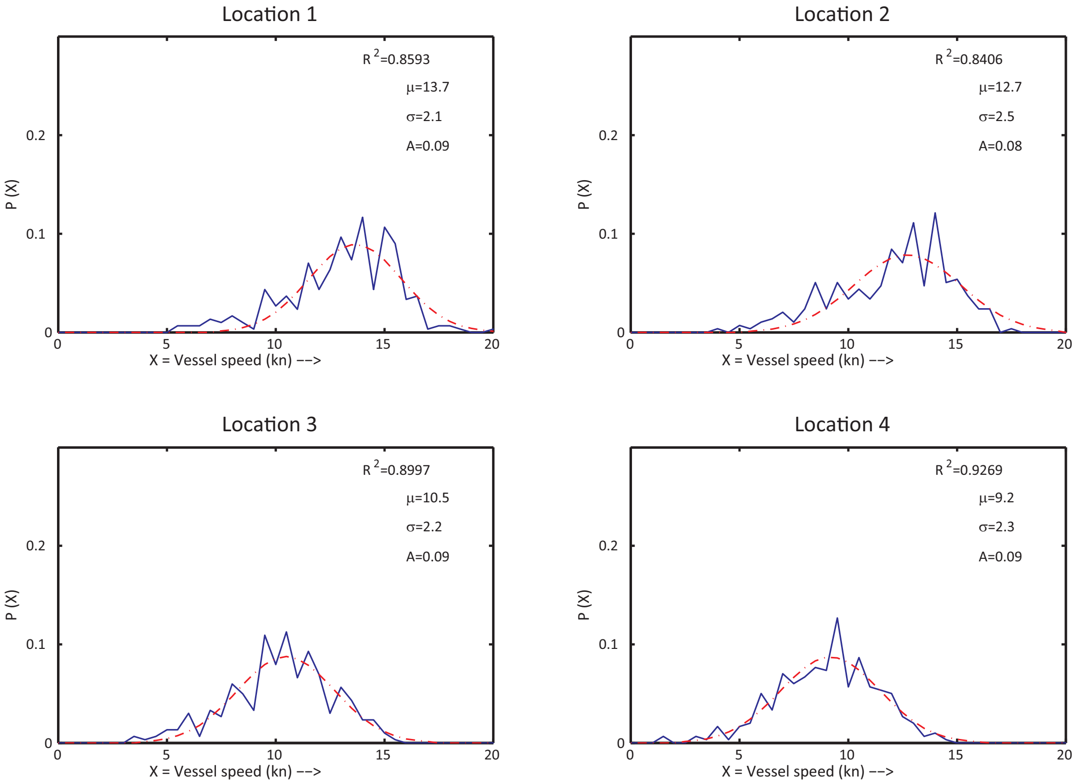

Figure F.11 Vessel speed distribution on location 1-4, for incoming vessels from size class <10,000 dwt

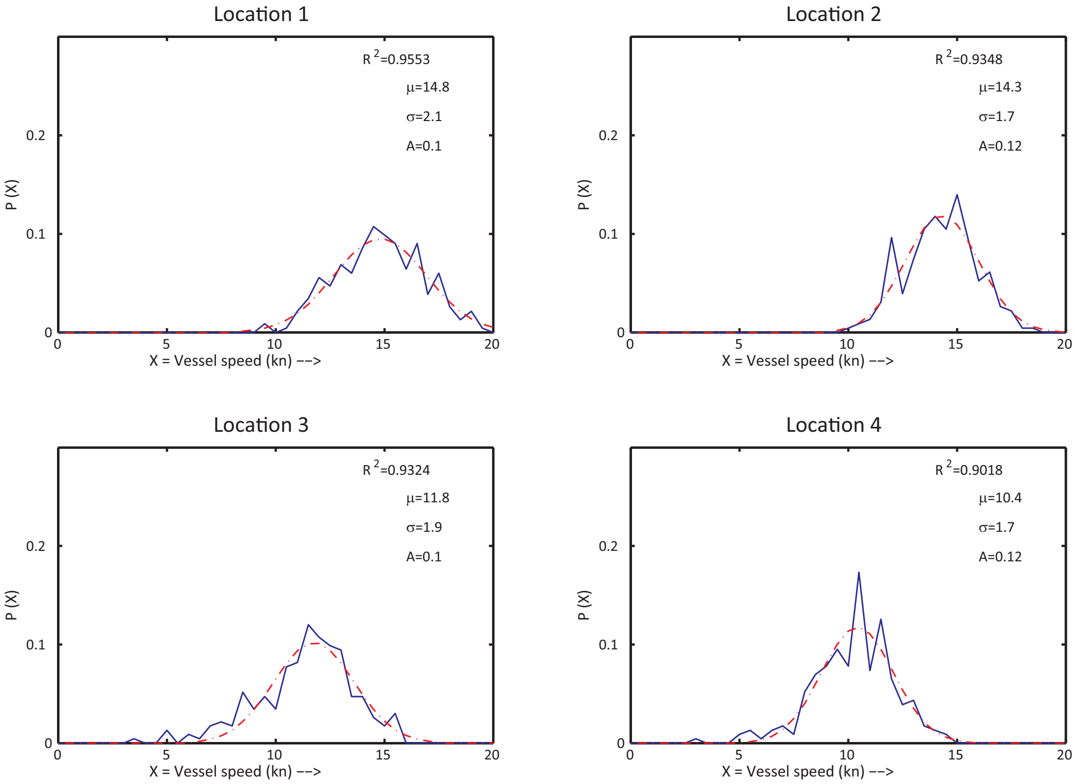

Figure F.12 Vessel speed distribution on location 1-4, for outgoing vessels from size class <10,000 dwt

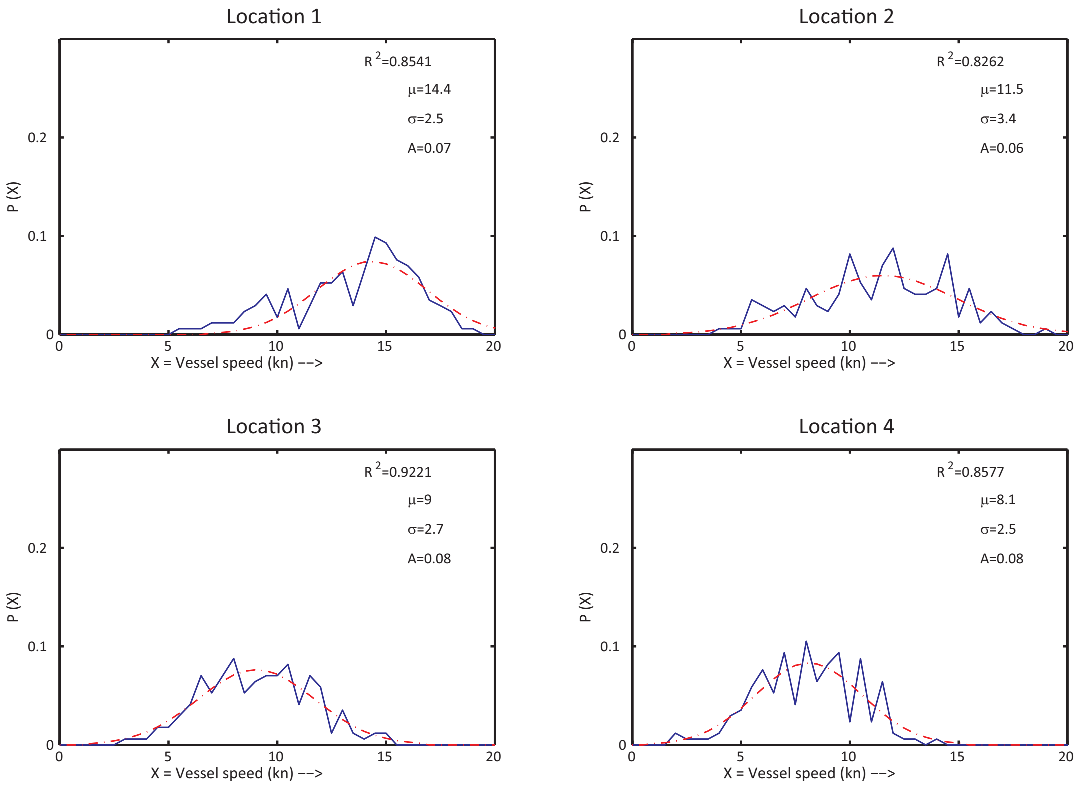

Figure F.13 Vessel speed distribution on location 1-4, for incoming vessels from size class 10,000-40,000 dwt

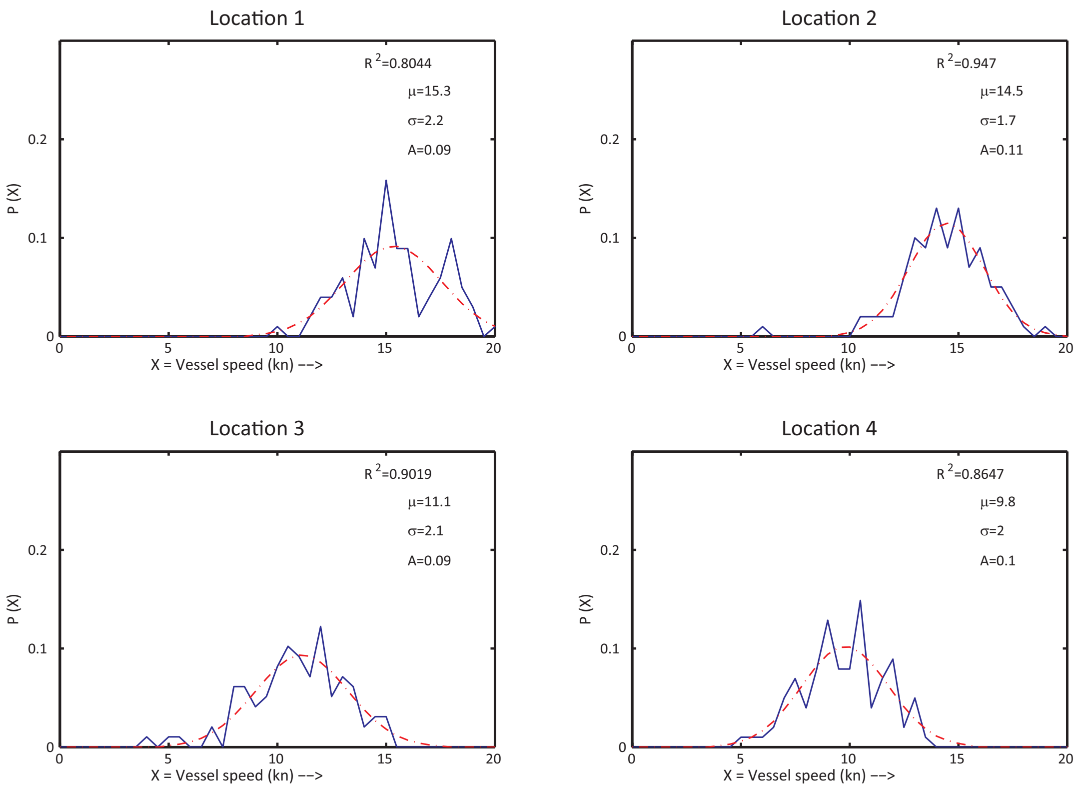

Figure F.14 Vessel speed distribution on location 1-4, for outgoing vessels from size class 10,000-40,000 dwt

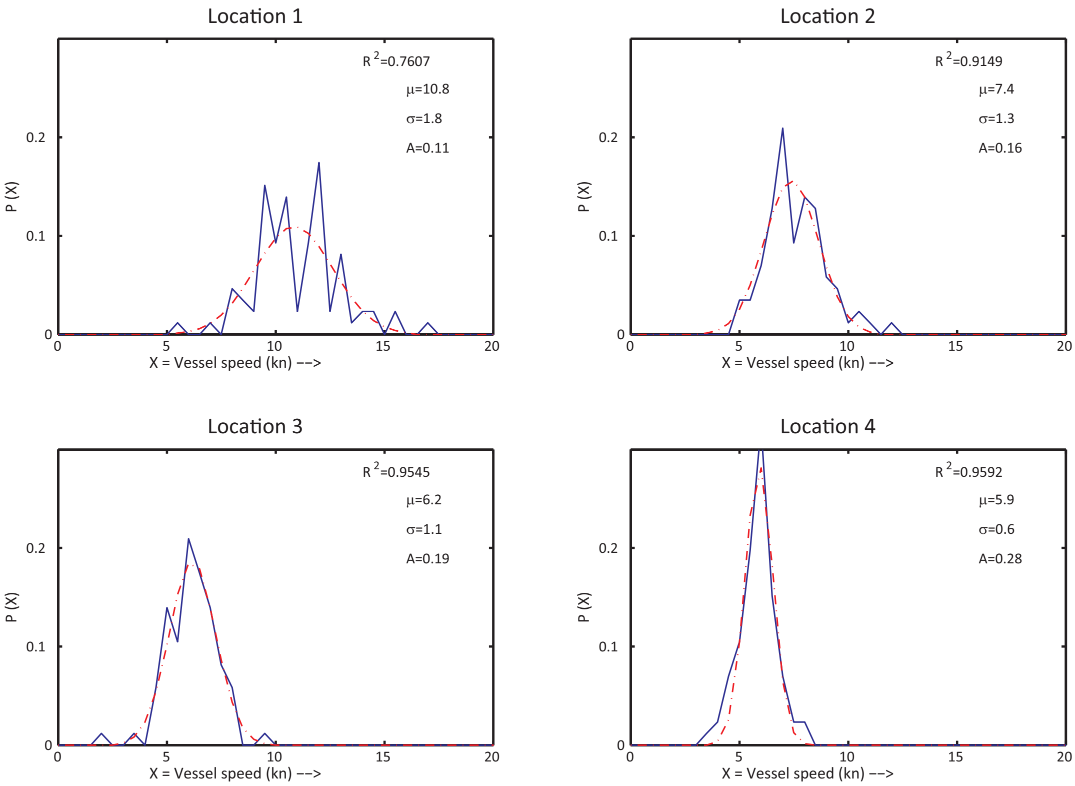

Figure F.15 Vessel speed distribution on location 1-4, for incoming vessels from size class 40,000-70,000 dwt

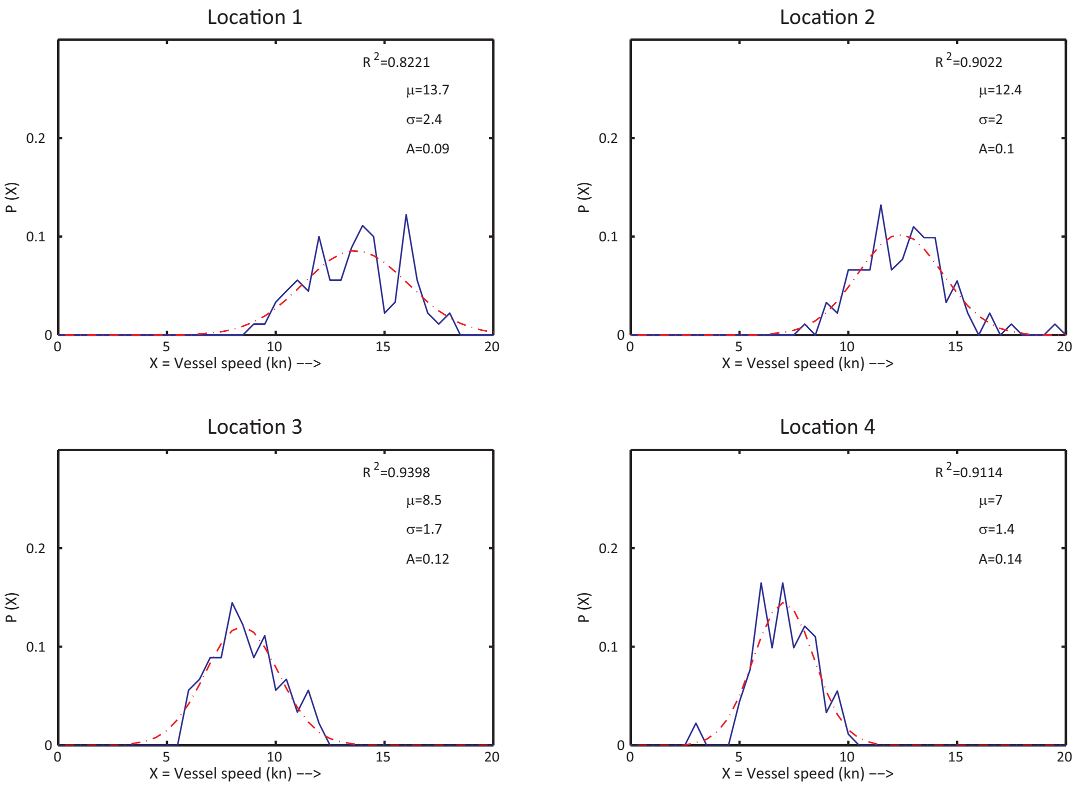

Figure F.16 Vessel speed distribution on location 1-4, for outgoing vessels from size class 40,000-70,000 dwt

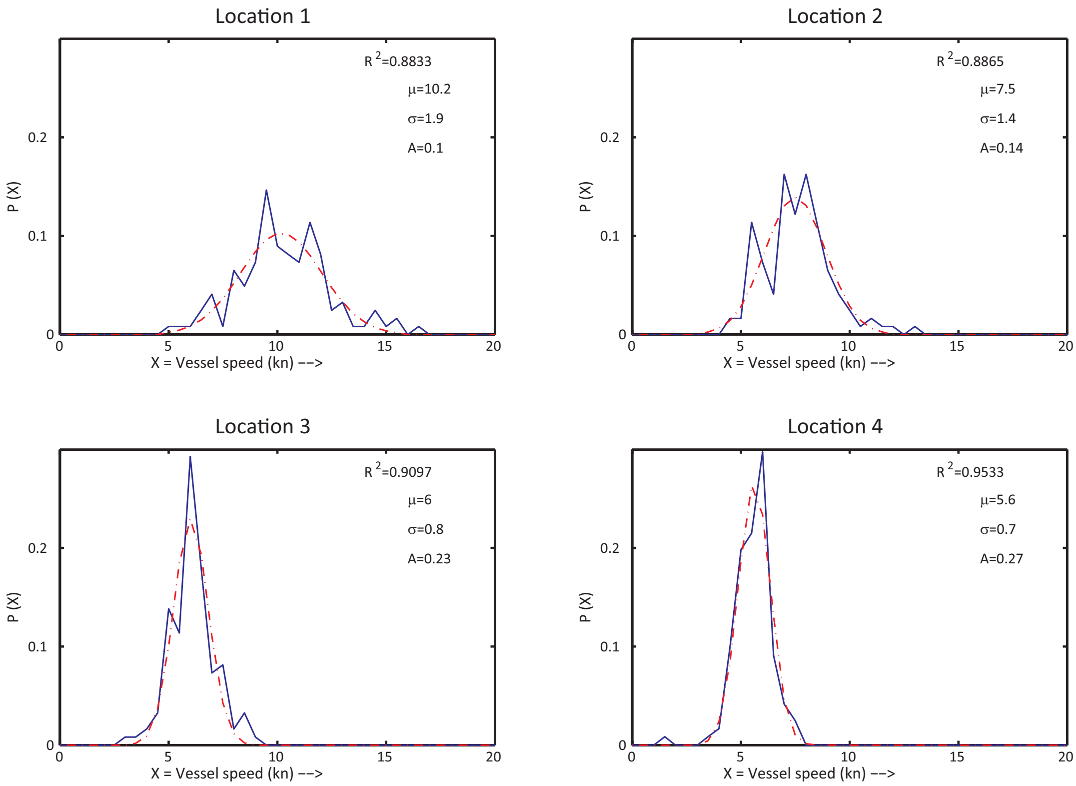

Figure F.17 Vessel speed distribution on location 1-4, for incoming vessels from size class 70,000-100,000 dwt

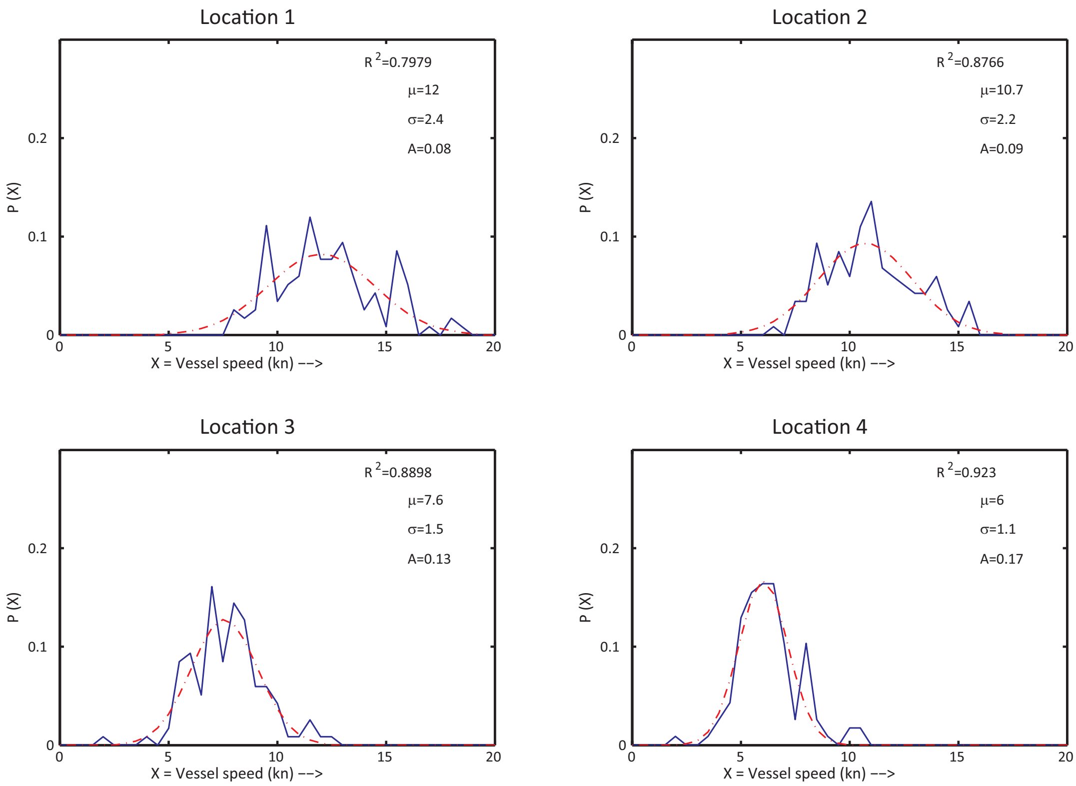

Figure F.18 Vessel speed distribution on location 1-4, for outgoing vessels from size class 70,000-100,000 dwt

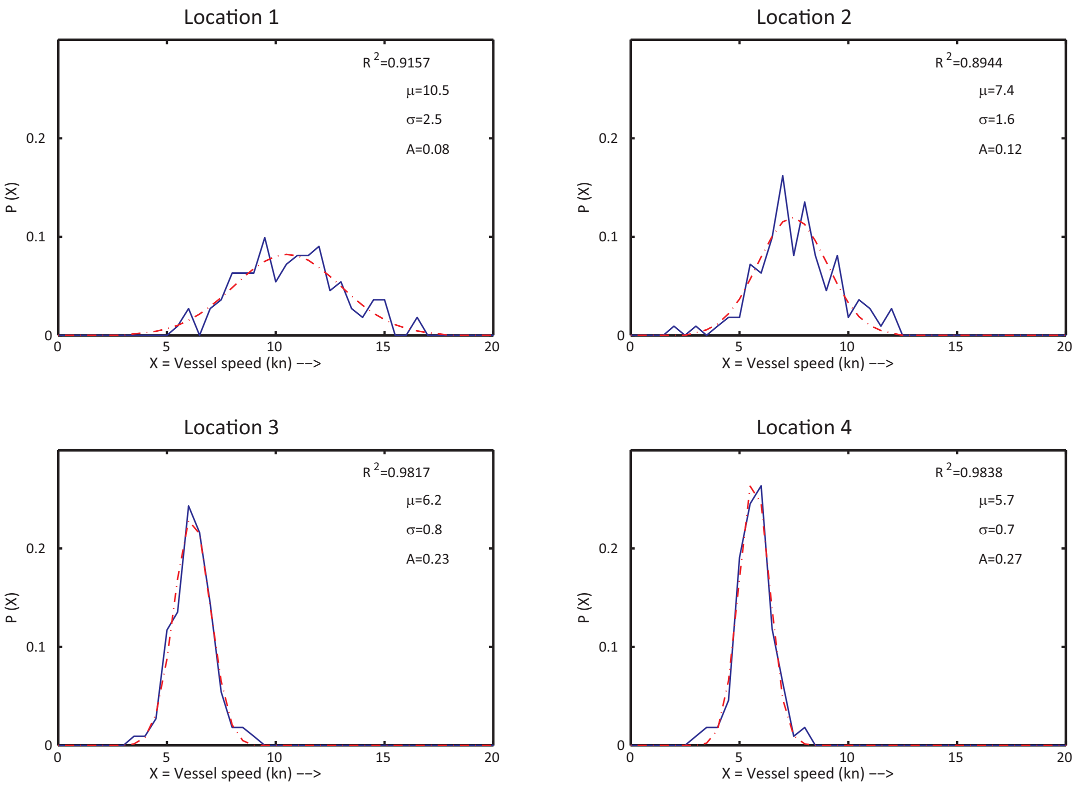

Figure F.19 Vessel speed distribution on location 1-4, for incoming vessels from size class >100,000 dwt

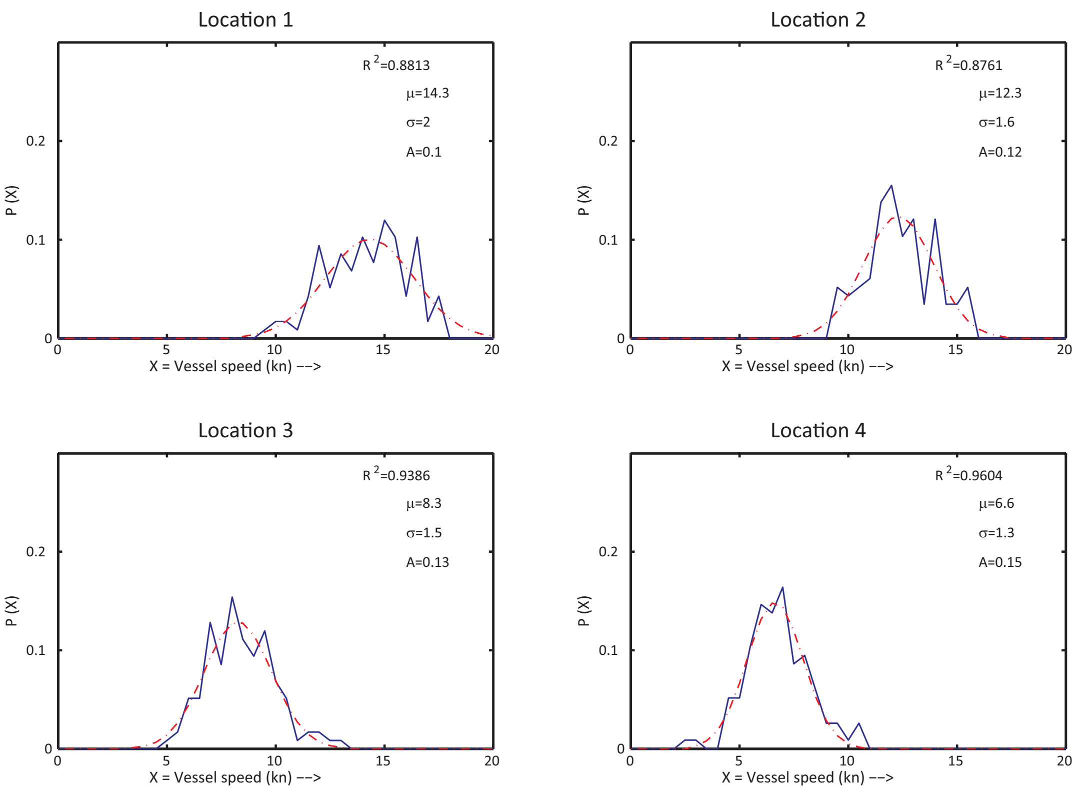

Figure F.20 Vessel speed distribution on location 1-4, for outgoing vessels from size class >100,000 dwt

F.3 Vessel speed distribution over cross section

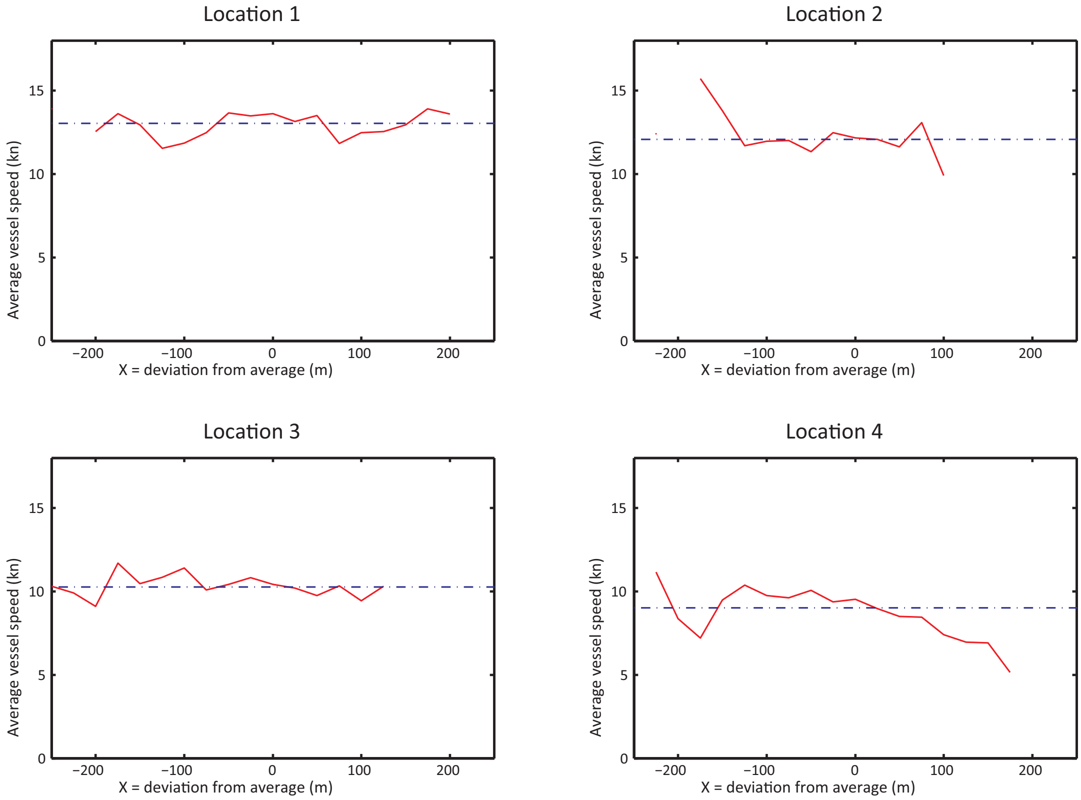

Figure F.21 Vessel speed distribution over cross sections 1-4, for incoming vessels from size class <10,000 dwt

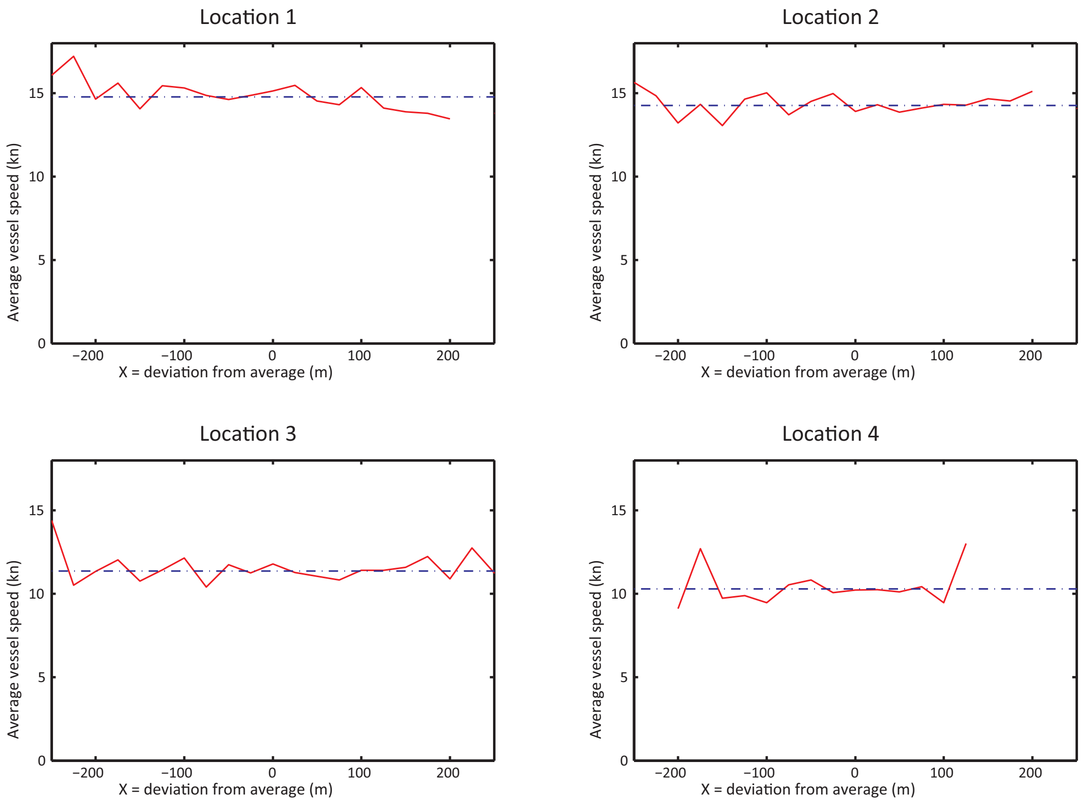

Figure F.22 Vessel speed distribution over cross sections 1-4, for outgoing vessels from size class <10,000 dwt

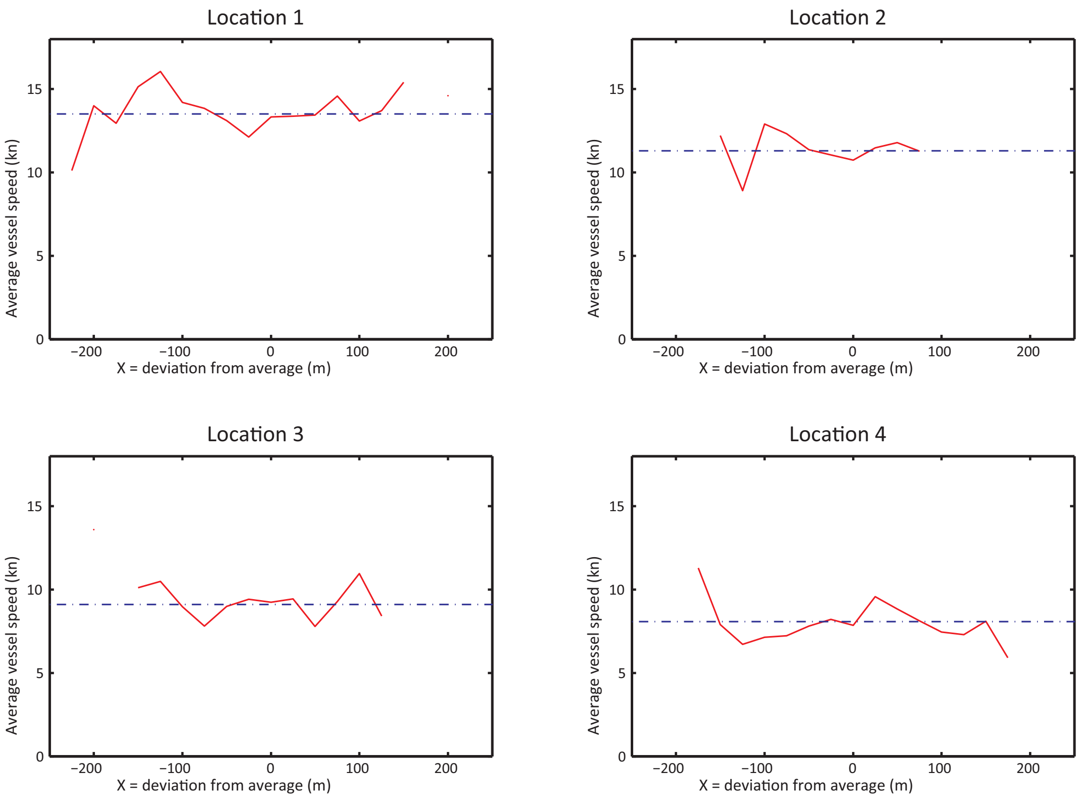

Figure F.23 Vessel speed distribution over cross sections 1-4, for incoming vessels from size class 10,000-40,000 dwt

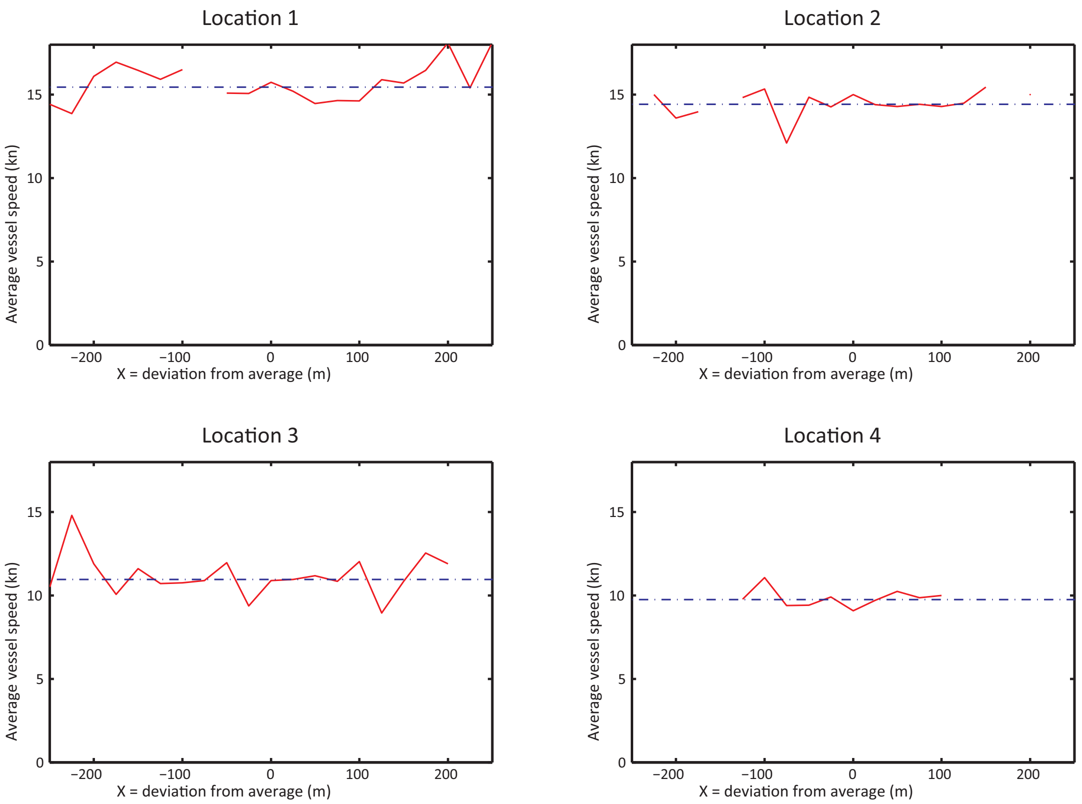

Figure F.24 Vessel speed distribution over cross sections 1-4, for outgoing vessels from size class 10,000-40,000 dwt

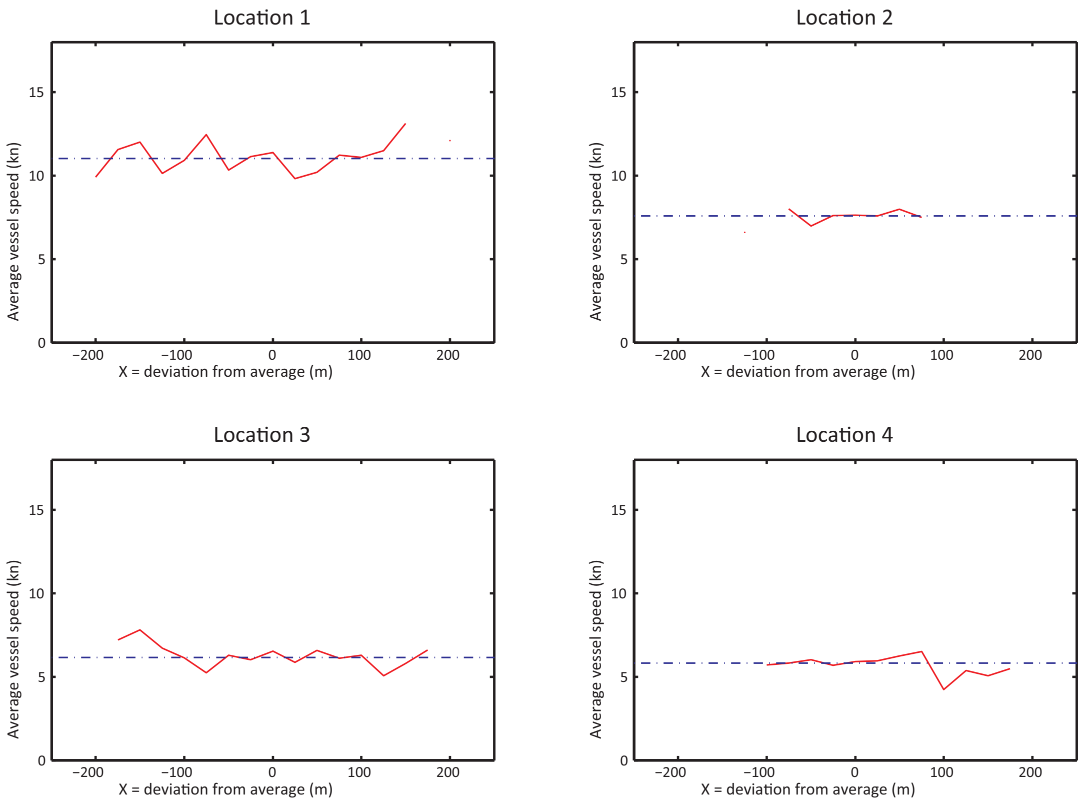

Figure F.25 Vessel speed distribution over cross sections 1-4, for incoming vessels from size class 40,000-70,000 dwt

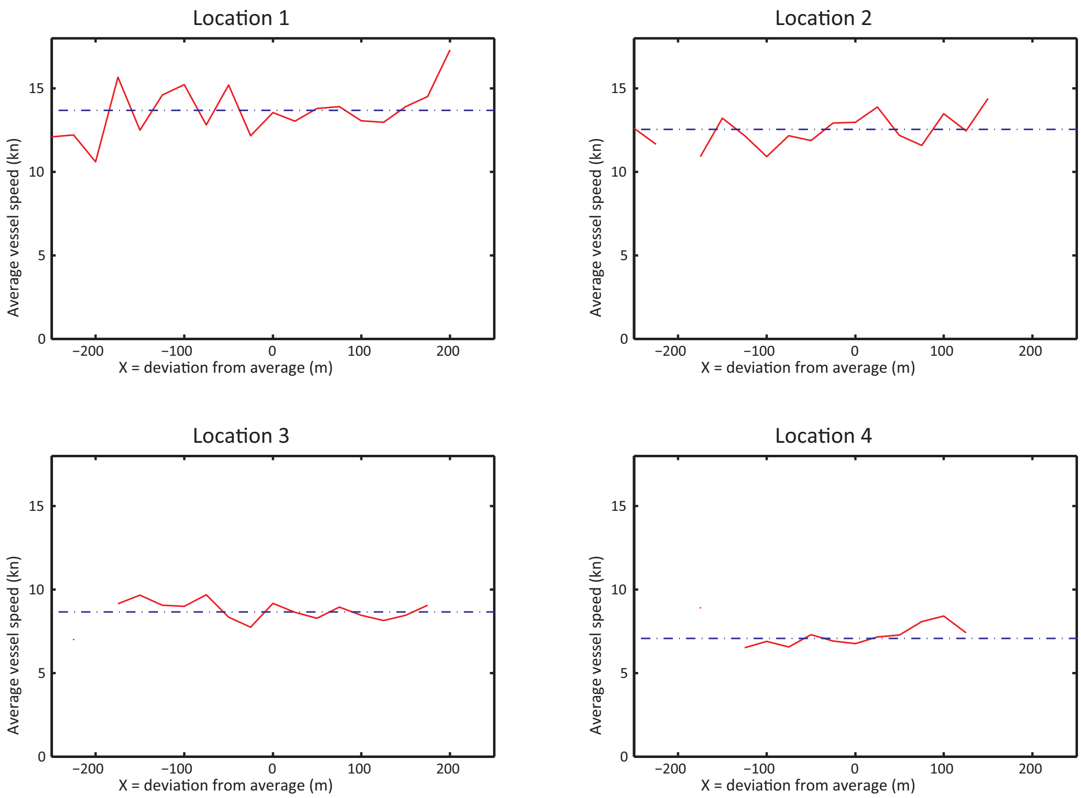

Figure F.26 Vessel speed distribution over cross sections 1-4, for outgoing vessels from size class 40,000-70,000 dwt

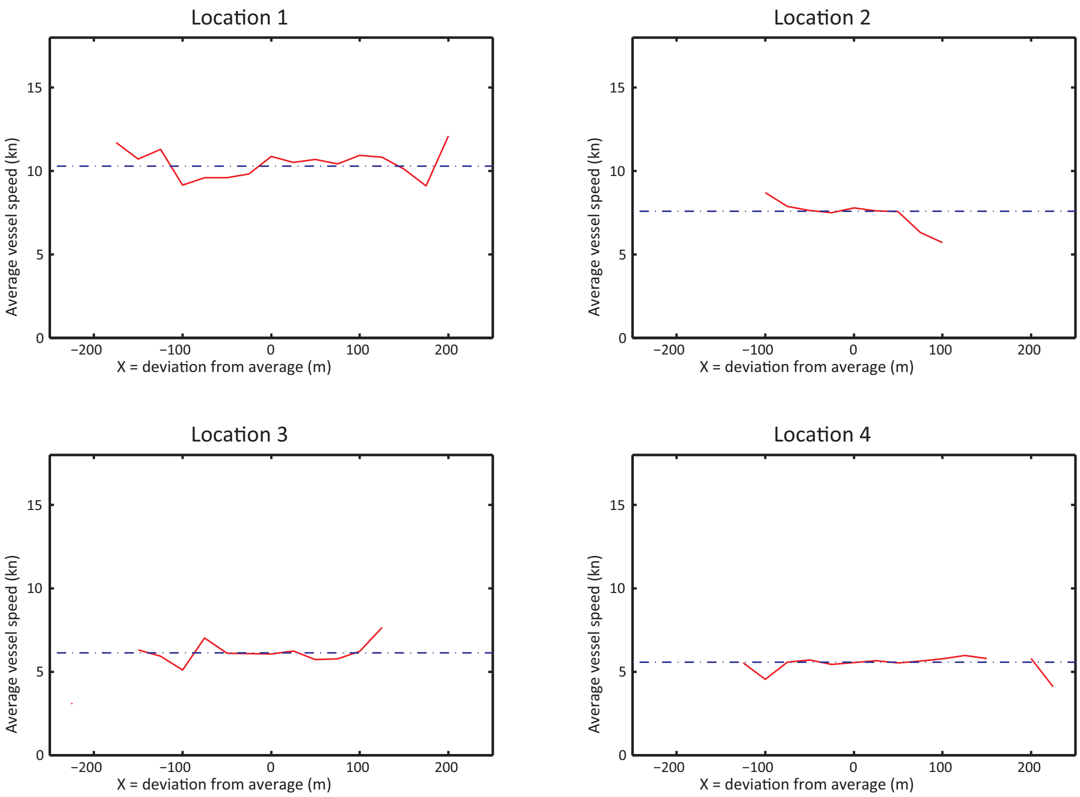

Figure F.27 Vessel speed distribution over cross sections 1-4, for incoming vessels from size class 70,000-100,000 dwt

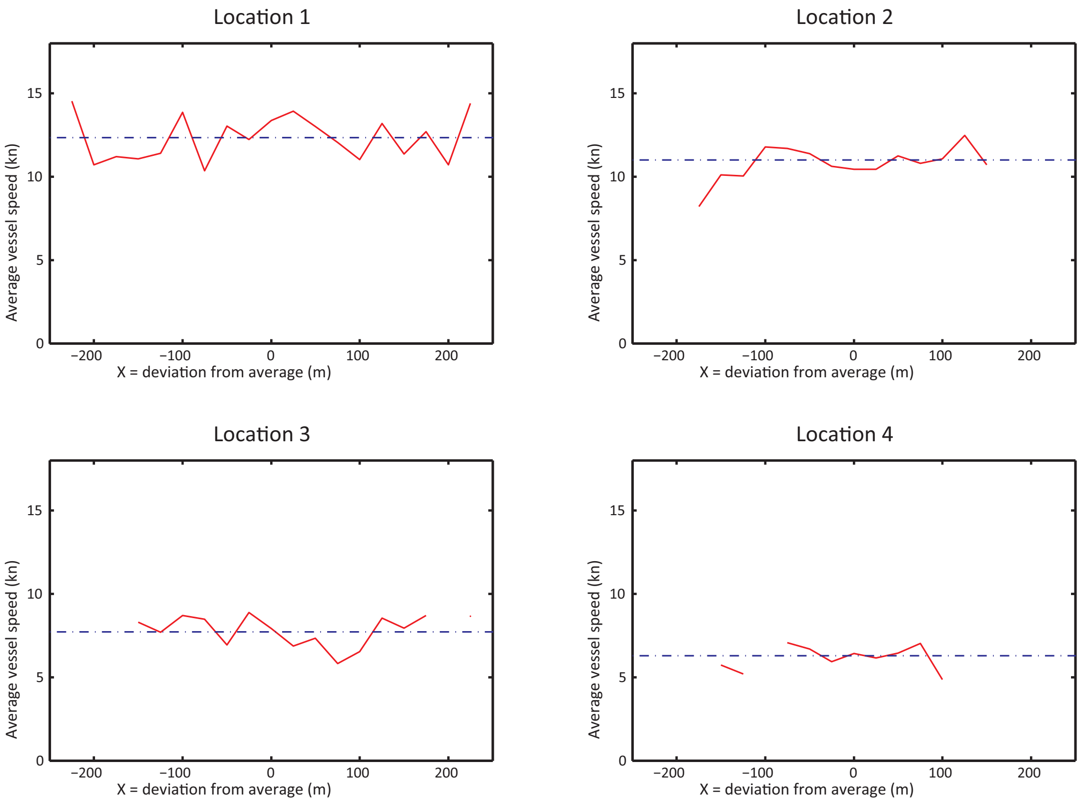

Figure F.28 Vessel speed distribution over cross sections 1-4, for outgoing vessels from size class 70,000-100,000 dwt

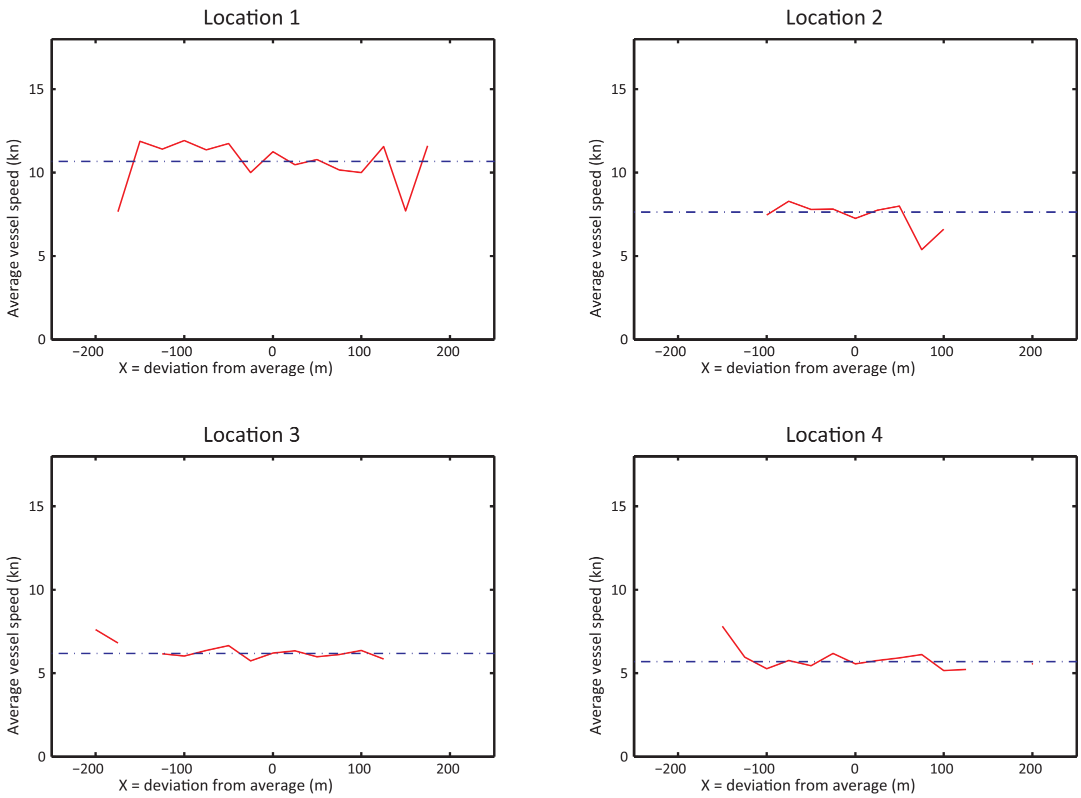

Figure F.29 Vessel speed distribution over cross sections 1-4, for incoming vessels from size class >100,000 dwt

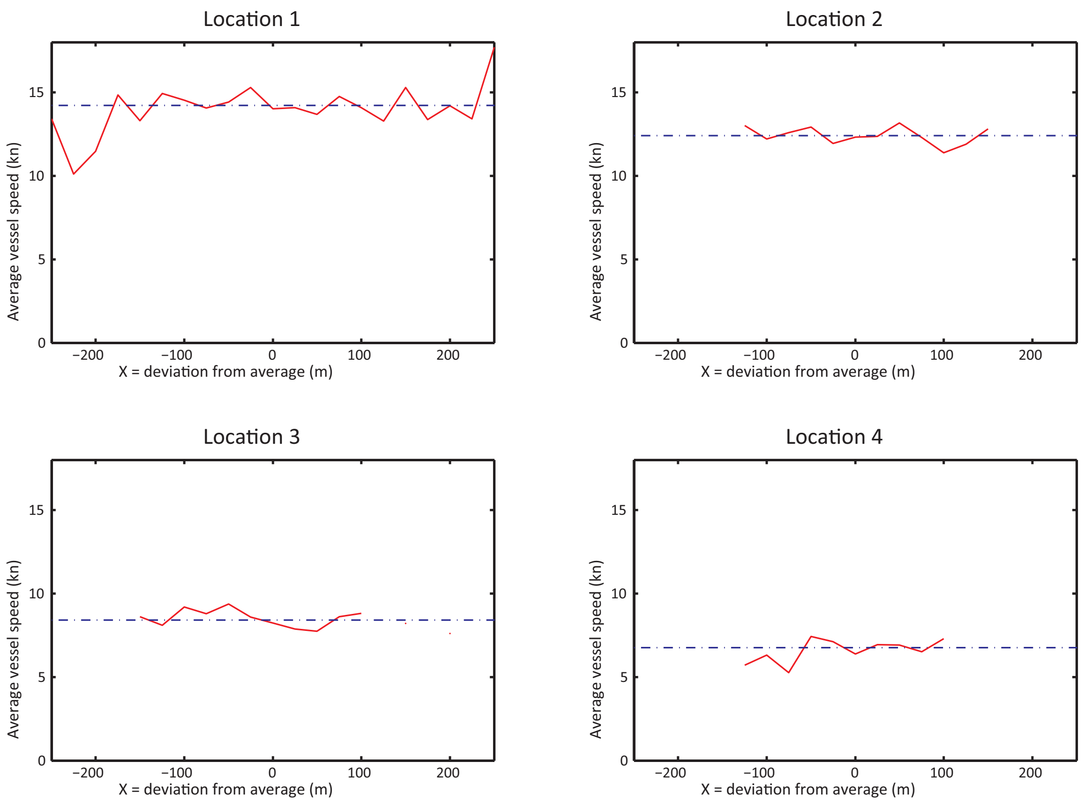

Figure F.30 Vessel speed distribution over cross sections 1-4, for outgoing vessels from size class >100,000 dwt

Appendix G

Generic rules

Appendix G Generic rules

This appendix shows the characteristics of the derived generic normal distributions for the different pre-defined cross sections. The results are presented in tables, in which the distribution for every size class is present. Also the influence of the external circumstances is handled in this appendix. Several figures show the relationship between the external influence and the deviation from the average vessel path and vessel speed.

G.1 Vessel and vessel speed distribution

The different parts in which the total case area is split, are introduced in Chapter 8. Below first a figure of the specified part is given, together with the cross sections that are handled.

G.1.1 Part 1

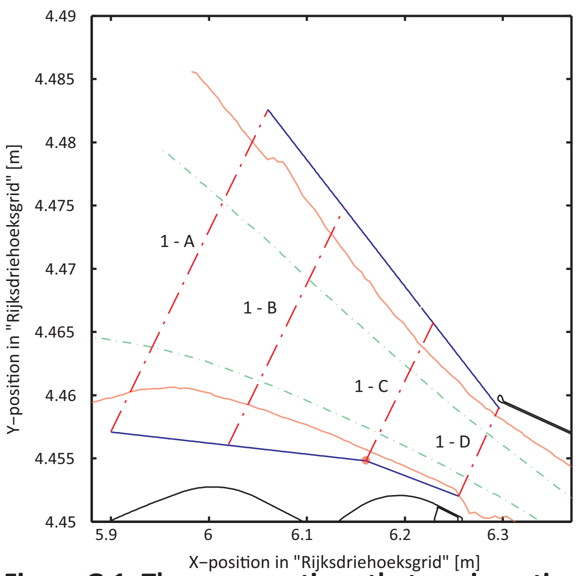

Figure G.1 The cross sections that are investigated in part 1

Table G.1 Characteristics of the different size classes in cross section 1-A

Width of the waterway: 3000 meters								
Size class (dwt)	Incoming				Outgoing			
	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	2310	210	14.5	1.9	880	190	13.9	2.2
10,000-40,000	2240	310	15.1	2.1	970	230	14.7	2.5
40,0000-70,000	2100	290	11.9	2.3	1080	300	13.2	2.5
70,000-100,000	1960	250	11.5	2.2	990	370	11.5	1.9
>100,000	1900	270	12.6	2.7	1250	880	13.6	2.3

Table G.2 Characteristics of the different size classes in cross section 1-B

Width of the waterway: 2200 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	1630	130	14.1	1.9	680	160	14.3	2.1
10,000-40,000	1600	130	14.7	2.4	760	180	15.1	2.4
40,0000-70,000	1490	140	11.5	2.1	820	210	13.4	2.4
70,000-100,000	1430	140	11	2.1	860	260	11.8	2.4
>100,000	1400	130	11.7	2.8	910	260	14.2	2.2
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.74	0.06	0.97	1.00	0.31	0.07	1.03	0.95
10,000-40,000	0.73	0.06	0.97	1.14	0.35	0.08	1.03	0.96
40,0000-70,000	0.68	0.06	0.97	0.91	0.37	0.10	1.02	0.96
70,000-100,000	0.65	0.06	0.96	0.95	0.39	0.12	1.03	1.26
>100,000	0.64	0.06	0.93	1.04	0.41	0.12	1.04	0.96

Table G.3 Characteristics of the different size classes in cross section 1-C

Width of the waterway: 1300 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	1100	90	13.9	2.1	460	120	14.7	2.2
10,000-40,000	1080	100	14.6	2.4	520	130	15	2.1
40,0000-70,000	1000	90	11.1	1.5	560	120	13.6	2.3
70,000-100,000	980	90	10.6	1.8	600	140	12	2.4
>100,000	970	90	11	2.4	630	160	14.3	2
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.85	0.07	0.96	1.11	0.35	0.09	1.06	0.95
10,000-40,000	0.83	0.08	0.97	1.14	0.40	0.10	1.02	0.84
40,0000-70,000	0.77	0.07	0.93	0.65	0.43	0.09	1.03	0.92
70,000-100,000	0.75	0.07	0.92	0.82	0.46	0.11	1.04	1.26
>100,000	0.75	0.07	0.87	0.89	0.48	0.12	1.05	0.87

Table G.4 Characteristics of the different size classes in cross section 1-D

Width of the waterway: 800 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	660	60	13.6	2.2	230	110	15	1.9
10,000-40,000	640	60	13.8	3	240	110	15.3	2
40,0000-70,000	580	80	10.1	1.7	280	70	13.3	2.2
70,000-100,000	560	60	9.2	1.6	320	100	11.8	2.6
>100,000	560	70	9.4	2	320	110	14	1.9
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.83	0.08	0.94	1.16	0.29	0.14	1.08	0.86
10,000-40,000	0.80	0.08	0.91	1.43	0.30	0.14	1.04	0.80
40,0000-70,000	0.73	0.10	0.85	0.74	0.35	0.09	1.01	0.88
70,000-100,000	0.70	0.08	0.80	0.73	0.40	0.13	1.03	1.37
>100,000	0.70	0.09	0.75	0.74	0.40	0.14	1.03	0.83

G.1.2 Part 2

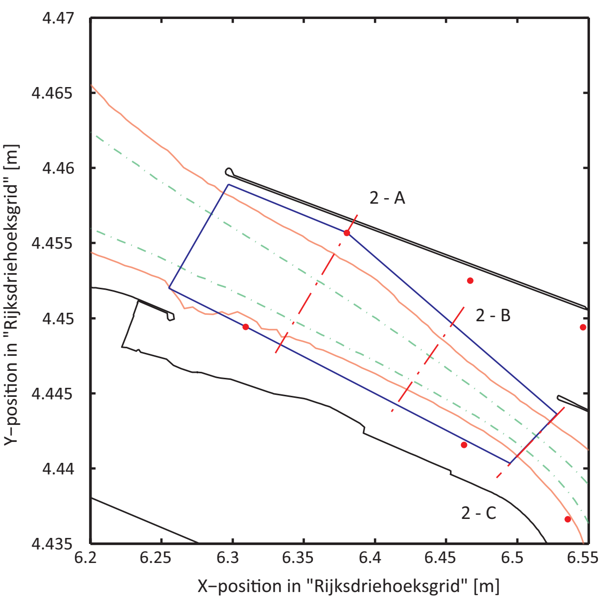

Figure G.2 The cross sections that are investigated in part 2

Table G.5 Characteristics of the different size classes in cross section 2-A

Width of the waterway: 850 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	700	50	13.2	2.3	360	100	14.7	1.6
10,000-40,000	680	40	12.4	3.4	410	100	14.8	1.5
40,0000-70,000	650	50	8	1.1	420	60	12.8	2.1
70,000-100,000	640	40	7.5	1.4	460	90	11.2	2.4
>100,000	640	60	7.1	1.4	460	100	13.2	2
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.82	0.06	0.91	1.21	0.42	0.12	1.06	0.73
10,000-40,000	0.80	0.05	0.82	1.62	0.48	0.12	1.01	0.60
40,0000-70,000	0.76	0.06	0.67	0.48	0.49	0.07	0.97	0.84
70,000-100,000	0.75	0.05	0.65	0.64	0.54	0.11	0.97	1.26
>100,000	0.75	0.07	0.56	0.52	0.54	0.12	0.97	0.87

Table G.6 Characteristics of the different size classes in cross section 2-B

Width of the waterway: 650 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	480	30	12.4	2.5	250	70	14	1.8
10,000-40,000	470	30	10.7	3.3	280	60	14.1	1.8
40,0000-70,000	440	40	7	1.4	290	60	11.7	1.9
70,000-100,000	440	40	6.8	1.1	310	60	10.2	2
>100,000	430	40	6.8	1.2	320	70	11.7	1.5
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.74	0.05	0.86	1.32	0.38	0.11	1.01	0.82
10,000-40,000	0.72	0.05	0.71	1.57	0.43	0.09	0.96	0.72
40,0000-70,000	0.68	0.06	0.59	0.61	0.45	0.09	0.89	0.76
70,000-100,000	0.68	0.06	0.59	0.50	0.48	0.09	0.89	1.05
>100,000	0.66	0.06	0.54	0.44	0.49	0.11	0.86	0.65

Table G.7 Characteristics of the different size classes in cross section 2-C

Width of the waterway: 450 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	340	40	11.7	2.4	190	80	12.9	1.7
10,000-40,000	320	30	10.1	2.8	190	70	12.3	1.7
40,0000-70,000	270	50	6.6	1.2	190	60	10.1	1.8
70,000-100,000	270	40	6.7	1.1	200	50	8.6	1.6
>100,000	270	40	6.5	1.3	200	40	9.6	1.5
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.76	0.09	0.81	1.26	0.42	0.18	0.93	0.77
10,000-40,000	0.71	0.07	0.67	1.33	0.42	0.16	0.84	0.68
40,0000-70,000	0.60	0.11	0.55	0.52	0.42	0.13	0.77	0.72
70,000-100,000	0.60	0.09	0.58	0.50	0.44	0.11	0.75	0.84
>100,000	0.60	0.09	0.52	0.48	0.44	0.09	0.71	0.65

G.1.3 Part 3

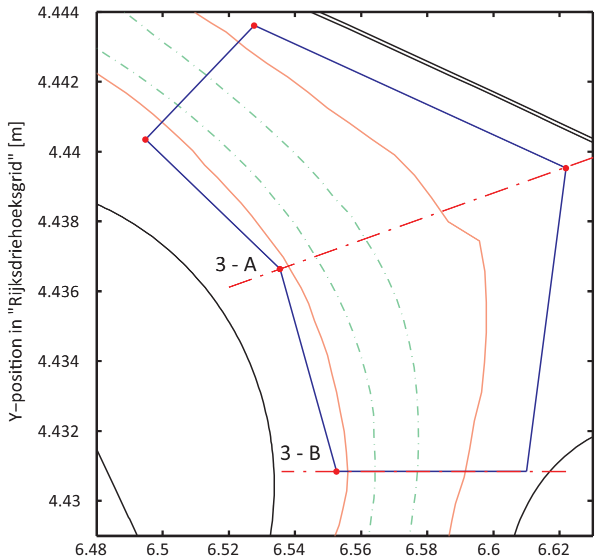

Figure G.3 The cross sections that are investigated in part 3.

Table G.8 Characteristics of the different size classes in cross section 3-A

Width of the waterway: 900 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	820	40	10.8	2.3	650	130	11.9	1.9
10,000-40,000	800	50	9.3	2.8	620	120	11.4	2.2
40,0000-70,000	710	70	6.3	1.1	630	90	8.8	1.7
70,000-100,000	720	50	6.2	0.9	630	70	7.7	1.5
>100,000	700	60	6.2	1	650	70	8.6	1.6
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.91	0.04	0.74	1.21	0.72	0.14	0.86	0.86
10,000-40,000	0.89	0.06	0.62	1.33	0.69	0.13	0.78	0.88
40,0000-70,000	0.79	0.08	0.53	0.48	0.70	0.10	0.67	0.68
70,000-100,000	0.80	0.06	0.54	0.41	0.70	0.08	0.67	0.79
>100,000	0.78	0.07	0.49	0.37	0.72	0.08	0.63	0.70

Table G.9 Characteristics of the different size classes in cross section 3-B

Width of the waterway: 550 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	480	40	10	2.1	320	80	11.5	2.1
10,000-40,000	450	60	8.6	2.5	310	60	11	2
40,0000-70,000	380	60	6.1	0.7	310	40	8.3	1.6
70,000-100,000	380	60	5.7	0.8	320	40	7.1	1.5
>100,000	380	60	6	0.9	330	60	7.8	1.6
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.87	0.07	0.69	1.11	0.58	0.15	0.83	0.95
10,000-40,000	0.82	0.11	0.57	1.19	0.56	0.11	0.75	0.80
40,0000-70,000	0.69	0.11	0.51	0.30	0.56	0.07	0.63	0.64
70,000-100,000	0.69	0.11	0.50	0.36	0.58	0.07	0.62	0.79
>100,000	0.69	0.11	0.48	0.33	0.60	0.11	0.57	0.70

G.1.4 Part 4

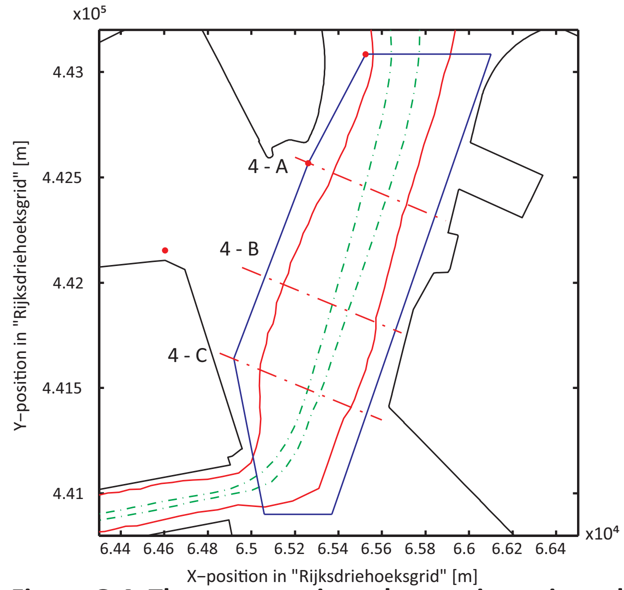

Figure G.4 The cross sections that are investigated in part 4

Table G.10 Characteristics of the different size classes in cross section 4-A

Width of the waterway: 700 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	400	70	9.2	2.3	290	60	10.4	1.7
10,000-40,000	370	70	8.1	2.5	300	50	9.8	2
40,0000-70,000	300	50	5.9	0.6	310	30	7	1.4
70,000-100,000	310	50	5.6	0.7	320	30	6	1.1
>100,000	300	60	5.7	0.7	330	30	6.6	1.3
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.57	0.10	0.63	1.21	0.41	0.09	0.75	0.77
10,000-40,000	0.53	0.10	0.54	1.19	0.43	0.07	0.67	0.80
40,0000-70,000	0.43	0.07	0.50	0.26	0.44	0.04	0.53	0.56
70,000-100,000	0.44	0.07	0.49	0.32	0.46	0.04	0.52	0.58
>100,000	0.43	0.09	0.45	0.26	0.47	0.04	0.49	0.57

Table G.11 Characteristics of the different size classes in cross section 4-B

Width of the waterway: 700 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	350	80	8	2.1	290	80	9.9	1.6
10,000-40,000	320	70	7	2.3	300	60	8.6	2
40,0000-70,000	250	40	5.1	0.9	310	60	6	1.1
70,000-100,000	250	40	4.9	0.7	300	30	5.2	0.9
>100,000	260	40	5.1	0.8	320	30	5.4	0.8
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.50	0.11	0.55	1.11	0.41	0.11	0.71	0.73
10,000-40,000	0.46	0.10	0.46	1.10	0.43	0.09	0.59	0.80
40,0000-70,000	0.36	0.06	0.43	0.39	0.44	0.09	0.45	0.44
70,000-100,000	0.36	0.06	0.43	0.32	0.43	0.04	0.45	0.47
>100,000	0.37	0.06	0.40	0.30	0.46	0.04	0.40	0.35

Table G.12 Characteristics of the different size classes in cross section 4-C

Width of the waterway: 750 meters								
	Incoming				Outgoing			
Size class (dwt)	Spatial distr. (m)		Speed distr. (kn)		Spatial distr. (m)		Speed distr. (kn)	
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean	St Dev
<10,000	350	90	6.3	1.9	310	90	8.6	1.8
10,000-40,000	320	90	5.8	1.7	310	70	6.7	2
40,0000-70,000	230	30	4.3	0.9	320	70	4.6	0.8
70,000-100,000	280	70	4	0.8	300	50	3.7	0.6
>100,000	250	40	4	0.9	300	40	3.8	0.9
	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}	μ / B	σ / B	μ / μ_{V0}	σ / σ_{V0}
<10,000	0.47	0.12	0.43	1.00	0.41	0.12	0.62	0.82
10,000-40,000	0.43	0.12	0.38	0.81	0.41	0.09	0.46	0.80
40,0000-70,000	0.31	0.04	0.36	0.39	0.43	0.09	0.35	0.32
70,000-100,000	0.37	0.09	0.35	0.36	0.40	0.07	0.32	0.32
>100,000	0.33	0.05	0.32	0.33	0.40	0.05	0.28	0.39

G.2 External influences

As explained in chapter 8 of the main report, the results from the case study concerning the external influences are tranformed into generic rules. This is done by generalising the X-axis, after which a quantified linear relationship is obtained. Below this is done for every external influence that is found.

G.2.1 Wind influences

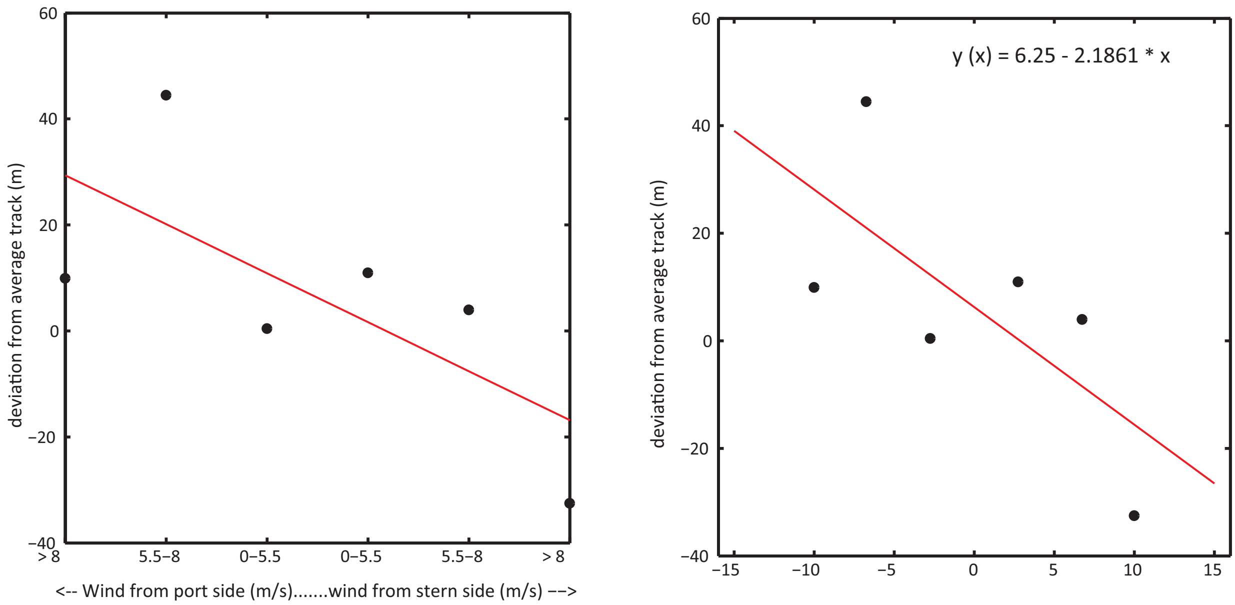

Figure G.5 Influence of cross winds in the Maasmond on the average path. The left figure shows the split up in different wind speed classes.

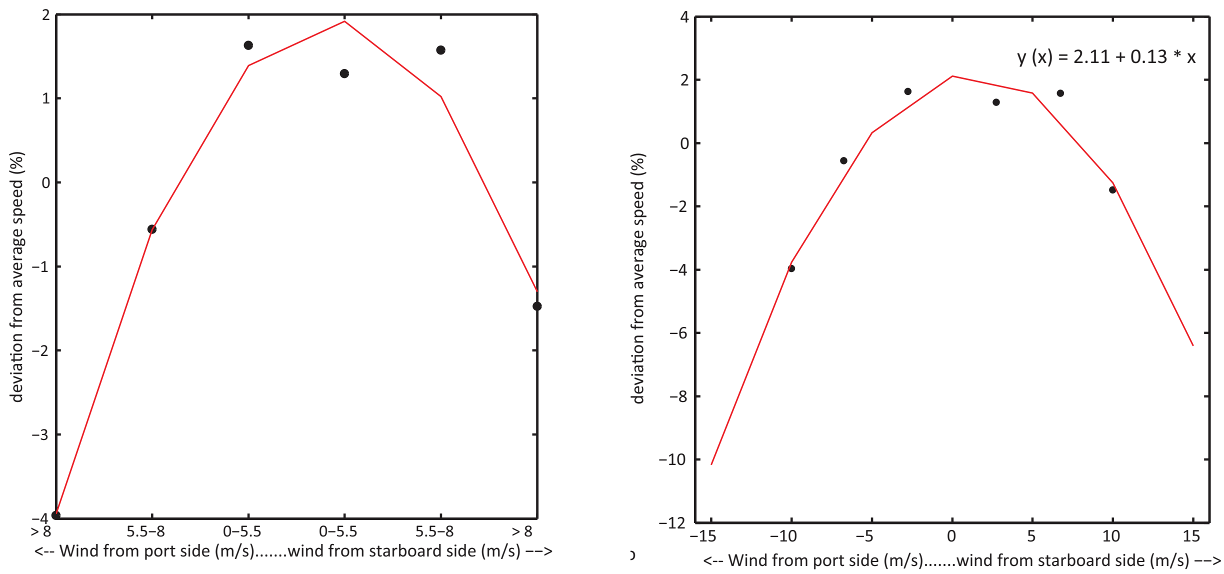

Figure G.6 Influence of cross winds in the Maasmond on the average speed. The left figure shows the split up in different wind speed classes.

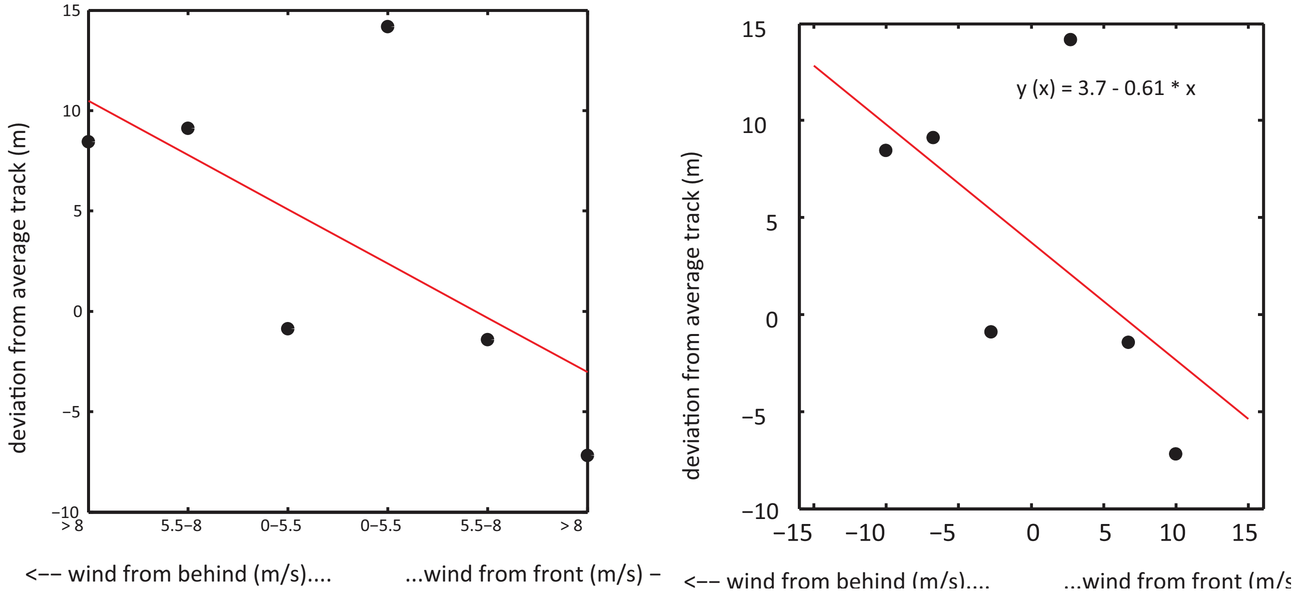

Figure G.7 Influence of parallel winds in the Maasmond on the average path. The left figure shows the split up in different wind speed classes.

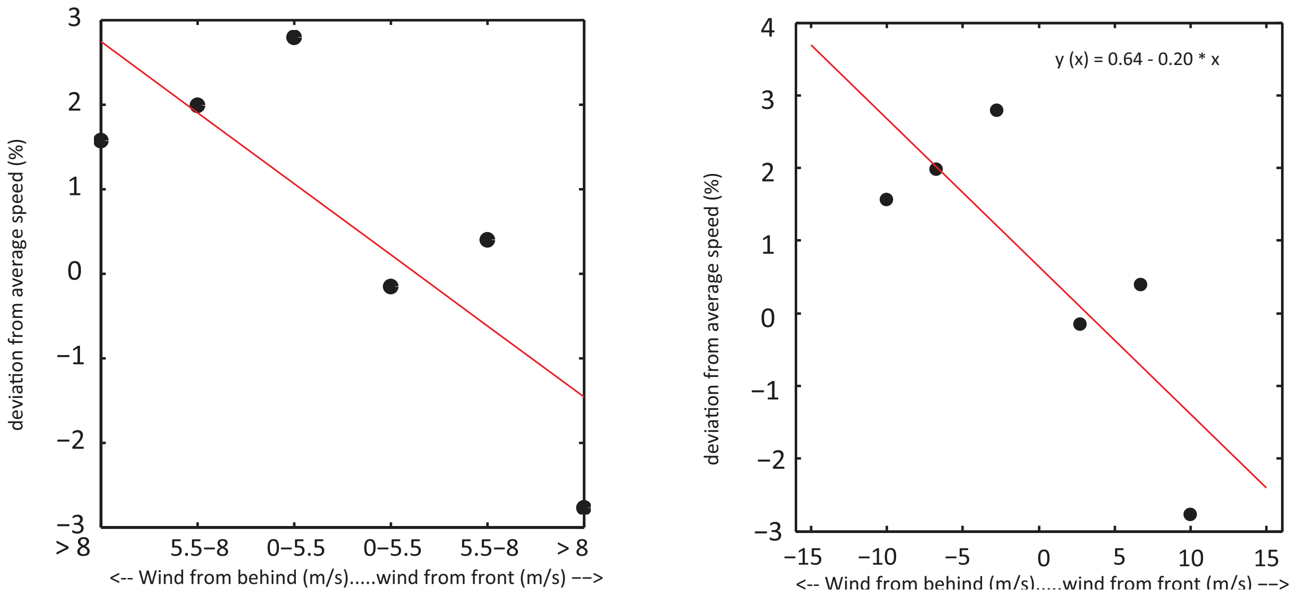

Figure G.8 Influence of parallel winds in the Maasmond on the average speed. The left figure shows the split up in different wind speed classes.

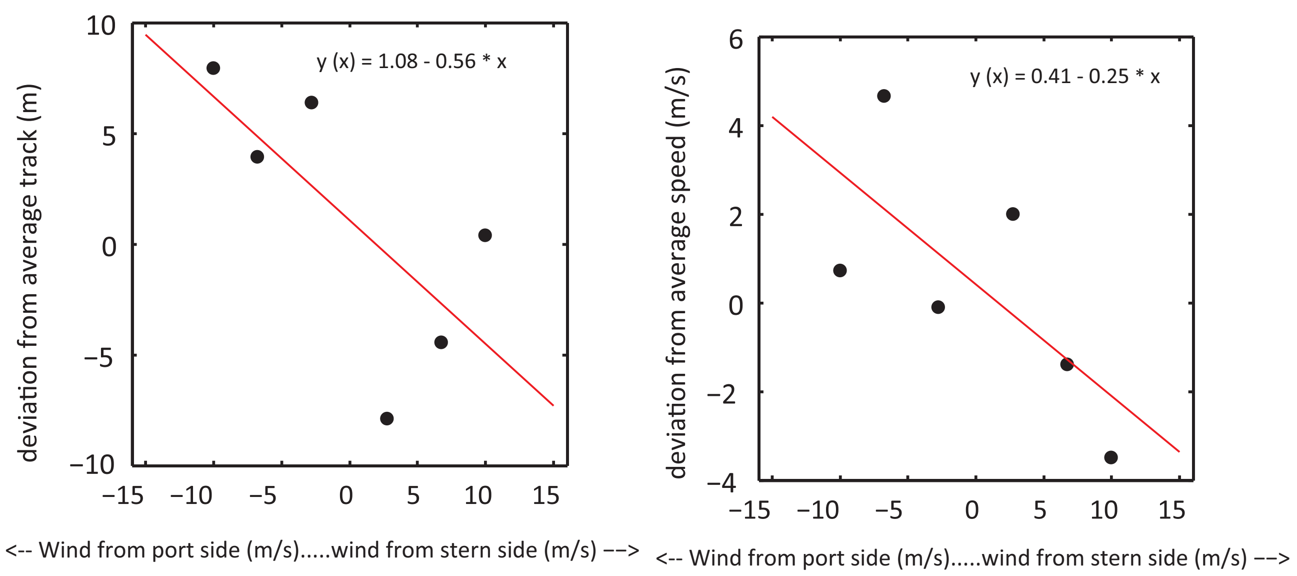

Figure G.9 Influence of cross winds in the Beerkanaal on the average path (left) and speed (right).

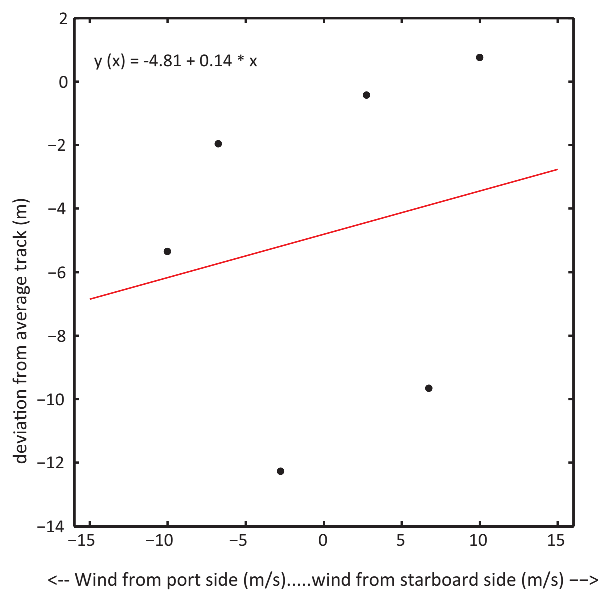

Figure G.10 Influence of parallel winds in the Beerkanaal on the average path.

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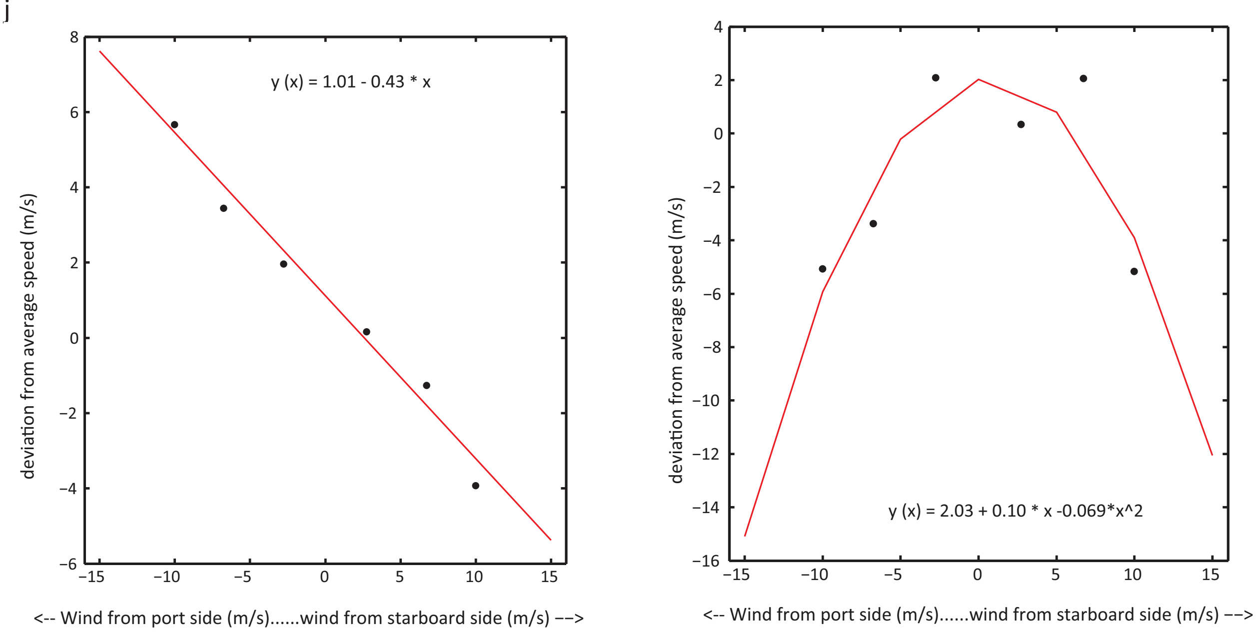

Figure G.11 Influence of parallel winds in the Beerkanaal on the average speed, for incoming (left) and outgoing (right) vessels.

G.2.2 Current influence

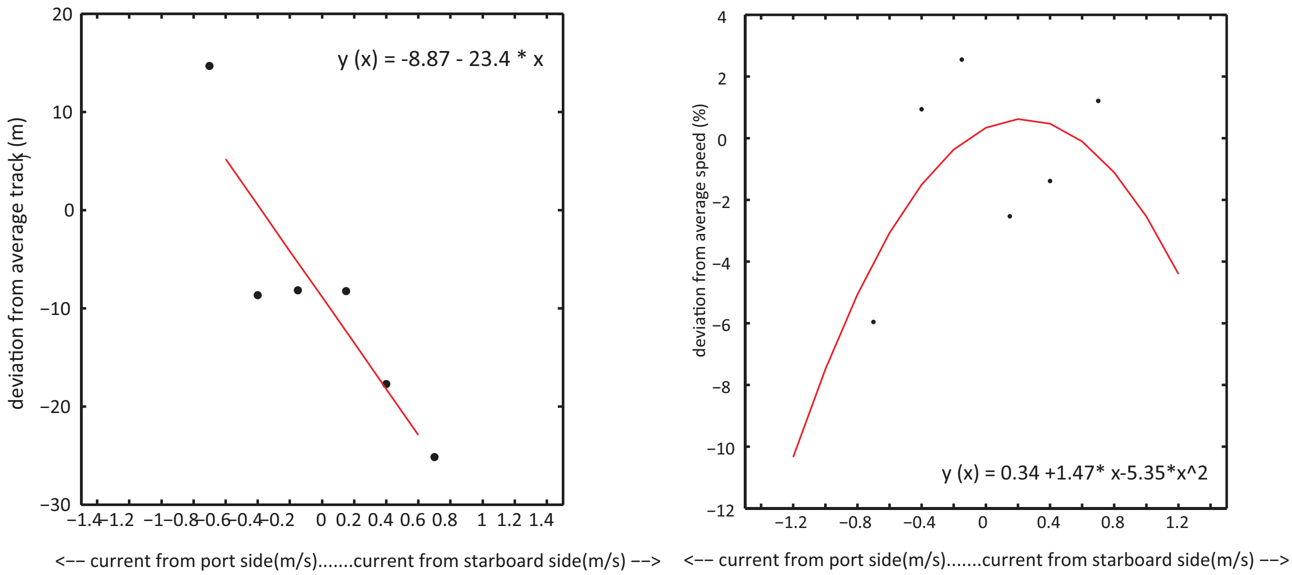

Figure G.12 Influence of cross current in part 1 on the vessel path (left) and vessel speed (right)

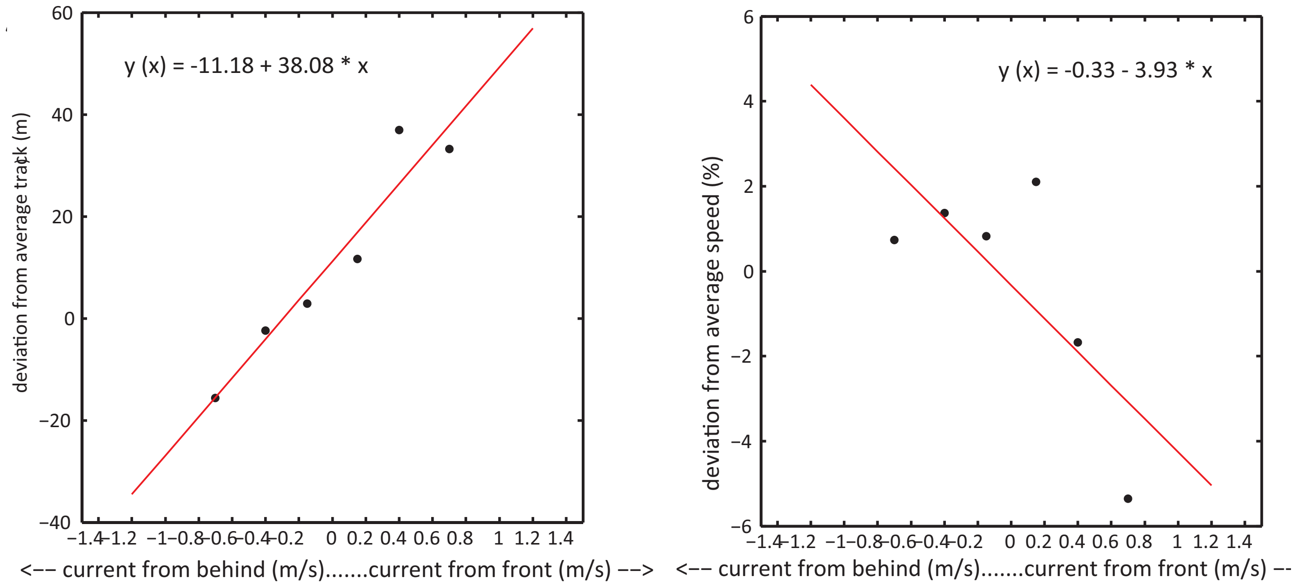

Figure G.13 Influence of parallel current in part 1 on the vessel path (left) and vessel speed (right)

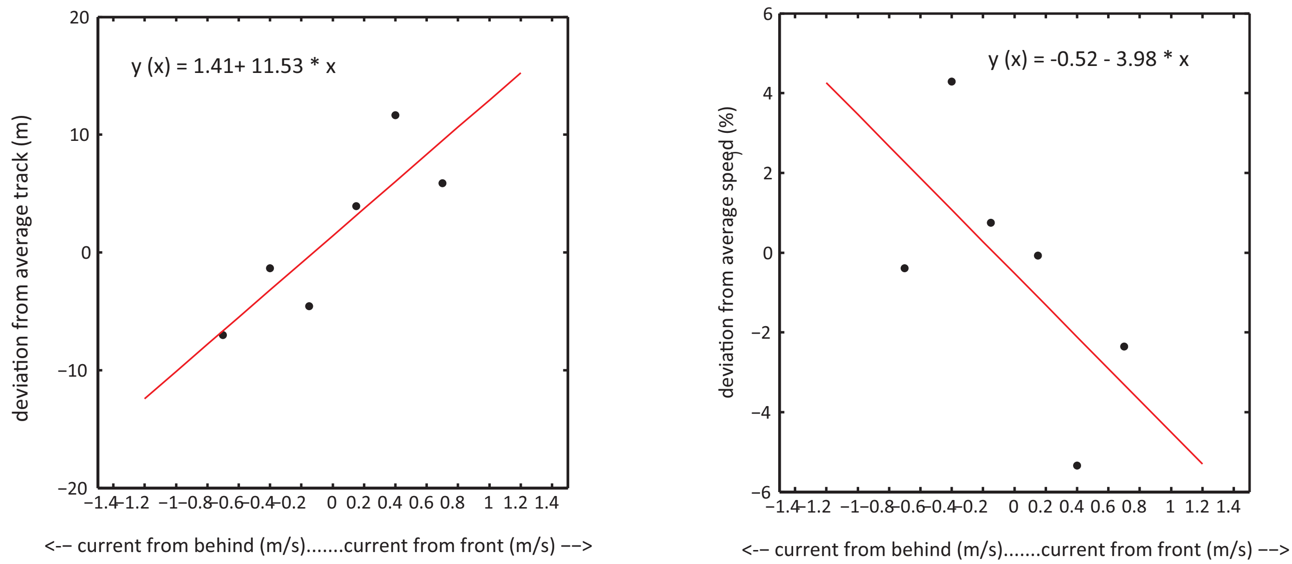

Figure G.14 Influence of parallel current in part 2 on the vessel path (left) and vessel speed (right)

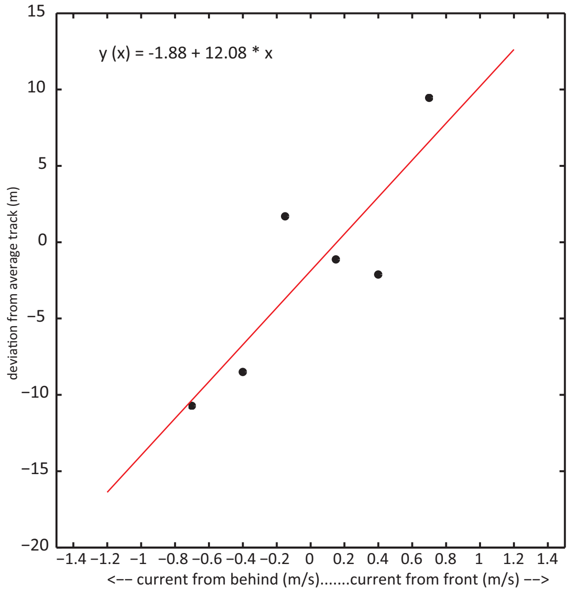

Figure G.15 Influence of parallel current in part 4 on the vessel path.