Understanding the locking process using vessel tracking data

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by

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Preface

The thesis is about the movement of vessels passing locks and came about in two phases. The phases of data processing and developing the locking model were enjoyable to be working on. Despite some hard moments when I got stuck in the process. A hard lesson learned was that asking questions and asking for help can make things a lot easier for myself and my thesis.
I am thankful to Mark, Solange and Floor for helping me keeping an overview on the work and on the thesis itself. Also, I want to thank the people close to me. My family, friends and girlfriend did all they could to help me by listening, motivational speeches, reading parts of the report and, sometimes, being a distraction.

F. Kuiper
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Abstract

Lock passage can potentially make up a third of a vessel's travel time for inland waterway transport and therefore has a large impact on inland waterway and multimodal transport networks.
To reduce the overall environmental and economical impact of transport, there is an increasing interest in inland waterway transport relative to road and rail transport. To keep up with this shift towards inland waterway transport, models are created for the optimal arrangement of multimodal transport and transport on inland waterway networks. Hence, lock operations need to be carefully modelled. The modelling of lock passage is often based on historical data and generalised for all the locks on the network. However, there are uncertainties in historical data, especially with the prospect of an increasing fleet size and more extreme seasonal changes. Additionally, locks can vary in functionality (e.g. recreational or professional use), operability and strategy (e.g. filling and emptying), structural design (e.g. capacity of lock chamber), and environmental conditions (e.g. water level differences). These variations impact the passage time of phases in the locking cycle. An overgeneralised validation for a simulation model can result in inaccurate simulations for a specific lock.
Therefore, it is desired to use more lock specific data, which can be achieved by applying vessel specific data in the form of AIS (Automatic Identification Systems). AIS, live location data of professional vessels, is used in waterway traffic management, but is also collected for research purposes. The data is easily accessible for a desired period of time and area.
Literature studies show that analyses and validations of simulation models is a common practice with the combination of GPS based data. Some studies use AIS data around locks, only to find the total passage time of the vessel. A lock passage can be divided in more phases that impact the total passage and waiting time of a vessel, examples are the entering and exiting of the vessel and the operating time of the lock itself.
The objective of this study is to find a generic method to derive validation parameters for simulation models of locks. Data derived from this study can further be used in the optimisation of lock passages in simulation models. In this way, any desired lock and for any circumstances (e.g. seasonal changes or periods of maintenance) a validation can be performed.
A method was created to translate AIS data to information that is relevant for a lock. This method enabled us to analyse the total passage time and the phases of a lock passage that impact this passage time. Based on the AIS data over a certain time period and considering the geometry of the lock, trajectories of passing vessels were derived. These movements were combined into lock cycles and therefore the corresponding validation parameters could be identified. One example of these validation parameters was the lock operating time, which is estimated based on the principle that all vessels in the lock chamber stopped moving.
The lock specific data can be used to compare the data with the performance of a simulation model of a lock and period in time. This applies for models that only use the total passage time of a vessel, which in some situations might be sufficient. This also applies to models that consider more detailed lock passage. Since the method is based on positional data, the boundaries of the lock sections can be adjusted to the definitions used in the model.
The method is applied on a cases study of the Volkerak and Kreekrak locks. Firstly, the AIS data translation is performed for a lock to create data sets of the lock passages. Also, data of the water level at the lock is linked to each locking cycle. Secondly, this data is compared to a lock simulation in the same situation. The arrival rates, arrival speed, vessel dimensions and water level difference are used as input to create a base simulation for various configurations. The lock simulation module of OpenTNSim is used because this is an open-source transport network simulation model developed at TU Delft.
The simulations are compared to the collected data, for a total of 18 segments on the trajectory passing the lock. The segments correspond to the phases of a locking cycle. The average passage time of each segment is compared between the vessels of the simulated and the collected data. Because of the large sample sizes, these comparisons created a view on the overall performance of the simulation for each segment.

The information found in the base simulations was further used to calibrate the OpenTNSim package. The vessel speed was adjusted on the approach and leaving of the lock chamber to match the trajectory of the arriving vessels. Also, the filling time of the the lock chamber was optimised for the simulation.
The Volkerak had a total of 24,446 vessels passing over the time period, this is comparable to the 24,570 vessels that were counted by Rijkswaterstaat in the same period. Three cases were selected to compare the simulation model, one vessel passing without waiting, one vessel passing with waiting and two vessels passing. These resulted in sample sizes of 943, 89 and 561 lock cycles respectively. The case study shows that, with a small sample size of 89 locking cycles, there can be large variability in passage times.
The largest deviations of the simulations relative to the collected data were found in the passage time of the segments between the waiting area and the lock chamber. Another deviation was found in the lock operating time for the case of two vessels passing.
The method used can give a large and useful data set of vessels passing a certain lock. The lock data can be used for statistical analyses. An example includes the number of vessels per locking cycle or the entering time or speed. Also, each locking cycle can be assessed and visualised individually or for a desired time span.
When the data is used for the validation of a simulation model, a large data set is needed to give reliable results. After all there can be large outliers and the performance of the lock is dependent on human interaction, the lock operator and the vessel's captain. A combination of the AIS based data with other additional data can expand the method.
In conclusion, a highly suitable method was found that enables to use AIS data for the validation of a simulation model of a lock. The method is sufficient for most applications of a lock simulation model, despite being limited to just the movement of the vessels. However, when an accurate simulation of a lock phase like the closing of the gate is desired, other data sources might be more suitable. While this research has a focus on the comparison of the collected data to a lock simulation, the data can also be used for a statistical analysis of the lock when looking at fleet composition, arrival rates and stopping distances.

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t_d : net lock delay time of an individual vessel

t_w : waiting time

t_s : lock operating time

L_l : lock length (entry area and lock chamber)

V_{cr} : undisturbed vessel cruising speed

t_l : switch interval (or loop interval, interval between exit of last vessel of preceding locking operation and completed entry of first vessel of new locking operation)

t_i : entry interval (interval between completed entries of successive vessels)

t_u : exit interval (interval between completed exits of successive vessels)

T : total filling time of the chamber

A_{ch} : lock chamber area

H : water level difference

m : discharge coefficient of lock filling sluice

A_s : area of lock filling sluice opening

g : gravitational acceleration

DWT : dead weight tonnage

A_m : cross sectional area of the middle of a vessel

A_c : cross sectional area of a lock chamber

S_l : Loop distance

B_{ch} : Chamber width

T_1 : Lock filling sluice opening time

SR_1 : first vessel speed reduction

SR_2 : second vessel speed reduction

1
Introduction

Inland water transport is, compared to road and railway transport, an attractive way of transport when the cargo destination is close to or reachable from the waterway network. This mode of transport has a relatively high capacity and low costs and ecological impacts. Stimulation of inland water transport instead of road transport can therefore result in lower overall emissions and also reduce the traffic load on congested roads. On the other hand, inland water transport is slower than road or rail transport and navigational locks have, with other infrastructures such as bridges, a large impact on the travel time of an inland vessel. There is a shift in the modal split of inland transport in favour of inland shipping compared to road and rail transport, Port of Rotterdam aims to increase that shift over the coming years (Port of Rotterdam, 2022).

1.1. Background and motivation

This section gives background on the functioning of locks in the current and future inland waterway network, the development of inland waterway transport and tools to keep up with this development for inland waterway transport and navigational locks specifically.

1.1.1. Inland waterway transport development

There are two reasons for the shift in modal split towards inland water transport. Firstly, the economic crisis in 2008 lead to a need of cost reduction for the shipment of goods (Steadieseifi et al., 2014). Secondly is the increasing pressure on environmental impact of transport. A Green Deal for inland shipping was created in the Dutch coalition agreement of 2017 following the Paris Agreement of 2015 to limit the global warming and a national agreement in The Netherlands to reduce emissions in 2019 overall (Segers, 2021). The agreement aims at a reduction of CO_2 emissions in the coming years of 35 to 50% in 2035 relative to 2015 and climate-neutral and zero-emissions for inland shipping by the year 2050 (Green Deal, 2019).
The reduction of the costs and emissions of inland shipping can be achieved in two ways. The first way is by developing a more economically and environmentally friendly inland fleet, one of the considerations provided by the Green Deal is the use of biological fuel and the development of new standards for engines used for inland vessels. Secondly, the Green Deal aims at encouraging the logistics sector on the development and implementation of system innovations for combining cargo flows and reducing congestion (Green Deal, 2019).
Studies on the planning of multimodal freight transport are conducted to accommodate the shift towards inland waterway transport. The two main motivations for the investigation of multimodal freight are the need for cost reduction following the economic crisis in 2008 and the increasing environmental concerns. Multimodal transportation is defined as the use of multiple transport modes for the shipment of goods by road, rail or shipping vessel (Steadieseifi et al., 2014).
Synchromodal transport is a type of multimodal planning where the optimal arrangement of transport modes is chosen for each transport demand (Mes and Iacob, 2016). Freight can be routed based on data of possible modes of transport to meet the need for a cost efficient and environmentally sustainable freight transportation (Pamucar et al., 2022). A pilot study on synchromodal transport is per-

formed on the network between Rotterdam and Tilburg. This pilot led to a modal split in Rotterdam with 19% road transport, 25% rail transport and 46% inland water transport. To implement this synchromodal transport, cooperation is needed between the stakeholders of the corridor. Next, because the goal is to optimise the use of the available network, a network's capacity and bottlenecks are of importance. Simulations of the network, or parts of the network, can give an insight in the networks capacity (Lucassen and Dogger, 2012).

1.1.2. Navigational locks

Locks have a large impact on the travel time of a vessel for many network configurations. The case study of the Danube river by Hekkenberg et al. (2017) shows that the time passing locks takes almost a third of the total sailing time, with an estimated lock passage time of 0.75 hours for each of the 66 lock passing.
Despite having a large impact on the travel time for inland water transport, navigational locks are a necessity in some situations where a separation of bodies of water is required. Some of these situations are when

- the water level has to be set up for navigability;
- the water level has to be set up for a reservoir;
- the water level needs to remain constant on one side of the lock, in case of waves, tides or river discharge on the other side;
- the water is fresh on one side and saline on the other side, in case of a sea going lock.

Locks come in various sizes and uses, from large commercial waterway to small canals for recreational use (Van Koningsveld, 2021).
The waterways network needs to keep up with the increasing traffic volume, this in number of vessels and in vessel size. Therefore, many projects are carried out to improve the infrastructure of the waterways network and its connection to transport destinations and other modes of transport, besides that the focus is on improving the usage of the inland water infrastructure. An example includes improving the exchange of information and innovative strategies for lock operation by Rijkswaterstaat (2010). Another example is the Port of Rotterdam developing tools for route planning on inland waters and logistic planning of cargo to make the best use of the inland transport (Port of Rotterdam, 2022).

1.1.3. Lock analysis based on AIS

AIS data can be useful to decrease the dependency on historical data for lock calibration and validation. The data is widely available and is easy to derive for various locations and periods in time. AIS (Automatic Identification System) is a vessel tracking system used for traffic management and in research, an explanation of the data and studies using AIS can be found in Section 2.2.2. The use of AIS data is considered a principle for this research because of the availability, the volume and the accuracy of the data.
AIS is used in the analysis of locks in the mapping of travel times for the Ohio River, Upper Mississippi River and Illinois River. The purpose of this research was to find accurate origin - destination travel times for various locations along the rivers. The locks were considered as sections on the river and the average passage time was found with the AIS data (DiJoseph et al., 2019).
Segers (2021) uses AIS data to derive values for the average passage times of locks on the Rotterdam - Antwerp corridor. The average passage times are used on a network configuration of the total corridor in the mapping of inland shipping emissions.

1.1.4. Inland water transport simulation

The choice of transport mode and the distribution of transport in a synchromodal situation are dependent on the transport times, transport costs and the environmental impact of the different modes. These can be uncertain for inland water transport, especially compared to road and rail transport, due to variable waterway conditions and varieties in inland vessels (Hekkenberg et al., 2017).
A simulation of an inland waterway network can be used to have an indication of the costs, travel times and emissions. There are several models developed such as BIVAS (Rijkswaterstaat, 2022),

NODUS (Jourquin, 2022), OpenTNSim (Baart et al., 2022), FTIND (Zhang, 2013) and the model developed by Hekkenberg et al. that focus on the flow of vessels along a network. Chapter 2 gives an explanation and shows the differences for these models. One similarity for these models is the extensiveness of navigational locks in the waterway network. The passage of a lock have fixed passage times that are based on averages derived from historical data.

1.1.5. Lock simulation

SIVAK is currently the only simulation package that can simulate the lock passage of a single vessel for lock on the Dutch waterway network (Lamboo, 2015). Rijkswaterstaat uses SIVAK to simulate traffic around locks, bridges or channels. The SIVAK model is validated for standard inland locks in The Netherlands and so the calibration of the model is done with historical data of typical locks in The Netherlands, the SIVAK model is explained in 2.3.1 (Buro Sierenberg en De Gans, 1998). This works well for many cases, but can lead to uncertainties in specific situations. Situations like uncommon lock dimensions, locks for sea-going vessels or developing vessel dimensions and technological improvements.
A study on the Prinses Margrietsluis (Lamboo, 2015) is an example of a situation where SIVAK simulations provide inaccurate results. This lock has many passages of recreational vessels that use the same lock chamber as the professional vessels. Calibration of SIVAK was performed to improve the accuracy of the model for professional and recreational vessels. A recommendation that followed the study is to study the influence of the weather on the passage times of the lock, the weather has an impact on the number of recreational vessels.
Van Adrichem 2020 uses SIVAK in a lock scheduling model LOSCO to improve the passage time of a vessel by optimising the scheduling strategy. Because the model has a focus on the operation of the lock, the study uses constant values for entering, exiting and loop times. A suggestion is made by van Adrichem to gather data for entering and exiting times of the case studies to include these in the calibration of the model, which will improve the scheduling.
On the other hand, Chen et al. (2013) found that the simulation of two lock in the North region of Zhejiang Province, China, with SIVAK gave accurate results when compared to vessel traffic data collected using GPS.
Campbell et al. (2007) developed a simulation model for lock operation on the Upper Mississippi River, with the purpose of evaluating the current and alternative operation policies of the lock. The validation of the model was done with historical data of the area from the year 2000. The same as for the SIVAK model, the validation of the model is dependent on the availability, accuracy and framework of the historical data.

1.2. Problem definition

The current validation and calibration methods of lock simulation models and locks in transport network models are depended on historical data. This can be sufficient for many applications of the models. However, there is an increasing demand for inland waterway transport, a development in the fleet composition and an objective to evolve the Dutch waterway infrastructure and the lock operation strategies. This, combined with locks being a bottleneck on inland waterways, can conclude that there can be situations where the reliance on historical data is not sufficient.
Also, the most used lock simulation model SIVAK can give inaccurate results for lock that are different from a general lock. This can be in the form of dimensions, fleet composition, the function of the lock or the surrounding infrastructure. Examples are the impact of recreational vessels (Lamboo, 2015).
An extensive and lock specific calibration can improve a simulation model in situations that deviate from common locks and circumstances. When using a deviating framework for a lock simulation, in the form of lock dimensions, type of operation or exceptional situations such as high or low water levels, assumptions need to be made based on the historical data. This can lead to uncertainties in the simulation model when making estimations of future traffic volumes and scenarios.

1.3. Research objective

The objective of this study is to diminish the dependency of a simulation model on historical data for calibration and to improve the calibration for individual locks. The calibration of a model can improve

when there is data available for a desired period in time and for varying kinds of locks, so that the performance of a lock in different situations can be considered. The AIS data available for the research can give information of vessels in and around a considered lock, this data can be provided for vessels on all waterway in The Netherlands. This means that the data has information on any lock where vessels are passing. The objective is to create a method for the calibration of a lock simulation, that is applicable for any desired lock, circumstances and thoroughness. This leads to the research question:
How can the locking process be evaluated and the calibration of simulation models be improved for any lock, under arbitrary conditions, based on AIS data?
Four sub questions derive from this research question. Firstly, a locking process contains many variables that have a large or small impact on the process, Chapter 2 gives a description of the locking cycle. Not all these variable can be addressed in a lock analysis, that would lead to an overly complicated method. Also, the used data is only vessel specific, the lock variables can only be derived from the vessels in and around the lock. An understanding of the phases impacting the locking process is needed to create an accurate, but workable, method for analysing the lock. The first sub question is:
Which locking phases are distinguished when defining the locking process?
Secondly, a method is developed to convert AIS data into information on the defined locking phases. AIS data is, as it is introduced in 1.1.3, a source of vessel tracking data. The locking phases can be expressed or estimated based on location, speed and other characteristics of vessels passing a lock complex. The steps, assumptions and rules required to define the locking phases give an answer to the sub question:
How can these locking phases be found with AIS data for a specific lock?
Now, when the locking phases can be defined for a specific lock Thirdly, the calibration method should be applicable to any given lock, on the condition that the data is available. The third sub question considers the generic applicability of the method:
How can the locking performance be expressed and visualised for these phases, found with AIS data, in order to compare different locks and conditions?
Finally, the lock data can give a view of the phases of the locking process that have a high impact and phases that have a low impact on the locking times. The data can also give an indication on the effects of conditions such as the traffic volume, the water level difference and the fleet composition on the locking process. This can be used to implement, improve or omit phases of the locking process in the OpenTNSim lock module, decisions can be made for increasing or decreasing the complexity of the simulation to create a balance in accuracy and computational demand. Afterwards, a prediction can be made on the need for additional data sources and further research. This leads to the sub question:
Which improvements can be made to a lock simulation model, based on the comparison of the locking performance resulting from AIS data and the lock simulation?
The calibration process is developed and tested using a case study on the Volkerak locks.

1.4. Scope

The research aims at a generic method that is applicable for the calibration of any simulation model of a navigational lock and for any existing lock and period in time. However, the method relies on the availability of AIS data. AIS is mandatory at sea, but there is not an international requirement on AIS for inland vessels (Hadley, 2016). Because inland AIS is mandatory in The Netherlands ("Binnenvaartpolitiereglement", 2022) and the data is available at Rijkswaterstaat, the research has a scope of locks only in The Netherlands. A remark on the AIS data is that the use of AIS is only mandatory for professional vessels and not for recreational vessels, which means that locks for recreational vessels are not considered.
This study has a focus on locks in inland water traffic. However, the same method can be used for sea-going locks. The difference between sea-going locks and inland locks might demand extensions or changes of the method. Also, only the AIS data and water level data are used for this research. Extensive analyses of locks can be done with many sources of data, but this can make the method more dependent on data availability.
The AIS data used for this research spans a time period of three months, from August 1, 2019 until October 31, 2019. The data considers the vessel on the corridor between Rotterdam and Antwerp,

the lock that are used in the case study are on this corridor, these are the Volkerak locks and the Kreekrak locks.

1.5. Report layout

This report consists of the chapters *Literature review, Materials and methods, discussion and conclusion*. Chapter 2 *Literature review* gives an overview of the current research that leads to this study and what methods and materials are applied for other situations that can be useful for the calibration of a locking model. A combination of the literature is a foundation for the materials and methods used for this research in Chapter 3 *Materials and Methods*. A method was created for both the translation of AIS data to suit a lock and for the calibration of a locking model. These methods are applied to a case study to show the functioning and the application of the method. The case study is also used to provide quantitative results in Chapter 4 *Results*. These results of the case study and the choices made for the materials and methods are discussed in Chapter 5 *Discussion*. Finally, conclusions can be drawn based on the report in Chapter 6 *Conclusions and Recommendations*.

2
Literature review

The validation of a lock model using AIS data, that uses GPS location, is based on other research to the simulation of locks and waterway transport and on the use of GPS data to validate simulation models in other fields of transport. This chapter first shows the literature available on the phases of a lock passage. Afterwards, an overview of location data and the application in model development and validation. And finally, the passage of a lock for current models is described.

2.1. Locking cycle phases

There are two points of view in the locking process to consider: the view of the lock operator and that of the vessel using the lock. The perspectives have overlapping phases when the vessel passes the lock. Both perspectives are described in Sections 2.1.1 and 2.1.2.

2.1.1. Vessel's perspective

When taking the point of view of the users of the lock, the vessels, the passage time is the most important phase of the lock. The passage time can be described as the time needed to pass the lock, relative to the time needed to pass the distance with normal cruising speed (equation 2.1) (Van Koningsveld, 2021). The phases of a vessel passing a lock can best be shown in a time - distance diagram like Figure 2.1.

$$t_p = t_w + t_s - L_{lock}/V_s \tag{2.1}$$

where:

t_d	= net lock delay time of an individual vessel,
t_w	= waiting time,
t_s	= locking time,
L_{lock}	= lock length (entry area and lock chamber),
V_s	= undisturbed vessel cruising speed.

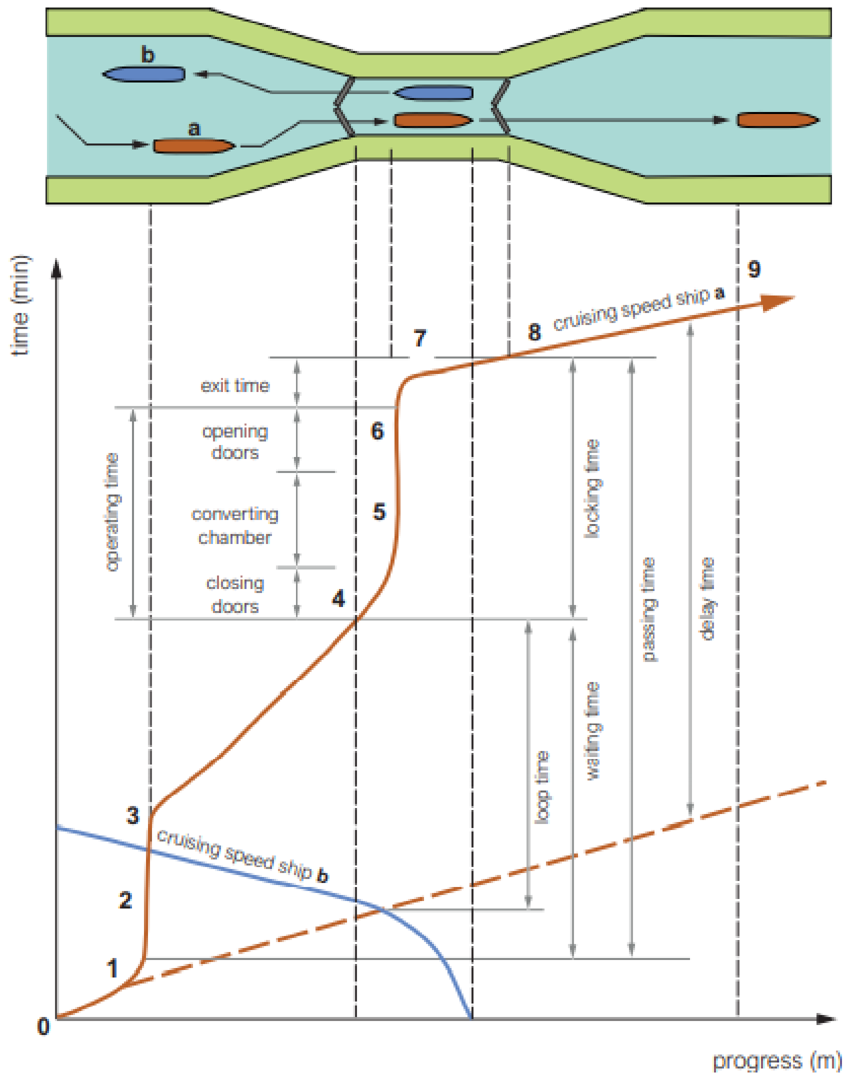

Figure 2.1: Phases of a vessel passing a lock (by TU Delft - Ports and Waterways is licensed under CC-BY-NC-SA 4.0).

The lines **a** and **b** are vessels passing the lock. The phases of the passage of vessel **a** are described with the following numbers (Van Koningsveld, 2021):

0-1 = cruising speed

1-2 = reducing speed and stopping

2-3 = waiting in lay-by

3-4 = entering of the lock

4-5-6 = operating time (T_b)

6-7-8 = exit from lock

8-9 = cruising speed

2.1.2. Lock operator perspective

From the view of the lock operator, the locking process is a cyclical process of repeating lock operations, the process can be seen as a locking cycle. The locking cycle is shown in Figure 2.2, with the components described in Tables 2.1 and 2.2. A full locking cycle is considered to be an upstream lockage followed by a downstream lockage.

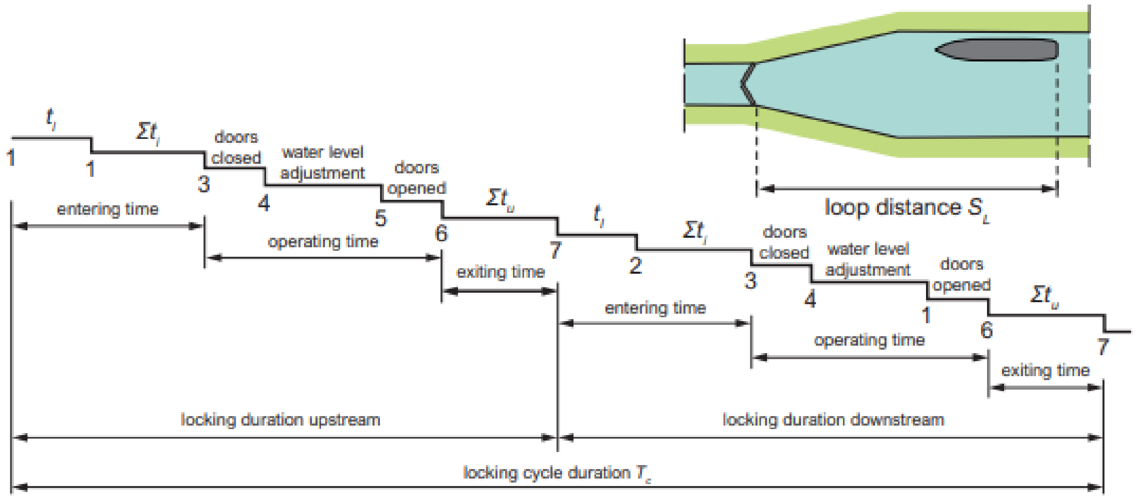

Figure 2.2: Phases of a locking cycle (bu TU Delft - Ports and Waterways is licensed under CC BY-NC-SA 4.0).

1. Stern of vessel of previous lockage passes gates.
2. Stern of first vessel to enter passes gates.
3. Stern of last vessel to enter passes gates.
4. Entry gates closed.
5. Exit gates start opening
6. Stern of last vessel leaving passes gates.

Table 2.1: Point of time.

t_l	= switch interval (or loop interval, interval between exit of last vessel of preceding locking operation and completed entry of first vessel of new locking operation),
t_i	= entry interval (interval between completed entries of successive vessels),
t_u	= exit interval (interval between completed exits of successive vessels).

Table 2.2: Symbols

Operating time

The operating time, or T_b, of a locking consists of closing the gates, levelling the chamber and opening the gates. The opening and closing time of a gate is dependent on the type of gate and the width of the chamber. Table 2.3 contains the operating times of lock gates (Groenveld, 1999).

Gate type	Chamber width [m]	Closing gate [min]	Opening gate [min]	Total [min]
Sliding gate	12	1.2	0.7	1.9
Vertical lift gate	14 - 18	3 - 3.3	2 - 2.3	5 - 5.6
Mitre gate	16 - 24	1.3 - 2.5	1.2 - 1.6	2.5 - 4.1

Table 2.3: Lock gate operating times

The levelling of the chamber is based on the equation for filling a lock by Groenveld (1999) (equation 2.2). To reduce the impact of a translatory wave from the sudden opening of the filling sluice, the sluice is opened gradually over a time of T_1.

$$T = \frac{T_1}{2} + \frac{2 * O_k * H}{m * A_s * \sqrt{2gH}} \tag{2.2}$$

where:

- T = total filling time of the chamber,
- O_k = chamber area,
- H = water level difference,
- m = discharge coefficient of the sluice, between 0.6 and 0.9,
- A_s = area of the sluice opening,
- g = gravitational acceleration.

The operating time of a lock does not change with the number of vessels in a lockage, it is only dependent on the operating of the gate and the filling sluice and the water level difference.

Entering, exiting and loop time
The entering time can be defined as $T_i = t_l + \Sigma t_i$, which is the combination of the loop interval and the sum of the entry intervals of all vessels in the lockage. The entry interval of a vessel can be defined as the time between a vessel entering the lock chamber and the previous vessel entering the lock chamber.
The loop interval is the time between the last vessel leaving the lock of the previous lockage and the first vessel entering of the current lockage. More precisely, the time between the stern of the last vessel of the from the previous locking passing the gates and the stern of the first vessel of the current locking passing the gates. The loop time is highly dependent on the loop distance of a lock, which is the distance of the gates to the stern of the first vessel waiting to enter. This distance is related to the geometry of the lock, the distance at which the vessels can safely pass each other.
The exiting time is the sum of the exiting interval of all vessels following the first vessel leaving the lock, $T_u = \Sigma t_u$. When the stern of the final vessel in the locking passes the lock gates, the loop time starts.
Since the entry and exit intervals are between successive vessels, there are no entering and exiting times for lockings with a single vessel. In this case there is only the loop time.

2.1.3. Summary
An description of a lock passage based on the literature can be found in Table 2.4.

	Function of	Parameters	Symbol
Entering time	Entry interval	Dead weight tonnage	DWT
	Loop time	Cross sectional area of vessel relative to the lock	A_m/A_c
		Laden or unladen	-
		Loop distance	S_l
Operating time	Gates opening / closing, Table 2.3	Type of gate	-
		Chamber width	W_{ch}
	Levelling time, Equation 2.2 $T = \frac{T_1}{2} + \frac{2*A_{ch}*H}{m*A_s*\sqrt{2gH}}$	Chamber area	A_{ch}
		Water level difference	H
		Discharge coefficient of the sluice, between 0.6 and 0.9	m
		Sluice opening area	A_s
		Sluice opening time	T_1
		Gravitational acceleration	g
Exiting time	Exit interval	Dead weight tonnage	DWT
	Loop time	Cross sectional area of vessel relative to the lock	A_m/A_c
		Laden or unladen	-
		Loop distance	S_l

Table 2.4: Overview of lock passage parameters in literature

2.2. Location data in model validation

GPS is used in many studies as a way to calibrate and validate the simulation of a specific mode of transport, for commercial shipping, public transport or people movements. These studies give a description of the application of the model and the GPS data.

2.2.1. GPS based models

Research on data-driven bicycle route choices was performed with data from Amsterdam (Ton et al., 2018) and from San Francisco (Hood et al., 2013). In both studies the data was collected by smartphone users. Hood et al. (2013) uses the collected data to compare a model that generates the shortest route to the chosen routes by the cyclists. Preferences in route choices are used for the investments in bicycle infrastructure in San Francisco.
Ton et al. (2018) developed a method to compare three algorithms for path selection to GPS data, that was applied to a data set of cyclists in Amsterdam. The performance of the three models was evaluated using the percentage of correctly predicted choices, the Root Mean Square Error to give an indication of the error between the observed and modelled routes and the Log-likelihood to compare all generated routes.
Another way of using GPS data in research is by analysing the movement of an object along a fixed trajectory. This method is used to find cyclists' waiting times at intersections in the city of Bologna, Italy (Rupi et al., 2020). The GPS data collected from the smartphones of the cyclists was mapped on a street map and converted to a speed plot for each cyclist. The cyclist was considered waiting when the speed was below a predefined threshold. Poliziani et al. (2022) tested and validated these waiting times with manually recorded cyclists' waiting times on the same intersections. A linear regression of the data showed that the GPS method gave a good indication of waiting times with an R^2 value of 0.95.

Another example of data-driven validation is in the field of public transport. Yu et al. (2006) showed a method for the calibration and validation of the microscopic traffic simulation model VISSIM. The study focuses on the speed of buses at a 20 meter interval. The vehicle speed on that section found with the simulation and the collected GPS data are compared using the Sum of Squared Errors (SSE). This is used to validate the parameters of the simulation model. The method is applied on a case study for the Beijing bus system. One of the recommendations was based on the uncertainty of the measure of effectiveness. Further research is recommended to include more measures.
Feng et al. (2017) used bus simulation models to simulate two possible scenarios for zero emission bus transportation. The scenarios are an on-route charging solution and a depot charging solution. GPS data is here used in two ways. First to find the bus routes input with an analysis of the current bus system and second to validate the model with field data of electric buses.

2.2.2. Automatic Identification System (AIS)

AIS data was used for this study, this data contains the GPS location of vessels besides other static and variable information of the vessels. This section shows the application of AIS data in other studies and a description of the data itself.

AIS in data research

Besides live tracking of the vessels, with the AIS information the course of a vessel can be followed over a period of time or for an area of interest. Since the use of AIS is mandatory for inland water transport vessels in The Netherlands since 2016 (“Binnenvaartpolitiereglement”, 2022), this can be done for all vessels in that time span or area. This results in a data set that can be used for analysing situations and comparing variables concerning inland or marine traffic. Recent studies which use AIS data to analyse vessel traffic have been conducted in the scope of the Port of Rotterdam.
AIS data is used by Bellsolà Olba et al. (2019) around intersections of waterways in the Port of Rotterdam, the data give a view of the traffic flow and an estimation of the capacity of the intersections. These were used to test a generic method for estimating the capacity of waterway intersections.
Another recent study by Zhou et al. (2020) combines AIS data and meteorological and hydrological data to analyse the vessels speed, path and drift angle for various situations of winds and currents. All the data was combined for a given moment in time, so that the meteorological and hydrological data can be assigned to each vessel individually. Afterwards, a statistical analysis was done to find impact of wind and current on the speed over ground for varying vessel dimensions.

AIS data description

The data used to analyse the locks is derived from the Automatic Identification System (AIS), which is developed for the communication between vessels or vessel and shore by The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). The main purposes for implementing AIS are (Hadley, 2016):

- Avoidance of vessel-to-vessel collision;
- a mean to obtain information about a vessel and its cargo; and
- a tool for Vessel Traffic Service (VTS) to improve traffic management.

The AIS automatically broadcasts the vessel information to the AIS stations on other vessels or on land, these stations have a display with a visualisation of the surrounding vessels. The information includes the vessel characteristics, such as dimensions, loading, vessel type and vessel name, besides local information as GPS location, vessel speed and heading for a certain timestamp. An example of the AIS data used in this research can be found in appendix A.

2.3. Simulation of a lock in a transport model

In the past, the turn-around times for vessels in waterway transport were long, with low navigational speed and less efficient loading and unloading. This means that the time needed to pass a lock was of secondary importance during the design of the lock, the main factor was the dimensions of the vessels that need to pass. However, when the waterway traffic volume and the development of vessels increased, the transit time became more important for inland water transport. The capacity of locks became an important factor in the flow of traffic, this resulted in the design of new lock with an efficient locking process. Capacities were estimated from existing lock and first was considered that the capacity of a lock was mostly dependant on the surface area of the lock (Kooman and Bruijn, 1975). Later, Kooman and Bruijn (1975) came with a definition for the capacity of a lock and the element of the locking process.

2.3.1. SIVAK

The simulation package SIVAK (Simulatiepakket voor VerkeersAfwikkeling bij Kunstwerken) is used by Rijkswaterstaat from 1990 to analyse the flow of vessel traffic around bridges, locks and narrow waterways. The simulations are used to design the main dimensions and expected congestion of a new civil work, but also to investigate future scenarios or different strategies of operation. The input needed to run a simulation using SIVAK is (Buro Sierenberg en De Gans, 1998):

- The network: lay-out, operating times and water levels.
- The vessel traffic: fleet with vessel dimensions, arrival distribution and vessel speed
- Optional road traffic: when the bridge or lock has impact on the road traffic flow.

When focusing on a lock simulation, the times for entering and leaving the lock or the time for levelling are based on data collected from different locks in The Netherlands. The level time is based on a base time and an extra time that has a linear connection with the water level difference. The entering and leaving times are dependent on the type of vessel, on whether the vessel is the first vessel or a following vessel and on whether the vessel is laden or unladen. The entering and leaving times are a function B_v/B_c for unladen vessels and a function of A_m/A_c for laden vessels (Rijkswaterstaat, 2000), with:

- B_v : the width of the vessel $[m]$,
- B_c : the width of the chamber $[m]$,
- A_m : the cross section of the middle of the vessel $[m^2]$, and
- A_c : the wetted area of the chamber cross section $[m^2]$.

While being a generic tool to simulate a lock, the are some limitations of SIVAK. The package uses input variables that are derived from locks with common dimensions and lay-outs, a square cross section and an even width. A result is that SIVAK can run an accurate simulation for a common style of lock and for a general traffic situation, but may require validation when used for a more specific lock or situation. The study by Ten Hove (2015) of the capacity of a sea-going lock at Terneuzen used SIVAK that included a validation considering the specific lock. This validation was based on data from 2012 of the vessels passing, the passage time and the waiting times of the lock. A study as such relies upon the availability and the extensiveness of the present data of the lock.

2.3.2. OpenTNSim locking module

The open-source transport network simulation model OpenTNSim is developed at the Ports and Waterways (P&W) department of TU Delft, Van Oord and Deltares and includes a lock simulation module (Baart et al., 2022). The locking module is currently in a development state, however this module does include a similar level of detail as SIVAK with variable lock dimensions and operating times and vessel dependable entering and exiting times.
OpenTNSim is a python package of a discrete event simulation that can be used to simulate water transport chains on a waterway network. The package is developed as a tool in the design and optimisation of port water areas and inland waterways. The discrete event simulation means that the transport network composes of nodes and edges connecting the nodes. During the simulation, variables can be assigned to a vessel on the passage of a node. This way, the passage of large and constant sections require little computation.

OpenTNSim locking module

The locking module for OpenTNSim is in the current version still in development, however in a working status. The module can simulate a one dimensional locking, with all vessels in a single line. This means that the model can only simulate a locking where the length of the vessels in the chamber combined is smaller than the length of the chamber.

The locking module also contains nodes, to which elements of the lock are connected. These elements are the waiting area, line-up area and the lock chamber. The vessel can pass the waiting area, only when there is sufficient capacity in the line-up area and enter the lock chamber when there is sufficient capacity in the camber and the water level coincides.

The vessel speed is adjusted during the approach of the lock to simulate the deceleration of the vessel. The vessel enters the lock area on a certain cruising speed, this will be reduced by half on the approach of the node that corresponds to the waiting area. The second vessel speed adjustment is at the approach of the line-up area. Again the speed is reduced by 50 percent, which results in 25 percent of the cruising speed. This speed is remained until the vessel reaches the assigned location in the lock chamber.

For the lock operating time Equation 2.2 or an predefined time value is used. After the lock operation, all vessels leave the lock with the initial cruising speed. In case more than one vessels in the locking, the following vessel starts sailing when the previous vessel has passed the line-up area of the returning direction.

	Function of	Parameters	Symbol
Entering time	Vessel speed	Initial vessel speed	V_{cr}
		Location of waiting area for 50% speed reduction	SR_1
		Location of line-up area for 25% speed reduction	SR_2
	Loop distance	Location of waiting area	S_l
Operating time	Gates opening / closing, Table 2.3	Type of gate	-
		Chamber width	B_c
	Levelling time, Equation 2.2	Chamber area	A_c
	$T = \frac{T_1}{2} + \frac{2*O_k*H}{m*A_s*\sqrt{2gH}}$	Water level difference	H
		Discharge coefficient of the sluice, between 0.6 and 0.9	m
		Sluice opening area	A_s
		Sluice opening time	T_1
		Gravitational acceleration	g
Exiting time	Vessel speed	Initial vessel speed	V_{cr}
	Loop distance	Location of waiting area	S_l

Table 2.5: Overview of lock passage parameters in OpenTNSim

2.3.3. Validation of locks in transport network models

There are more simulation models developed that include the passage of one or more locks. The complexity of the locking process in these models depends on the purpose of the model, the application and validation of some of these models are described below.

The discrete event Simulation for InterModal BArge transport, or SIMBA (Macharis et al., 2011), is a model for the waterway network of the port of Antwerp's hinterland. The model is complimentary to the NODUS model, which is considering multimodal freight transport. NODUS is used in studies for

freight transport planning and infrastructure cost benefit analyses (Jourquin, 2022). Macharis et al. (2011) describes the development of a lock simulation as ”A number of decision rules are defined to make the operations of the locks in the simulation model reasonably realistic.”. The passage of a lock is considered in SIMBA using average total locking times for each lock, which is the average total delay a vessel experiences compared to cruising speed.
Campbell et al. (2007) developed a discrete event simulation of the Upper Mississippi River to investigate alternative lock operations. Vessels on the Upper Mississippi River need to pass a total of 29 locks, the locking times are based on historical data for each lock, direction and vessel type. The simulation is validated by comparing the average monthly number of lockings, the utilisation statistics and the queueing statistics to the historical database for the year 2000.
Another study of the Ohio River on the economical impact of waiting times coming from lock operation uses average lock passage times for the validation of a simulation model. The validation is based on historical data from 1984. Part of the conclusion is that the model gives an accurate simulation of the lock performance, but more extensive data can improve the model on lock selection and fleet composition. Extensive analysis of data can be used to implement situations as lock maintenance and failures (Dai and Schonfeld, 1991).

2.4. Conclusion

Data-driven validation of simulation models is a widely used method for various transport models. When looking at the validation of models for inland water transport and to locks in particular, the validation of these models often rely on historical data, use general numbers for all locks or only use the total passage time of a lock. AIS Data can be used to analyse parts of a waterway network and to validate simulation models on a detailed scale. A validation using AIS data can be used to find and improve errors in a simulation model of a lock on a detailed level.
Using the found trajectory of a vessel through a lock, some of the lock characteristics of Section 2.1 can be analysed. The trajectories can be combined for all vessels during a locking cycle. This can all be used to quantify the phases of a lock, although the data only shows the vessel track what can limit the accuracy of some of the lock’s operational phases.

3

Method and materials

The method consists of two phases, starting with the AIS data around a lock. A process is developed to translate this data to information on a lock and the lock phases specified in chapter 2. The method creates a data set that can be used in the analysis of a lock and to compare the performance of a lock simulation model. The second part of the method is to compare the data to a model and to use this comparison for the calibration and validation of this model.
A case study is performed on the Volkerak locks and Kreekrak locks to show the working principle of the method. The materials used for this case study are an AIS data set of the area around the two locks and the lock simulation model OpenTNSim. The locks and simulation model that were used for this case study are explained in Section 3.3.

3.1. Translation of AIS data to lock information

In this section the method for retrieving lock specific data from AIS is described. Firstly, the relevant phases of the locking cycle are defined. Secondly, the location and vessel speed are used to quantify these phases for each vessel passing the lock. Finally, the data on these vessels are combined to create a data set of all the locking cycles.
There are two perspectives that can be distinguished when looking at the performance of a lock. The first perspective is an individual vessel passing a lock, each vessel has its own passage time and delays due to the locking. Second, is the perspective of the lock itself. The lock can contain a number of vessels per locking dependant on the vessels waiting or arriving. Both of these perspectives are considered in the data translation.
There are also two output data sets generated from the method. One containing information of each vessel passing the lock and the other contains information of the lockings. The variables in both data sets are described in tables Vessels DataFrame (3.1) and Lockings DataFrame (3.2) Both tables are in the format of a Pandas DataFrame. DataFrame is a data structure used in the python package Pandas.

3.1.1. Lock cycle phases

The lock cycle phases that were considered in the method are based on the literature of Chapter 2. The phases can be found from the perspective of the vessel or the lock operator and the phases for both perspectives are described below.
The locking cycle from a vessel's perspective:

- Waiting time
- Entering time
- Time in lock chamber
- Exiting time

Locking cycle aspects from a lock operator perspective:

- Entering interval
- Operating time
- Exiting interval
- Loop time and loop distance
- Number of vessels in the lock
- Vessel distribution in chamber

3.1.2. Extracting individual vessels passing a lock

In this research the AIS data is used to create an overview of the movement of vessels around locks, which can be derived easily for any given lock. The method uses the input of the AIS data combined with the location of the lock to retrieve information about each vessel passing the lock. The required input to use the method for a certain lock is:

- AIS data of vessels in an area containing the lock, for any time span,
- the area of the lock as a set of coordinates,
- the area of each of the lock chambers as a set of coordinates, and
- the area of each of the waiting and lineup areas as a set of coordinates.

The process to generate the Vessels DataFrame takes both the AIS data and the lock dimensions as input, the process is describes in a flowchart in Figure 3.3. A Python algorithm is created in Jupyter Notebooks for this process.

1. Define lock chambers and direction
First, the locations of the lock chambers are defined, based on the input coordinates of the chambers. Also, the angle of both directions of the lock is derived from the lock coordinates and defined as direction 1 and 2.

2. Filtering the AIS data
Each row of AIS data is transmitted by a single vessel with a timestamp and a longitude and latitude. The data is filtered on vessels that pass the lock in the area of the selected lock chamber. The data is further filtered on a single vessel by the vessels identification number. It is possible this vessel passes this lock chamber multiple times during the time span of the data set, so these passages are separated. A minimum time period between two data points of 30 minutes is used to define a new lock passage.
Now, trajectories are created with the data of each individual vessel passage. Figure 3.1 shows the trajectories of five vessels passing the Volkerak locks, found with the data used in the case study of Section 3.3. The lock passages are visualised in a time - distance diagram that resembles the theoretical example of Figure 2.1. This example shows three lockings where two vessels (*testschip-739* and *testschip-3711*) need to wait for passing of the first two vessels (*testschip-988* and *testschip-3200*).

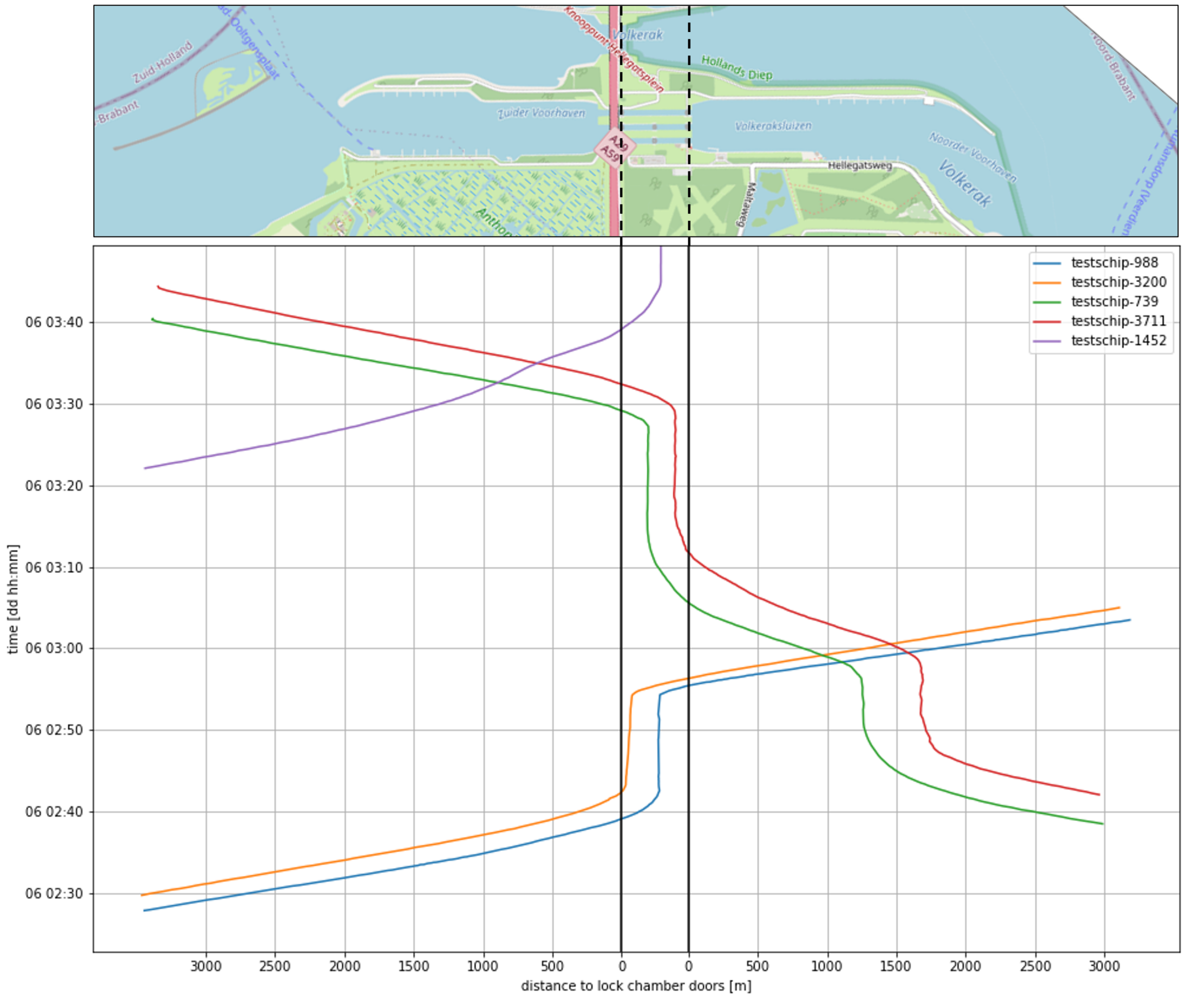

Figure 3.1: Example of a time - distance diagram of chamber 1 of the Volkerak locks.

3. Direction of the vessel passage
When it comes to the majority of the locks, there are vessels passing in both directions. These directions are found with the bearing angle of the lock chamber and the vessel. The bearing angle between two data points of a vessel track before and after passing the lock chamber is compared to the bearing angle found with the lock chamber coordinates. The vessels in the first direction match the chamber angle and the vessels in the second direction deviate by 180 degrees.

4. Remove outlier data points
The AIS data can have some outliers, coming from a bad GPS signal or a badly assigned timestamp. The outliers are found by comparing each data point with the expected direction, speed and distance. A threshold value is used to filter the outliers on speed of the vessel, wrong GPS coordinates probably give a large distance from the previous data point that result in a high vessel speed derived from the distance and the time interval.
In the data used for the case study was found that most of the outliers had the wright timestamp connected to the wrong coordinates of a previous data point. These outliers are found by the direction of the vessel relative to the overall direction of the vessel. When the azimuth between a data point and the previous data point is out of a 180 degrees range and the covered distance is larger than 10 meters, the data point is considered an outlier.

5. Define variables based on speed and location
Now, with a clean and filtered data set of a single vessel passage, the phases that are relevant for the lock passage are assigned. The variables are derived from the speed of the vessel and the time

at specifically selected locations. For example is the enter time assigned as the timestamp of the first data point inside the lock area and is the timestamp of the first data point with a speed of 0 assigned as the start of the vessel stopped in the lock chamber. These variables are appended to the Vessels DataFrame.
Figure 3.2 gives an example of the speed of a vessel during the passage of a lock. Here, the time of entering and leaving the lock area is shown with the red green lines. The yellow and red lines indicate the time the vessel is stopped, in the waiting area and the lock area respectively. From the case study data was found that there are large intervals at the first data point after the vessels starts sailing. The starting point of sailing is found by interpolation of the first data points after passing the threshold of 0.5 knots.

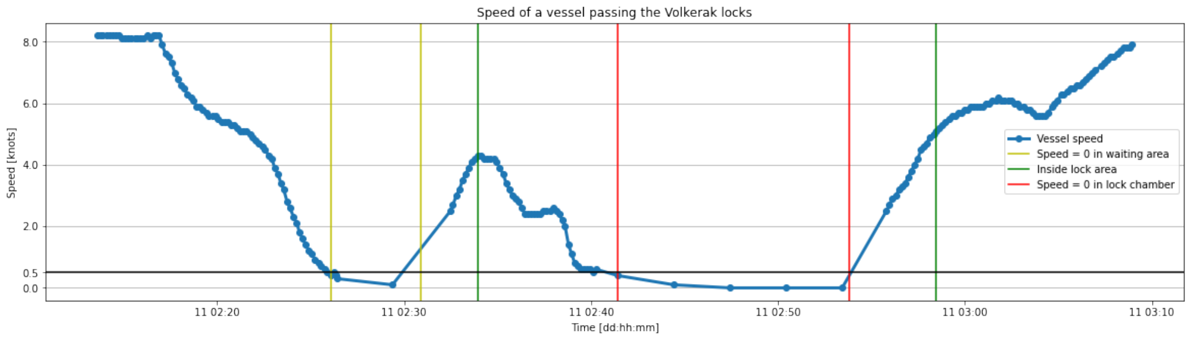

Figure 3.2: Example of a speed plot of a vessel passing the Volkerak locks.

Also, the geographical trajectories of the vessels like in the example of Figure 3.1 are used to assign which lock chamber is used and what the position of the vessel is in the chamber and in the waiting area.

6. Loop if needed
The process is looped for each passage of the vessel, vessel in the chamber and chamber of the lock to create the output Vessels DataFrame.

Variable	**Description**
vessel name	Name of the vessel
vessel type	Type of vessel as defined in Rec. ITU-R M.1371-5
Chamber	Chamber used during locking
Enter time waiting area	Time of entering assigned waiting area
Enter time	Time of entering assigned lock
Exit time	Time of leaving assigned lock
Speed = 0 start	Time of start laying in the lock
Speed = 0 stop	Time of start sailing in the lock
Position in lock	Position of the vessel laying in the lock
Time in lock	Time between entering and leaving the lock
Waiting time	Time of laying in waiting area
Length	Length of the vessel [m]
Beam	Beam of the vessel [m]
Draught	Draught of the vessel [m]

Table 3.1: Variables Vessels DataFrame

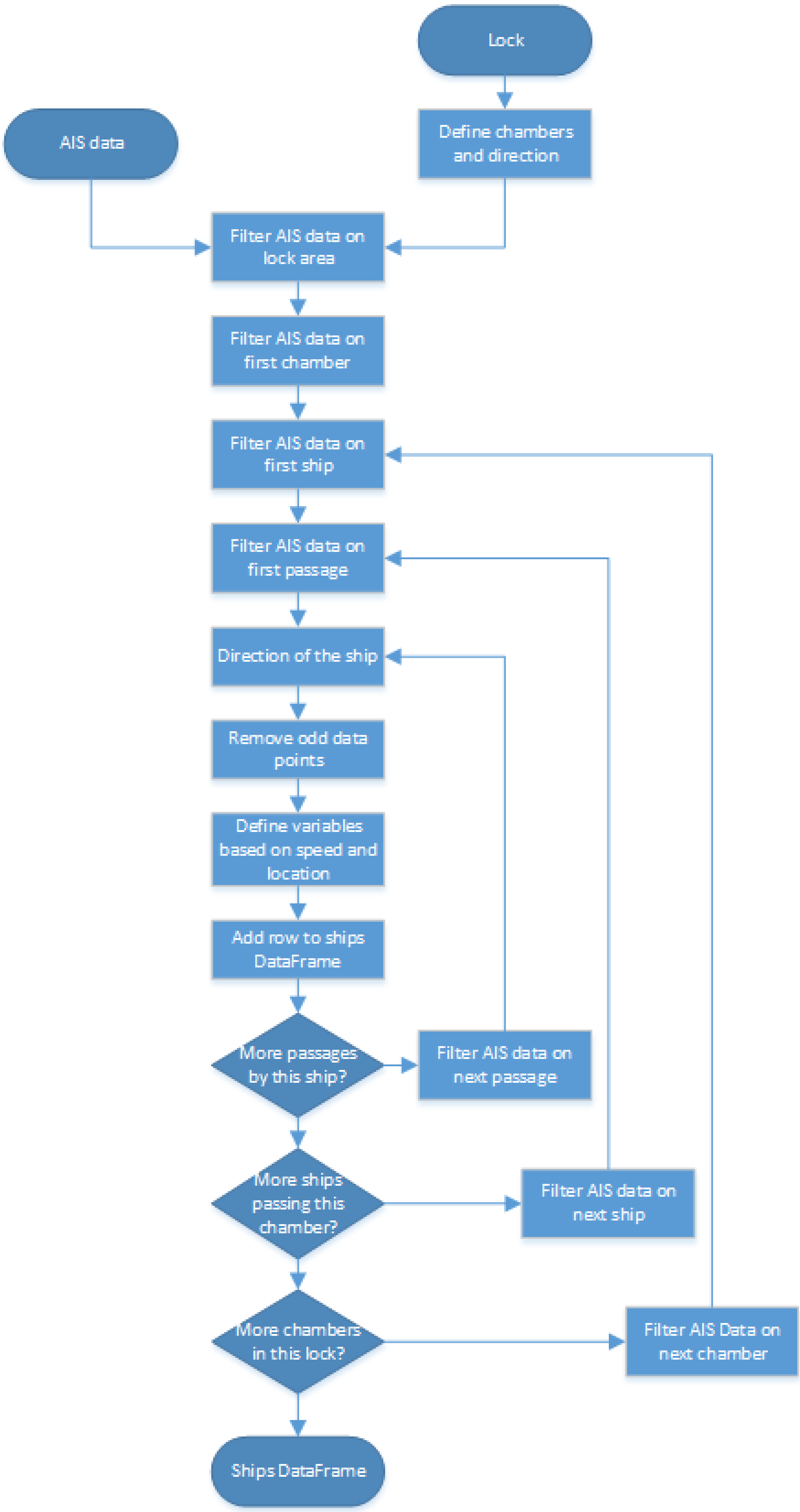

Figure 3.3: Process to Vessels DataFrame

3.1.3. Combining vessels in locking cycles

Another DataFrame is created for the lock perspective, this process also uses a Python algorithm in Jupyter Notebooks. Figure 3.4 contains a flowchart that takes as input the Vessels DataFrame from 3.1.2 and results in the Lockings DataFrame. The Lockings DataFrame is decribed in Table 3.2 and the parts of the process as shown in the flowchart as explained below.

1. Select first chamber
The procedure start by selecting the first chamber of the lock, which is the same procedure as for the Vessels DataFrame.

2. Start of a locking
Each row of Vessels DataFrame represents one passage of a single vessel and all rows are sorted on the time of entering the lock, only one vessel can enter a lock chamber at a time. The start of a locking is defined by the first row that is not assigned to a previous locking. In case of the first row, this is the fist vessel in the locking. The locking now has a chamber, a direction and a starting time and a stopping time, based on the first vessels time of entering and leaving the lock.

3. Combine all vessels in locking
Next, all vessel passages, if any, that share the chamber and direction with the first vessel and have an entering time later than the starting time and earlier than the stopping time of the locking are combined. This means that these vessels are all in the same locking. The vessels all have a time where the speed equals 0 and the vessels are laying still in the chamber, the time of levelling is derived from the time that all vessels are laying still in the lock chamber. So, from the latest time of *Speed = 0 start* until the first time of *Speed = 0 stop*.
These variables are appended to the Lockings DataFrame, in the form of Table 3.2. Also, the Vessels DataFrame rows of the vessels in the locking are collected and added to the Lockings DataFrame.

4. Loop if needed
If there is another vessel in the Vessels DataFrame, that is not assigned to a locking, the process is repeated for a new locking with the next vessel as the first vessel of the locking.

5. Add empty lockings
There are situations where a vessel enters the lock and an empty locking is needed to have the lock chamber on the right side of the lock. Since this method is based on vessel data, the empty lockings are not detected. However, when a locking is following a locking with the same chamber and direction, an empty locking in the other direction is needed between these lockings. These empty lockings are included in the Lockings DataFrame, but do not have information on level times for example.

Variable	Description
Chamber	Chamber used during locking
vessels	Number of vessels in locking
Start	Time of first vessel entering the lock
Start level	Time of last vessel entering starts laying in lock
Stop level	Time of first vessel leaving starts sailing
Stop	Time of last vessel leaving the lock
Direction	Direction of the locking [1 or 2]
Locking time	Time between first vessel entering and last vessel leaving the lock
vessel characteristics	Table 3.1 of all vessels in locking

Table 3.2: Variables lockings DataFrame

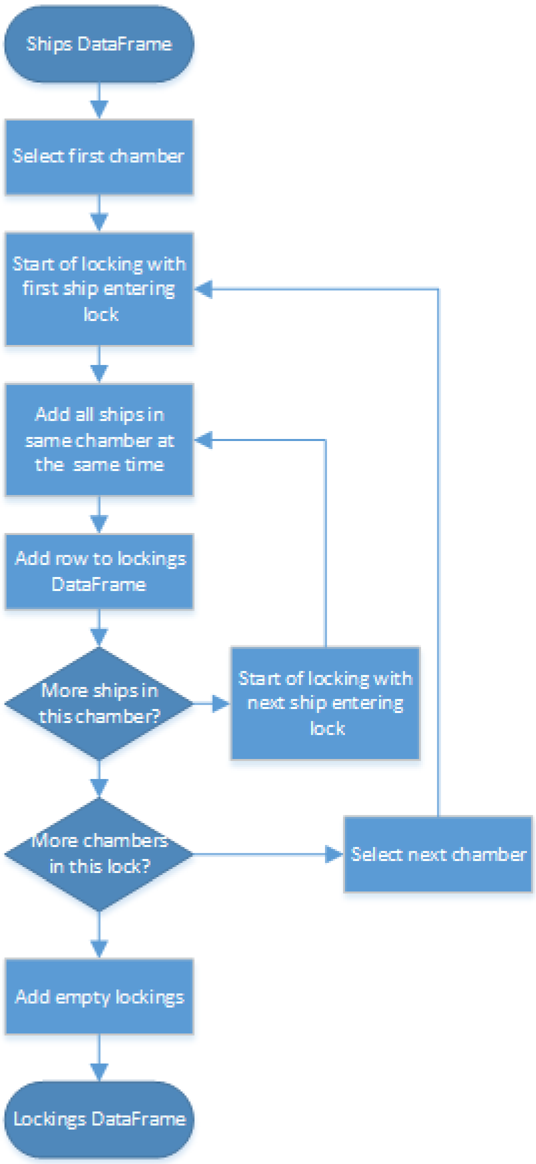

Figure 3.4: Process to lockings DataFrame

3.2. Comparison with a simulation model

For the locking module, nodes are assigned to the waiting areas, the line-up areas, the lock gates and the lock chamber. The nodes are assigned with a capacity, for the lock chamber this is the length of the chamber. When a vessel arrives at the node of the lock chamber, it occupies the length of the vessel of the lock chamber. Whether a vessel can pass the lock depends on the capacity of the lock chamber and the queue waiting for the lock.

3.2.1. Validation approach of a simulation model

There are two factors that impact the passage times of a vessel, the vessel speed and the operating time of the lock. In Section 3.3.2 is the OpenTNSim lock simulation compared to the data found with AIS, the passage time of a node is based on the vessel speed when the are no obstacles in this section. For the passage of the lock, the vessel needs to wait on the operating of the lock before it can proceed with a given vessel speed.

Operating time
The operating time is validated by adjusting the levelling time, where the time for opening and closing the gates is held constant. The operating time therefore depends on the parameters of equation 2.2, with the water level difference coming from the water level at the time of the AIS lockings DataFrame.

Vessel speed
The entering and exiting times of a vessel are defined by the speed of the vessel when approaching and leaving the lock. The simulation of the gradual deceleration and acceleration of a vessel for a discrete event model can be approached by assigning a factor on the initial speed of the vessel. A validation of the relative speed at specific nodes of the network around a lock is done to match the travel time between various nodes.

Location in the lock
At this point, the current version of OpenTNSim uses a one dimensional arrangement of vessels in a lock. This means that each vessel joins the others vessels in line and the length of the lock chamber and the vessels is limiting the total number of vessels that fit the chamber. Obviously, a lock chamber also has a width and some locks might fit multiple vessels side by side. The AIS data gives a location of the vessel in the lock chamber during levelling, so it can be used to validate the arrangement of the vessels in a lock simulation but this is not the case for the current situation.

3.2.2. Comparison of simulation and AIS data

The performance of the simulation model for a case can be evaluated using a goodness-of-fit measure. Popular measures are the mean error (ME), the mean percent error (MPE), the root-mean-square error ($RMSE$) and the root-mean-square percent error ($RMSPE$). Where the percent error measures give a dimensionless error relative to the resulted measurements. $RMSE$ and $RMSPE$ are measures that penalise large errors because of the quadratic application. Under or over predictions following the simulation are indicated by the ME and MPE. These are most useful when applied at each time-space point (Toledo and Koutsopoulos, 2004). For this, the ME and MPE are used to indicate the error on the passage times for each segment in the Volkerak case study. These two measures are given by

$$ME = \frac{1}{N}\sum_{n=1}^{N}(Y_n^{sim} - Y_n^{obs}) \tag{3.1}$$

$$MPE = \frac{1}{N}\sum_{n=1}^{N}\frac{Y_n^{sim} - Y_n^{obs}}{Y_n^{obs}} * 100\% \tag{3.2}$$

where:

Y_n^{sim} = the simulated value,

Y_n^{obs} = the observed value.

Values of 0 for the ME and MPE indicate a perfect fit of the simulation to the measured data. Singh et al. (2005) states that the error can be considered small when the ME value is less than half the standard deviation of the data.
The goal of the validation of the simulation model is to minimise the error of the simulation. The error is minimised when the biases reaches zero, so the bias found with the cases of the case study give an indication of the sections that need adjustment. The relative bias or percent bias ($PBIAS$) is found using Equation 3.3. A positive value for the relative bias mean that the simulated passage time is larger than the observed passage time found using AIS and vice versa, a relative bias of 100% means that the simulated passage time is twice as large as the observed passage time.

$$PBIAS = \frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{i=1}^{n}(Y_i^{obs})} \tag{3.3}$$

The relative bias is chosen as a measure to compare the simulations to the AIS data because $PBIAS$ can intuitively show underestimations with positive values and overestimations with negative values. This way, $PBIAS$ can clearly show poor model performance (Moriasi et al., 2007).
The validation process can depend on the intended use of the lock simulation. A validation to meet the total passage time of the lock might be enough when the lock is a small component of a large network, in terms of impact on the outcome of a simulation. In this situation, the validation can be defined as successful when the histograms of the total passage time give comparable results. When the model requires an accurate simulation of all segments in the locking process, the validation needs to minimise the bias for all the segments.

3.3. Case studies on Volkerak and Kreekrak locks

This case study is used during this report to explain the method and the results of the lock analysis. To show the generic applicability of the method, a brief analysis of the Kreekrak locks is done.

3.3.1. description of the case studies

Volkerak locks

One of the objects of this study is to create a generic method for analysing the traffic trough any lock, however the Volkerak locks are chosen as a case study. The Volkerak locks are among the most complex inland locks in The Netherlands, with three chambers, a tidal difference and the largest vessel throughput (Figee and Volker, 2015). The method takes as input the coordinates of the area of the lock that is analysed and the available AIS data for this area. The AIS data is provided by Rijkswaterstaat and has a time span of three months, from the 1^{st} of August until the 31^{st} of October of the year 2019.
The input areas of the lock, chambers and waiting areas of the Volkerak locks are shown in Figure 3.5.

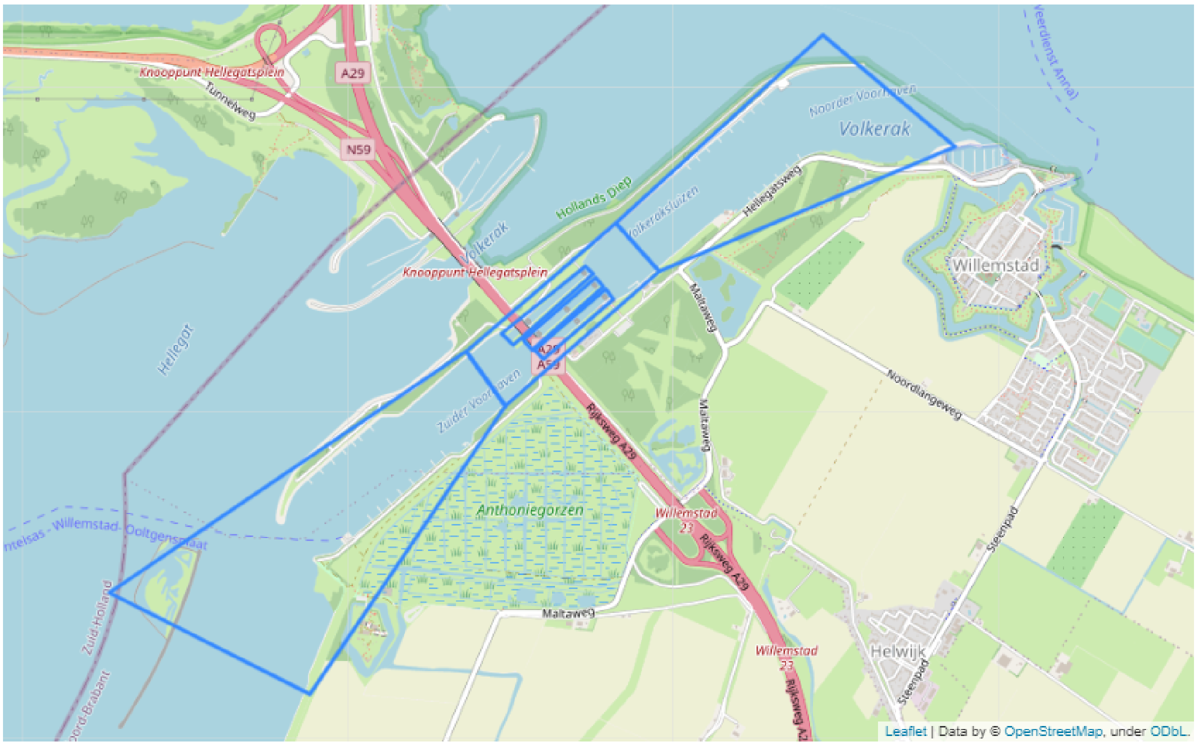

Figure 3.5: Volkerak areas

IVS to AIS comparison

The vessel tracking system that is used by Rijkswaterstaat is called IVS (*Informatie- en Volgsysteem voor de Scheepsvaart*) and logs all vessels passing a lock in The Netherlands in a 10 year database.

The data gives information of the vessel passing and the times of the traffic lights at the lock gates. IVS can be sufficient for a statistical analysis of a lock, however the data is not extensive enough to be used in the validation of a simulation model (De Jong, 2010). The vessels passing the Volkerak Locks and the number of vessels per locking that followed from the IVS data are used to compare the from AIS derived DataFrames as a verification.

Kreekrak locks

Another brief case study is done for the Kreekrak locks to show the generic use of the AIS data method. The Kreekrak locks are chosen mainly on the available data, since the data spans both locks on the Rotterdam - Antwerpen corridor. The lock complex of two chambers in the Schelde-Rijn channel has two chambers of the same dimensions as the Volkerak locks, a length of 320 meters and a width of 24 meters, and the positioning of a waiting area and line-up area are comparable to the Volkerak locks. There are also differences to the Volkerak lock, which is another reason to chose this case, so is the water level difference of the Kreekrak locks vary from 180 to 200 cm compared to a maximum of 80 cm for the Volkerak locks. The throughput of both locks compared, with the Kreekrak locks 70.000 vessels pass two chambers per year and with the Volkerak locks 150.000 vessels pass three chambers each year.

Apart from maintaining the water level difference, a purpose of the Kreekrak locks is to form a barrier between a fresh and a saline water body, the operation of the lock is designed to prevent spillage of salt in the fresh water body (Steenepoorte, 2016).

The input coordinates are used of the lock and chambers in the same way as for the Volkerak locks and, as an example, the vessels per locking and the operating time of the Kreekrak locks is compared to the Volkerak locks.

A comparison of different phases of a locking between two or more locks can be used in the decision making when validating a lock simulation model. This can substantiate the choice for doing a validation for each lock specifically in a case when there are multiple locks in a simulation network.

A time - distance diagram can be drawn for a lock to visualise the trajectory of the vessels passing the lock found with the AIS data. The time - distance diagram of Figure 3.6 is drawn using the AIS data for a time period of 8 hours and is comparable to the example of Figure 2.1. This diagram can be used in the validation process to visualise the location of the vessels in the lock chamber, in the waiting area or in the line-up area.

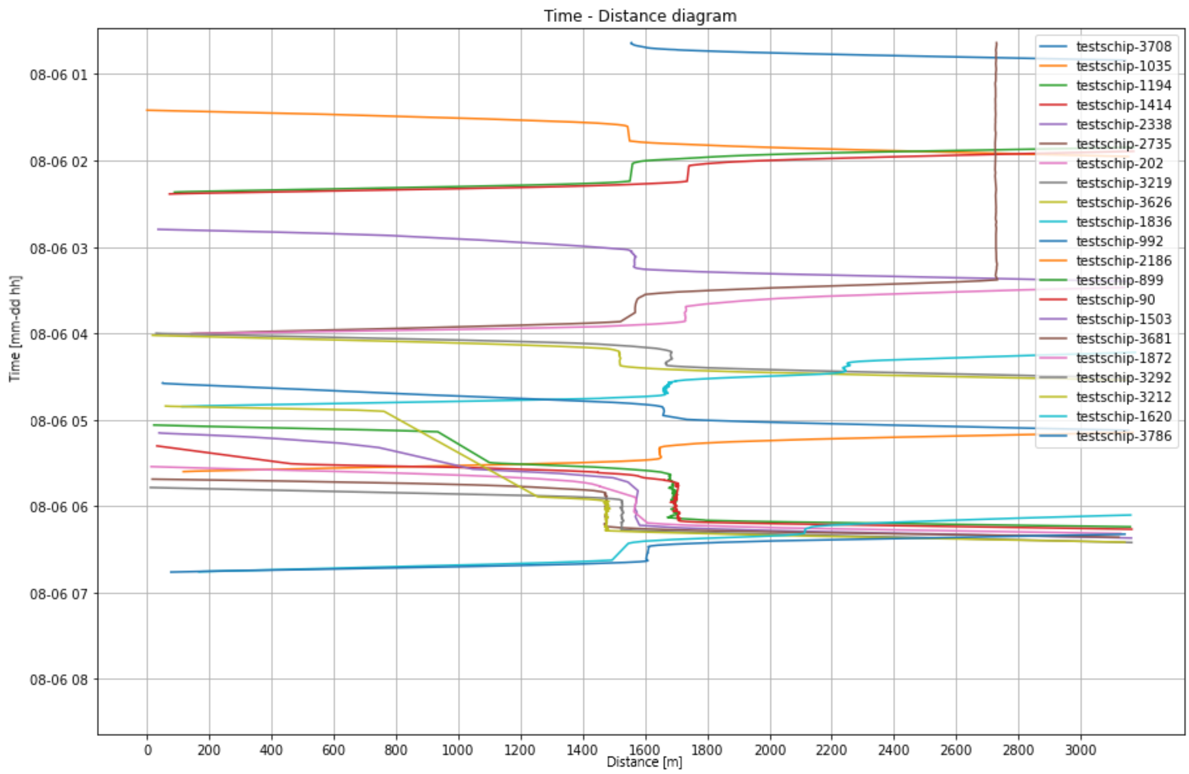

Figure 3.6: Example of a time - distance diagram of chamber 1 of the Kreekrak locks.

The analyses of the Volkerak and Kreekrak locks are used in this research for the validation of a locking model. The case studies are used to define the strategy of the validation, to calibrate the locking model and as a validation of the locking model. In the chapters 5 and 6, the validation process is explained and the results of this validation for the Volkerak case are shown in chapter 6.

3.3.2. OpenTNSim base simulation

The obtained lock relevant data is compared to a simulation of the same case study, which is the case study on the Volkerak locks. The base simulation can be considered as a simulation of the case study before any calibration or validation steps are followed. The base simulation was used to compare the simulations to the lock data. The working method of the OpenTNSim package and its locking module is described in the literature study in Chapter 2.
A network of nodes is created for the locks (figure 3.7), with the most North node numbered node 1 and the most south node 19. The waiting areas are on node 5 and 15 for both directions and the lineup areas are on node 7 and 13. The lock gates are assigned at nodes 9 and 11, with the lock chamber at node 10.

Figure 3.7: Nodes used in OpenTNSim network

In case of the Volkerak locks, mitre gates are used and, because the chamber width is 24 meters, the opening and closing times are set at 1.6 and 2.5 minutes respectively for the simulation, based on Table 2.3. The other component of the operating time, the level time, is based on equation 2.2. Figure 3.8 gives an example of a time - distance diagram for two vessels passing the Volkerak locks with the trajectories of both the simulation and the collected data. This example is used to show a way to visualise the collected data and the simulations. The process of comparing these trajectories that can be used for the validation of the simulation model is explained in Section 3.2.2.

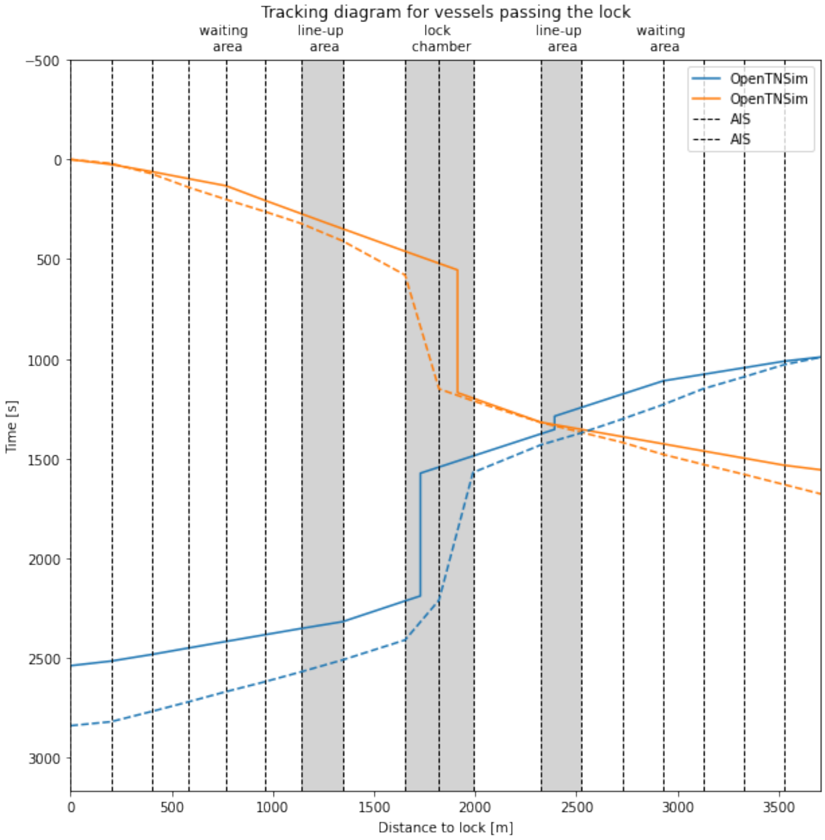

Figure 3.8: Example of two vessels passing the Volkerak locks.

Cases for validation
In order to make a comparison between the data derived from AIS and the lock simulation of OpenTNSim, some boundary conditions have to be considered. Cases are defined based on the number of vessels in the locking for a full locking cycle, so a passage exists in both directions. The cases are also defined on the need for waiting of the vessel, or vessels. For all situations where this cases applies, the time of arriving at the lock, the speed when arriving and the length of the vessel is used as input for the simulation. Combined with the water level difference at the time of passing the lock, the OpenTNSim lock simulation is run for each situation. The vessel type and other vessel characteristics are not taken into account and have a general value, since the lock module is only one dimensional in length.
The first two cases considered contain one vessel in the first locking and also one vessel in the following locking in the other direction. The two cases are divided by the waiting time, for the first case the vessel following from the other direction does not have to wait on the first vessel to pass. In the second case, the following vessel does have to wait on the first vessel to leave the lock. In this study, these cases will be referred to as Case A and Case B. In the third case, Case C, two vessels are passing the lock in one direction, followed by two vessels passing the lock in the other direction. The vessels do not have to wait on the first vessels to leave the lock.

3.3.3. Locking phases in simulation model

The locking phases, as described in Section 3.1.1, are part of the locking module of OpenTNSim. The phases are quantified as time spent at one of the node or the passage time between nodes. The model logs the activities from both the vessel's perspective and the lock's perspective.

Operating time
In the OpenTNSim log of the lock, the operating time is divided in closing the chamber doors, converting the water level and opening the chamber doors. The starting and stopping timestamp is logged

for each phase, with the number of vessels inside the chamber and the water level. The vessel's perspective has the operation time logged as the waiting time in the lock chamber. The lock chamber corresponds to one node in the simulation network and the lock operation starts when all vessels have arrived at this node. The timestamps of the waiting time in the lock chamber is logged with the coordinates of the vessel and the value of the waiting time.

	Parameter	**Volkerak**	**Kreekrak**
Entering time	V_{cr}	Input AIS	Input AIS
	SR_1, SR_2	50%, 25%	50%, 25%
	$SR_{1,node}$, $SR_{2,node}$	Node 5 / 15, Node 7 / 13 (waiting area and line-up area)	Node 5 / 15, Node 7 / 13 (waiting area and line-up area)
	S_l	Node 7 / 13	Node 7 / 13
Operating time	Type of gate	Mitre gate	Mitre gate
	W_{ch}	24 meters	24 meters
	A_{ch}	7920 m2	7680 m2
	H	Between 0.03 and 1.01 meters	Variable input
	m	0.8	0.7
	A_s	6 m^2	6 m^2
	T_1	0 min	0 min
	g	9.81 m/s^2	9.81 m/s^2
Exiting time	V_{cr}	Input AIS	Input AIS
	S_l	Node 7 / 13	Node 7 / 13

Table 3.3: Lock passage parameters base simulations Volkerak and Kreekrak with OpenTNSim

Waiting times
The waiting time of a vessel is located at the node corresponding to the line-up area. When the capacity is met of the line-up area, the vessels wait in the waiting area. The waiting time depends on the right of proceeding towards the next node given by the model. This right is based on the occupancy of the next node. The waiting time in the waiting area or line-up area is logged, combined with the coordinates of the vessel while waiting.

Entering and exiting
The speed of the vessel on the approach and the exiting of the lock is done by adjusting both the reduction factors used and the location of the speed reduction. In the initial situation of the OpenTNSim lock module, there are two speed reductions. The first speed reduction is after passing the waiting area with a factor of 0.5 times the initial speed. After passing the line-up area, the vessel approaches the lock chamber with a second speed reduction of 0.25 times the initial speed. On exiting the lock chamber the vessel speed is directly set at the initial speed.
Boundaries for the entering and exiting times must be determined before comparisons can be made. Kooman and Bruijn (1975) considers the entering time as the time a vessel needs to pass the loop distance. However, a vessel starts decelerating long before reaching the loop distance. In this case study, the series of nodes in the lock area are used to compare the vessel movements outside the lock chamber. The passage times on these segments give a comparison for varying distances in front and past the camber doors.

4

Results

This chapter shows the results that followed the case studies on the Volkerak locks and Kreekrak locks. The AIS data translation is performed for both cases and the Volkerak locks are used for the validation of the OpenTNSim locking module.

4.1. AIS data translation

The data can also give a view of a specific locking cycle. Figure 4.1 gives a visualisation of a locking cycle with 6 vessels in one direction and two vessels in the returning direction. As explained in 3.1, the locking phases are based on the movement of the vessels. Each bar in the figure represents a vessel in the locking cycle. The gate's operation and the levelling are assumed to be performed when all vessels lay still in the chamber. This is marked as the blue section in the figure.

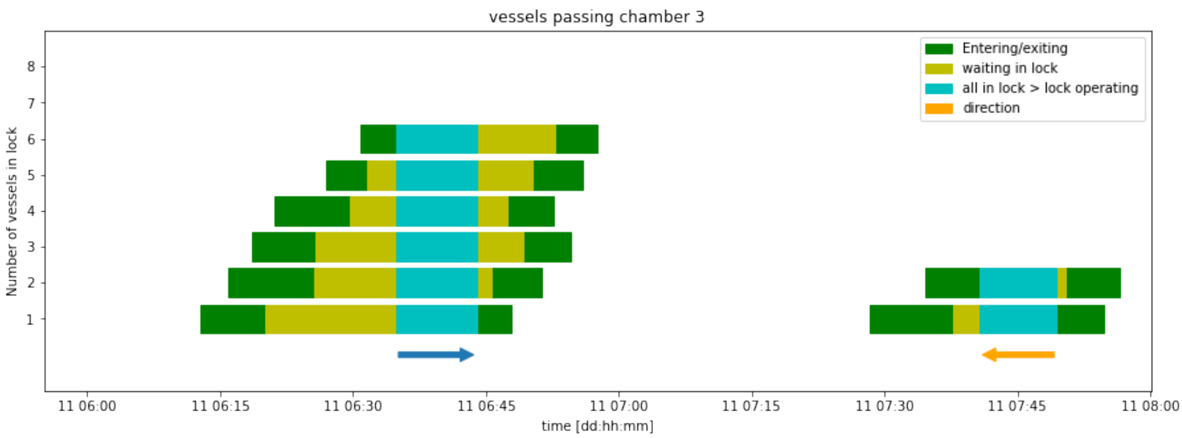

Figure 4.1: Example of a lock passage from AIS data of the Volkerak locks

AIS to IVS comparison

The total number of vessels in the time span described in Section 3.3 passing the Volkerak Locks is 24,446 vessels with the AIS method and 24,570 vessels in the IVS data. This means that the total number of vessels found with the AIS method deviates from the IVS data with 0.5%. The number of vessels in a locking is shown in Figure 4.2 from the Lockings DataFrame and the IVS data.

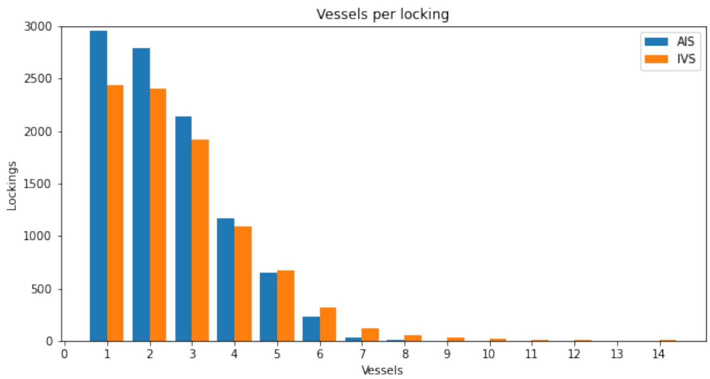

Figure 4.2: Vessels per locking, Volkerak Locks

The figure shows that the Lockings DataFrame has more lockings with one or two vessels and the IVS data shows more lockings with a higher number of vessels. This results in a total number of lockings over the time span of 9957 with the AIS method and 9067 from the IVS data.

Kreekrak locks
The method is applied to the Kreekrak locks as a second case to show the generic use and to compare the results to the Volkerak case. Figure 4.3 shows the number of vessels per locking and the level time in minutes for both cases. The Volkerak has, on average, slightly more vessels per locking. The level time of a locking at the Kreekrak locks takes on average 1.7 minutes longer that at the Volkerak locks.

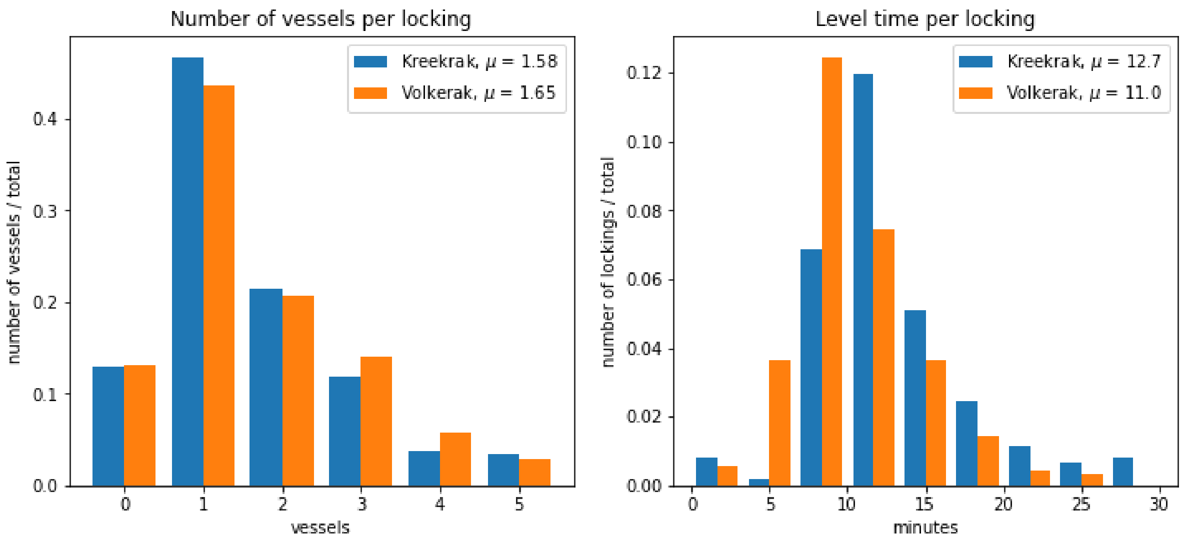

Figure 4.3: Comparison Kreekrak and Volkerak locks

4.2. Base simulation

The passage of a vessel through the lock is split into five parts to compare the performance of the OpenTNSim simulations to the AIS data, these parts are:

- total passage time, the time from the first node to the last node,
- time in lock chamber, time between the nodes at the gates of the lock,
- time in lock area, time of the vessel from the loop distance when entering until the loop distance when leaving.

- entering the lock, time between passing the waiting area and arriving at the gates, and
- exiting the lock, time between passing the gates on leaving and arriving at the waiting area.

4.2.1. Case A: One vessel, without waiting

Figure 4.4 shows these passage times of the OpenTNSim simulation and the AIS data, in the first histogram can be seen that the average total passage time of a vessel in OpenTNSim is about 4 minutes longer than found with AIS. The other histograms show that this longer passage time originates from the time in the lock and the entering of the lock, the exiting time of OpenTNSim is slightly shorter than the AIS data shows.

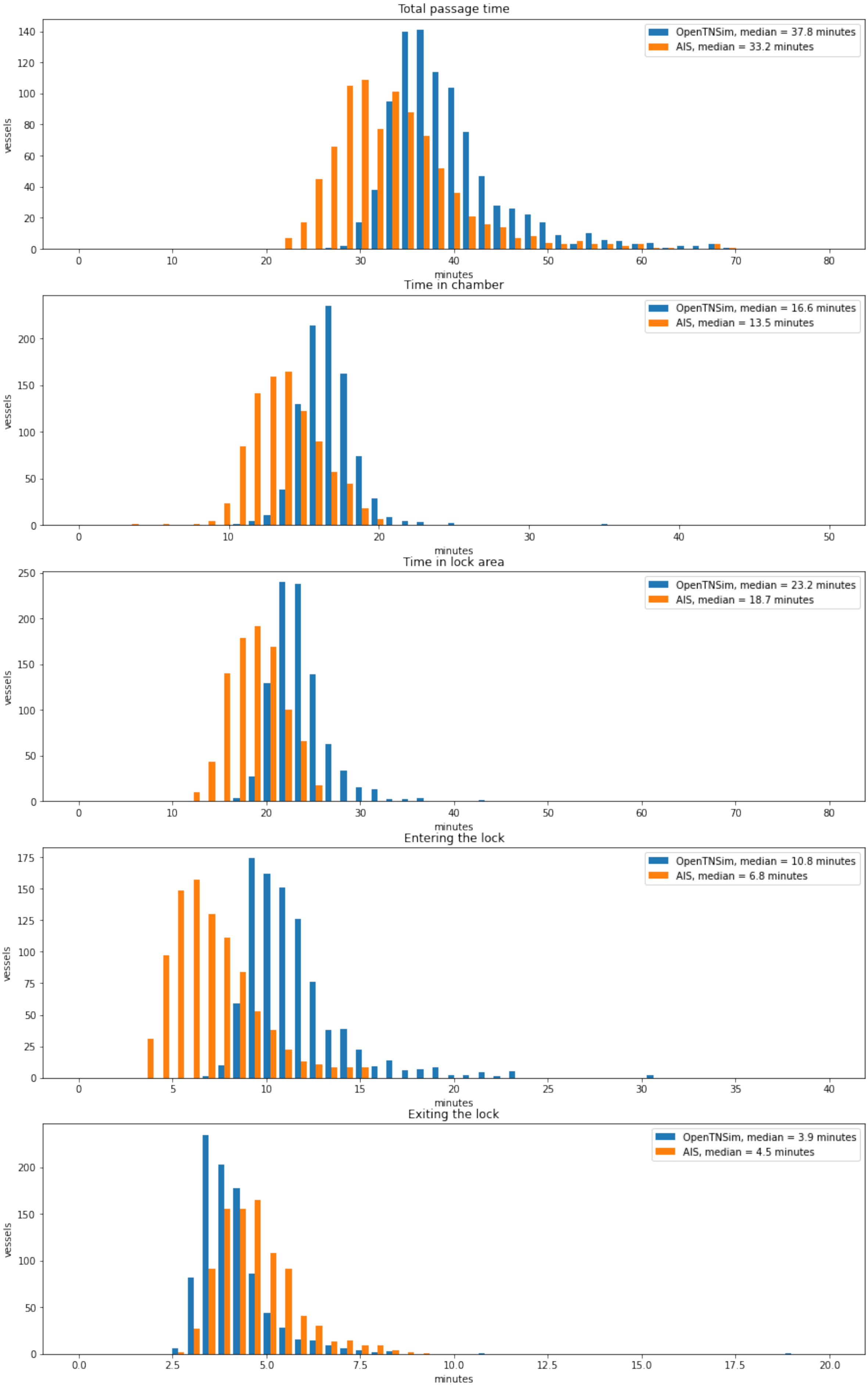

Figure 4.4: Passage time of OpenTNSim simulation and AIS data, 1 vessel per locking

The passage time is also compared between each node in the OpenTNSim network, Figure 4.5 shows three graphs with the average passage time of OpenTNSim and AIS data on the first graph. The seconds graph shows the bias of the simulation relative to the AIS data in percentages, the relative bias is found using equation 3.3. The bias decreases for a smaller difference between the simulation and the data.
Each bar shows the passage time between two nodes following the direction of the vessel, so a vessel in one direction enters the lock at node 1 and a vessel passing in the other direction at node 19. The location of the node assigned to the line-up area depends on the length of the vessel and the location of the vessel in the queue. The passage time between the nodes prior to and after the line-up area are combined to eliminate this variability. The nodes that span the lock chamber are also combined to eliminate the location of the vessel in the chamber. The line-up area is assigned to node 7 and the centre of the lock chamber to node 10, this leads to Figure 4.5 showing the passage time of node 6 to 8 and node 9 to 11.
The third graph of the figure shows a time - distance diagram of the average passage time for each node, the diagram does not show a vertical line when the vessel is in the lock chamber, like in Figure 2.1, because the nodes 9, 10 and 11 are combined. Nodes 9 and 11 are connected to both of the lock chamber doors. So, the trajectory between these nodes spans the length of the lock chamber.
The bars can visualise the node at which the simulation performs well and not so well. On the approach of the lock can be seen that up to the waiting area the passage time are larger for the simulation, after the waiting area is passed the passage times are shorter than the AIS data show up to the arrival at the lock chamber at node 9 or 11.
The passage time of the lock chamber is smaller than the AIS data shows, which was also visualised as the time in chamber of Figure 4.4. The first two bars following the lock chamber show that the passage time of the simulation is smaller than the AIS data, then the passage times are very close on the nodes after.

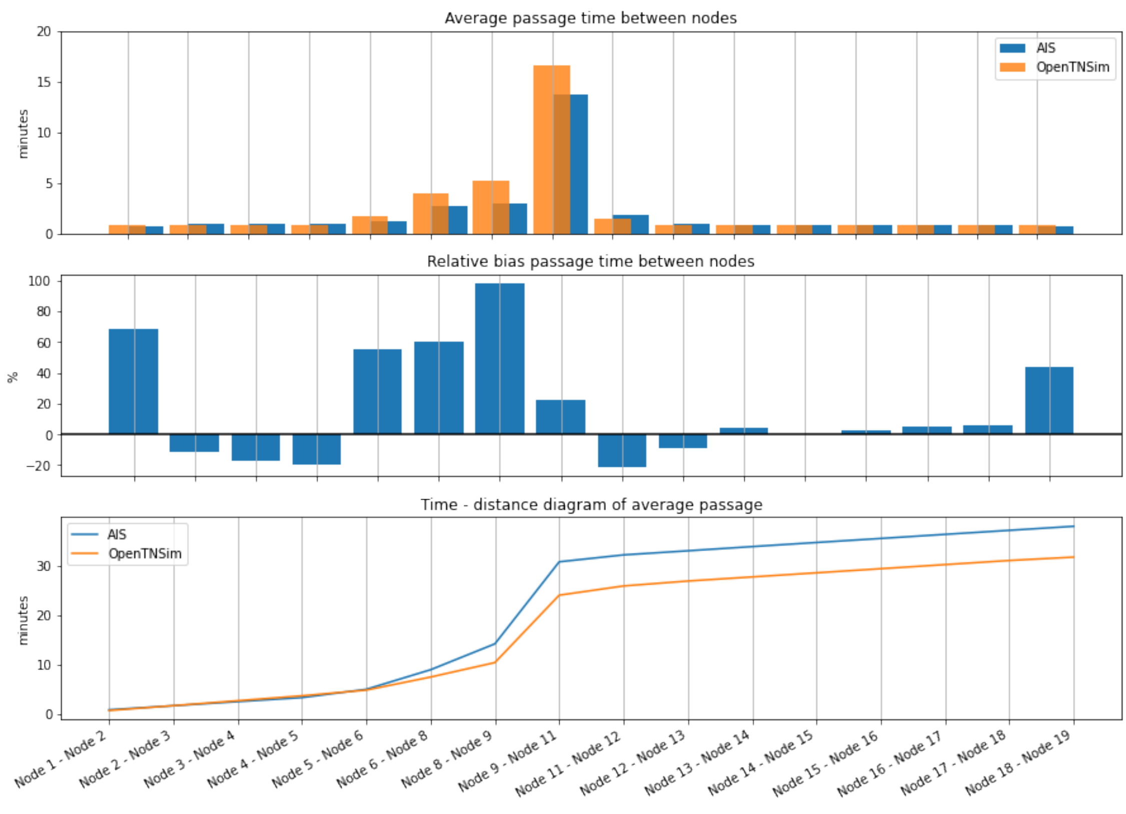

Figure 4.5: Passage time between nodes for OpenTNSim and AIS, 1 vessel per locking

4.2.2. Case B: One vessel, with waiting

A sample size of 89 situations was found or Case B where a single vessel passes the lock but has to wait or the previous locking. The procedure followed with Case A was also followed with Case B. This results in the figures B.1 and 4.6.

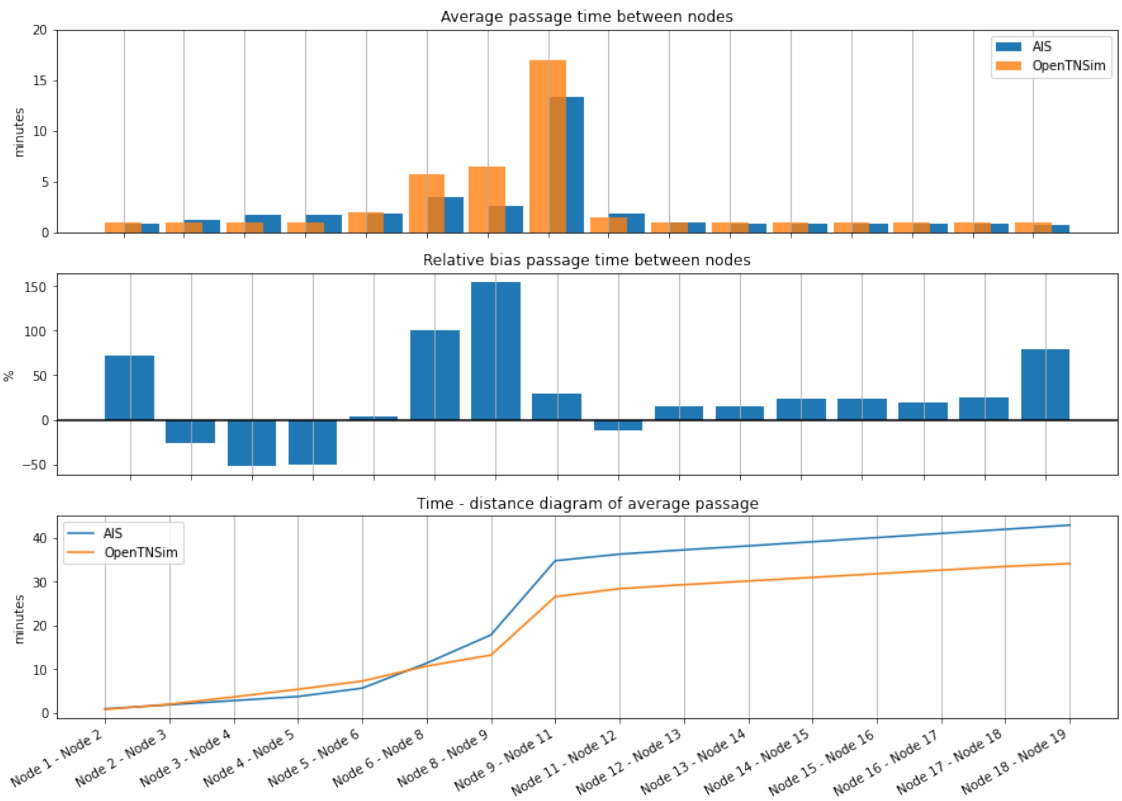

Figure 4.6: Passage time between nodes for OpenTNSim and AIS, 1 vessel per locking with waiting time

4.2.3. Case C: Two vessels, without waiting

The third case considers two vessel in a locking in both directions without waiting times. In total 561 samples were found for this case. The inter arrival times of the samples were used in the simulation. The locking model is designed to wait for the other coming vessels only when this vessel already arrived at the line-up area. The inter arrival time was larger for some samples, which led to the start of the locking with only the first vessel. To prevent this an extra waiting times was induced for the first vessel to compensate the waiting of the lock operator from the sample. Figures B.2, 4.7 and 4.8 give an overview of the base simulation of case C for the leading and the following of the two vessels in the locking.

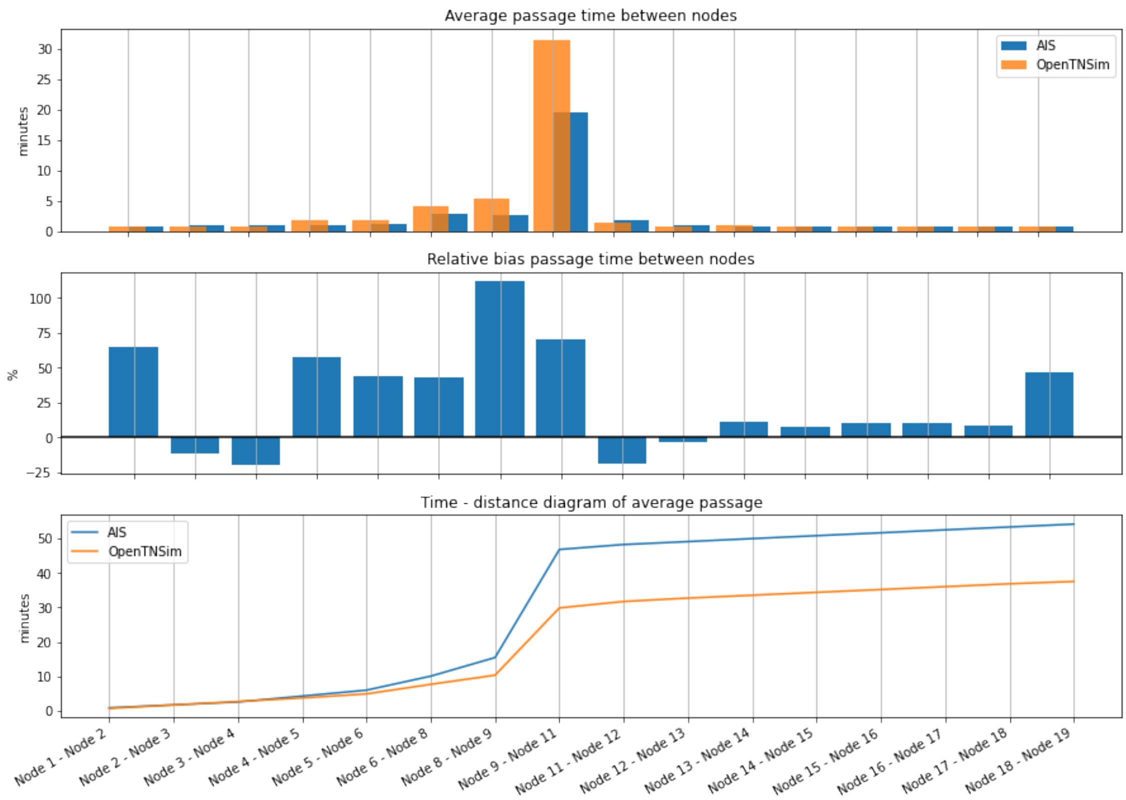

Figure 4.7: Passage time between nodes for OpenTNSim and AIS, second vessel of 2 vessels per locking, leading vessel.

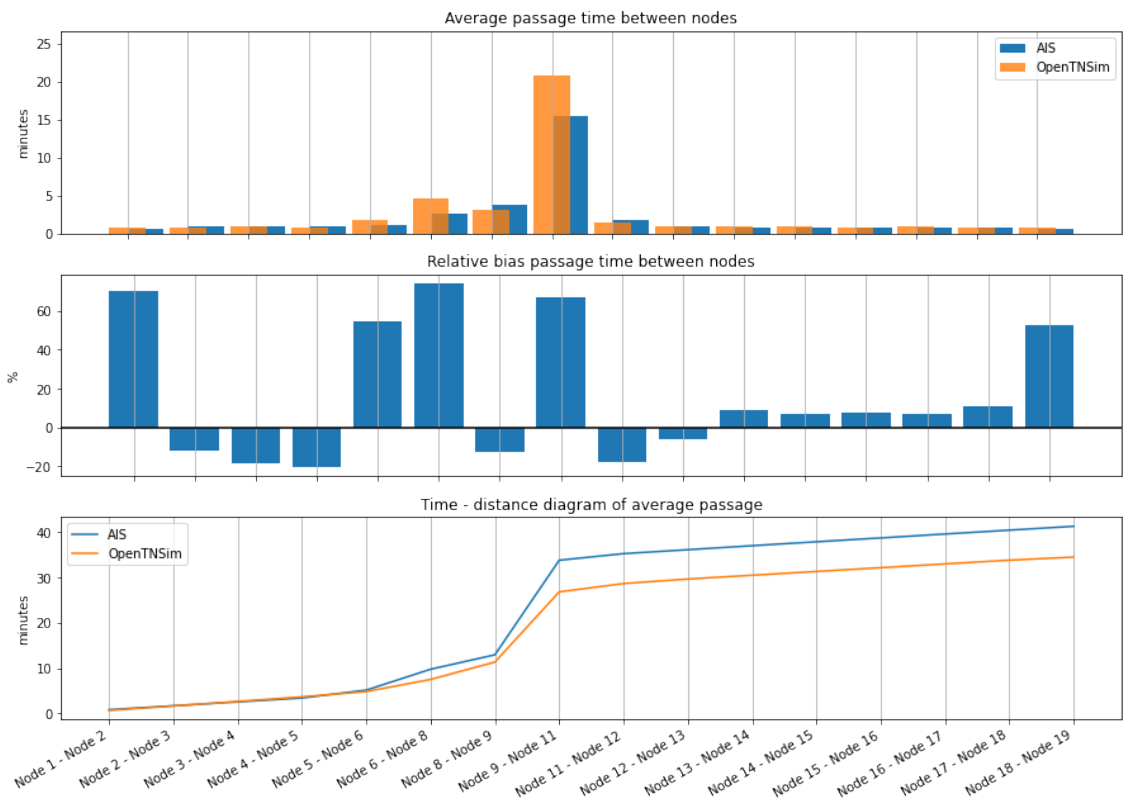

Figure 4.8: Passage time between nodes for OpenTNSim and AIS, second vessel of 2 vessels per locking, following vessel.

4.2.4. Base simulations overview

The biases of all three cases are shown in Table 4.1.

	Case A	Case B	Case C	
			Leading vessel	Following vessel
Node 1 - Node 2	68.2	72.8	65.2	70.6
Node 2 - Node 3	-11.1	-26.9	-11.3	-11.9
Node 3 - Node 4	-17.4	-52.4	-20.2	-18.6
Node 4 - Node 5	-19.4	-51.0	-22.1	-20.6
Node 5 - Node 6	55.2	4.0	43.1	54.5
Node 6 - Node 8	60.4	100.8	58.4	74.3
Node 8 - Node 9	98.1	155.1	23.2	-12.6
Node 9 - Node 11	22.5	29.8	231.8	67.3
Node 11 - Node 12	-21.4	-11.9	-19.2	-18.1
Node 12 - Node 13	-8.9	14.4	-3.0	-5.8
Node 13 - Node 14	4.3	14.6	10.8	8.9
Node 14 - Node 15	0.4	23.4	6.8	6.9
Node 15 - Node 16	2.2	23.1	7.9	7.4
Node 16 - Node 17	4.7	19.9	10.1	7.1
Node 17 - Node 18	5.9	25.6	8.4	10.6
Node 18 - Node 19	43.7	78.7	46.5	53.0

Table 4.1: Relative bias of the base simulation for each case in percentages.

The second measure to quantify the performance of the simulation model is by using the mean error (ME) of the passage times between each node. The values for ME were found with Equation 3.1 and are compared to standard deviation of the observed data. As Section 3.2.2 states, the mean error can be considered small when ME is smaller than halve the standard deviation. Figures 4.9, 4.10 and 4.11 give a visualisation of ME and halve the standard deviation for the base simulations of all three cases, the mean error in these figures are absolute values.

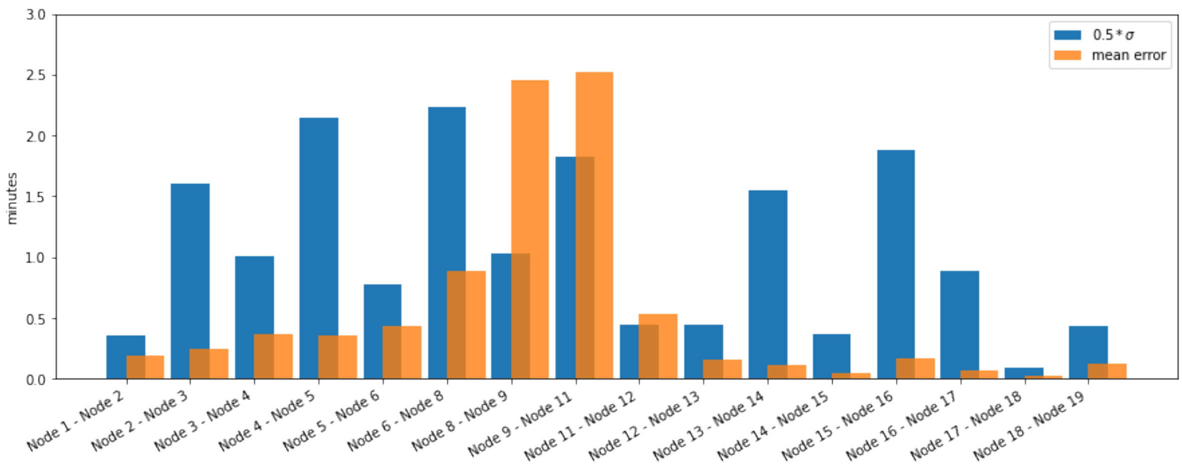

Figure 4.9: Mean error of base simulations for case A: one vessel, without waiting

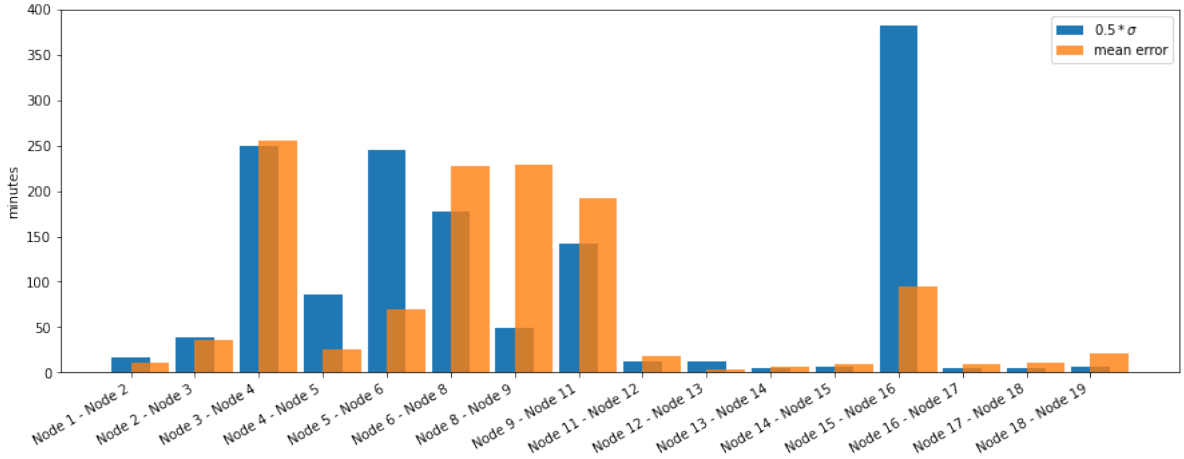

Figure 4.10: Mean error of base simulations for case B: one vessel, with waiting

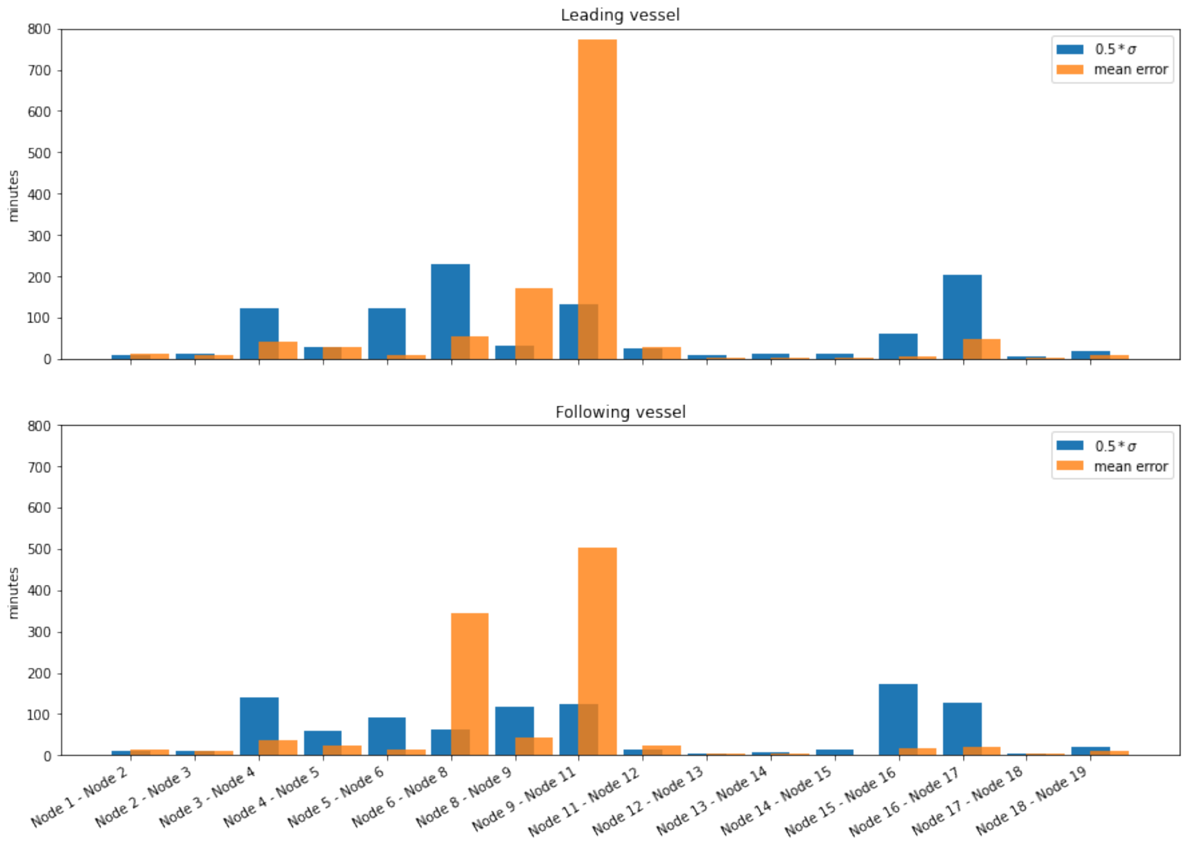

Figure 4.11: Mean error of base simulations for case C: two vessels, without waiting

The mean error of the segments passing the lock chamber (Node 9 - Node 11) and on the approach of the lock. The mean error of the first segments before entering the lock surpass the limit of halve the standard deviation for all three cases. Case A shows a gradual increase of the mean error on the approach of the lock chamber, where the error is more scattered for Case B when waiting is needed. The order of magnitude for the error in the Cases B and C are a factor 100 larger than for Case A.

4.3. Calibration of the simulation model

The results of the base simulations were used to calibrate the OpenTNSim lock module for this case study in the procedure of Section 3.2.2. Adjustments to the model were made on the phases that define the vessels deceleration and acceleration and the operating time of the lock camber. The made adjustments and the passage time of the vessels after the adjustments are described in this section.

4.3.1. Model adjustments

The operating time of the lock chamber depends on Equation 2.2. The parameters of this equation were adjusted within reasonable margins. Iterations with the parameters that define the operating time resulted in the values:

T_1 = 1 minute

A_s = 8 m^2

m = 0.75

The reduction factors that followed from the AIS data of the Volkerak locks are shown in Table 4.2. The factors are found with the observed data; the mean vessel speed when entering the waiting area and the line-up area relative to the speed when entering the lock area. A distinction is made for the leading vessel entering the lock chamber and for all following vessels. The locking module of OpenTNSim recognised whether a vessel is the first vessel entering or a following vessel.

	first speed reduction	**second speed reduction**
leading vessel	0.76	0.40
following vessel	0.78	0.23

Table 4.2: Speed reduction Volkerak locks

The speed reduction factors are applied to a vessels speed when the vessel passes an assigned node. A speed reduction at the second node and the node corresponding to the line-up area (Node 2/18 and Node 7/13 in Figure 3.7) were found to best match the speed profile of the vessels for this case study. Also, the first speed reduction factor is applied to the vessel leaving the lock chamber. The initial speed stands at the opposing line-up area.
These configurations of the simulation model are implemented for all three cases in the case study.

	Parameter	Base	After calibration
Entering time	V_{cr}	Input AIS	Input AIS
	SR_1, SR_2, leading vessel	50% and 25%	76% and 40%
	SR_1, SR_2, following vessel	50% and 25%	78% and 23%
	$SR_{1,node}$, $SR_{2,node}$	Node 5 / 15, Node 7 / 13	Node 2 / 18, Node 7 / 13
	S_l	Node 7 / 13	Node 7 / 13
Operating time	Type of gate	Mitre gate	Mitre gate
	W_{ch}	24 meters	24 meters
	A_{ch}	7920 m2	7920 m2
	H	Between 0.03 and 1.01 meters	Between 0.03 and 1.01 meters
	m	0.8	0.75
	$A_s l$	6 m^2	8 m^2
	T_1	0 min	1 min
	g	9.81 m/s^2	9.81 m/s^2
Exiting time	V_{cr}	Input AIS	Input AIS
	S_l	Node 7 / 13	Node 7 / 13
	SR_{exit}, leading vessel	None	40%
	$SR_{exit,node}$, following vessel	None	23%
	$SR_{exit,node}$	None	Node 7 / 13

Table 4.3: Lock passage parameters calibrated simulations Volkerak with OpenTNSim

4.3.2. Case A: One vessel, without waiting

The passage times of the simulation after validation are shown in Figures 4.12 and 4.13 for the case of 1 vessel per locking in the same format as used in Section 3.3.2. The total passage time after validation has an average value of 35.5 minutes, this equals the average passage time found with AIS data. The time in the chamber, that consists of the operation time and the movement of the vessel in the chamber, shows that the simulation is on average 1.1 minute slower than the AIS data and this difference proceeds to 1.4 minutes for the time in the lock area (lock chamber and the loop distance). The entering and exiting times show that the simulation is 0.4 minutes faster on entering and 0.3 minutes slower on exiting the lock when compared to the AIS data.

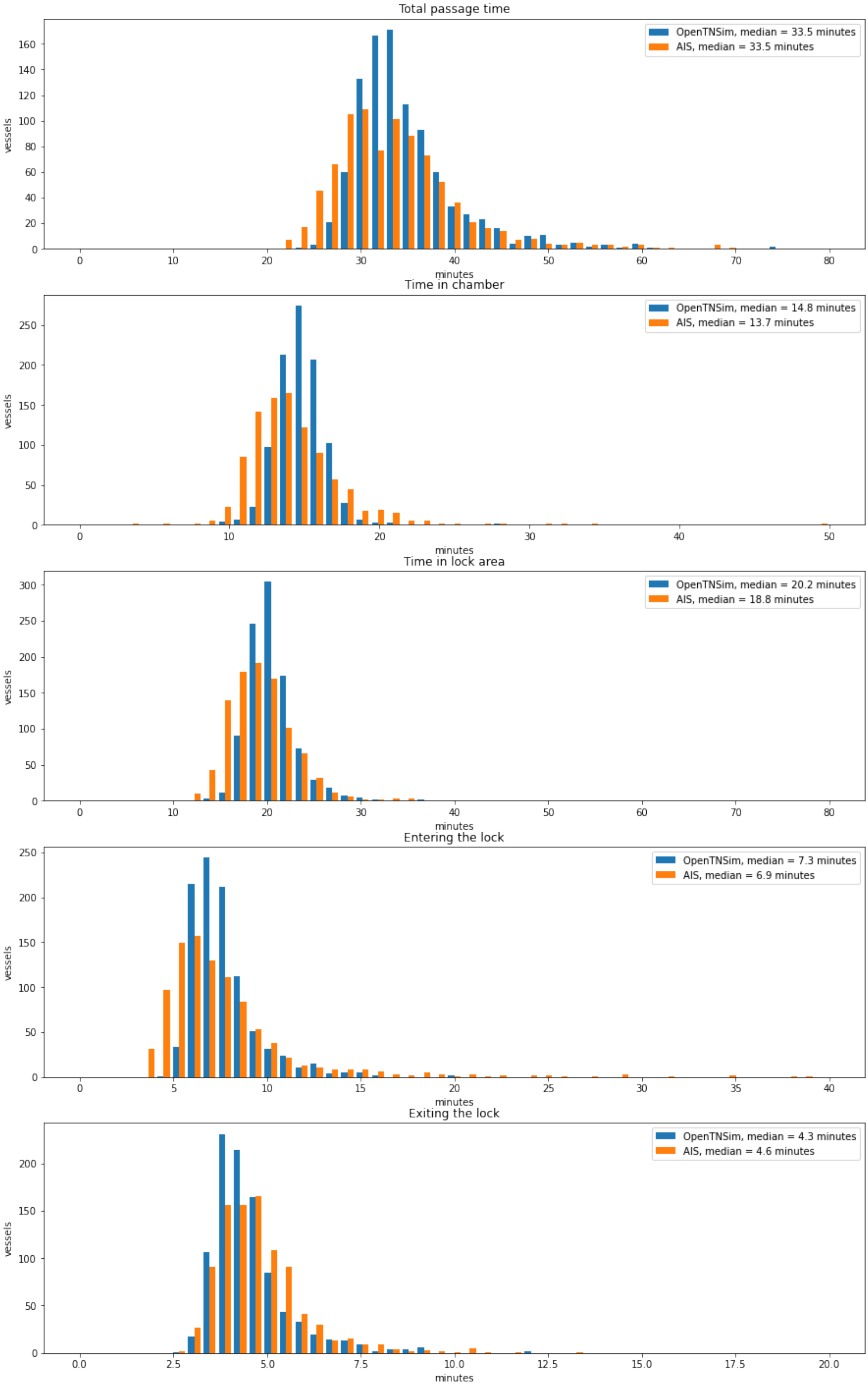

Figure 4.12: Passage time of OpenTNSim simulation and AIS data after validation, 1 vessel per locking

The passage times between nodes (figure 4.13) are close to matching the passage times found with the AIS data. The largest deviations can be found close to the lock chamber, both on the entering and the exiting side of the chamber. The largest absolute difference can be found during the passage of the lock chamber (node 9 - 10) and the section prior to entering the lock chamber (node 8 - 9). The middle plot of Figure 4.13 also show peaks in the relative passage time on the sections node 4 - 5 and node 12 - 13 and the first and last section. On the time - distance diagram visualises that the trajectories are close on the approach of the chamber, deviate slightly while inside the chamber and are close to parallel on exiting the chamber, these results correspondent to the results found in Figure 4.12.

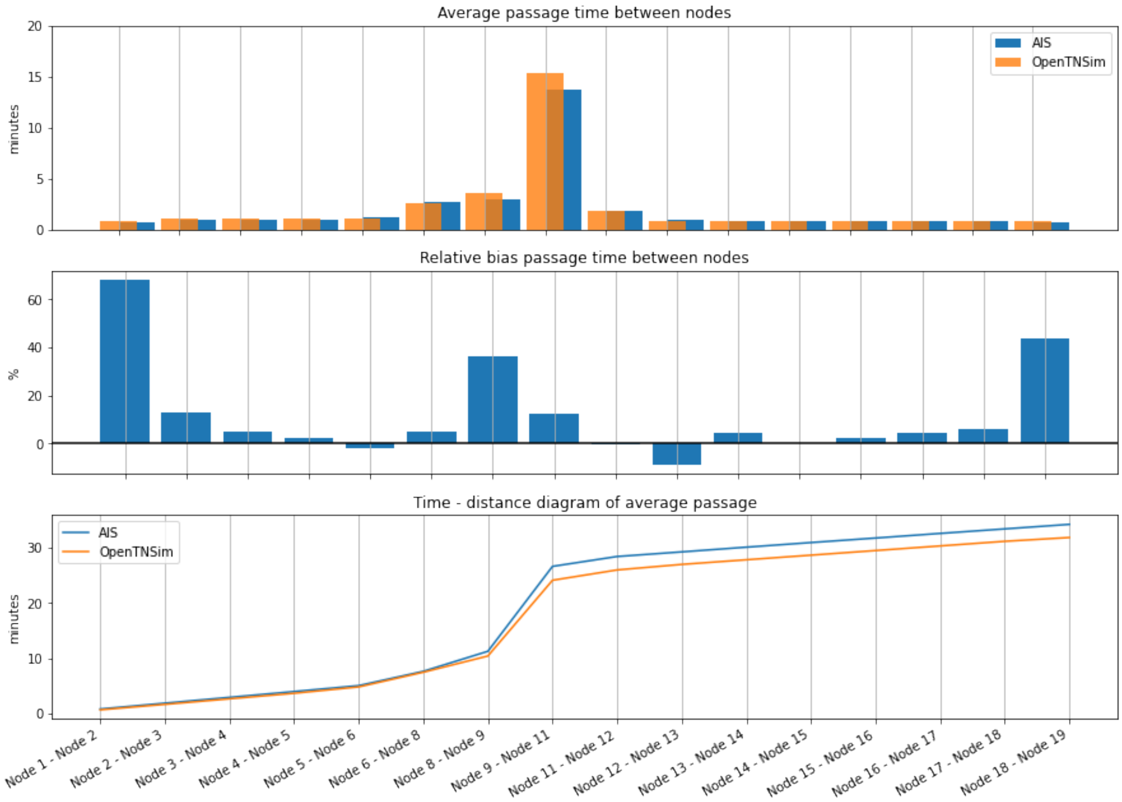

Figure 4.13: Passage time between nodes for OpenTNSim and AIS after validation, 1 vessel per locking

4.3.3. Case B: One vessel, with waiting

An accurate simulation of vessels passing a lock should result in an accurate estimation of the waiting times at the lock. The validated OpenTNSim simulation is run on case B, containing lockings with a single vessel that needs to wait. Histograms of the passage times of phases of the lock can be found in Appendix B.

The passage time of the nodes at the line-up area are much longer with the simulation, where the passage times of the nodes in around the waiting area are shorter than the AIS data.

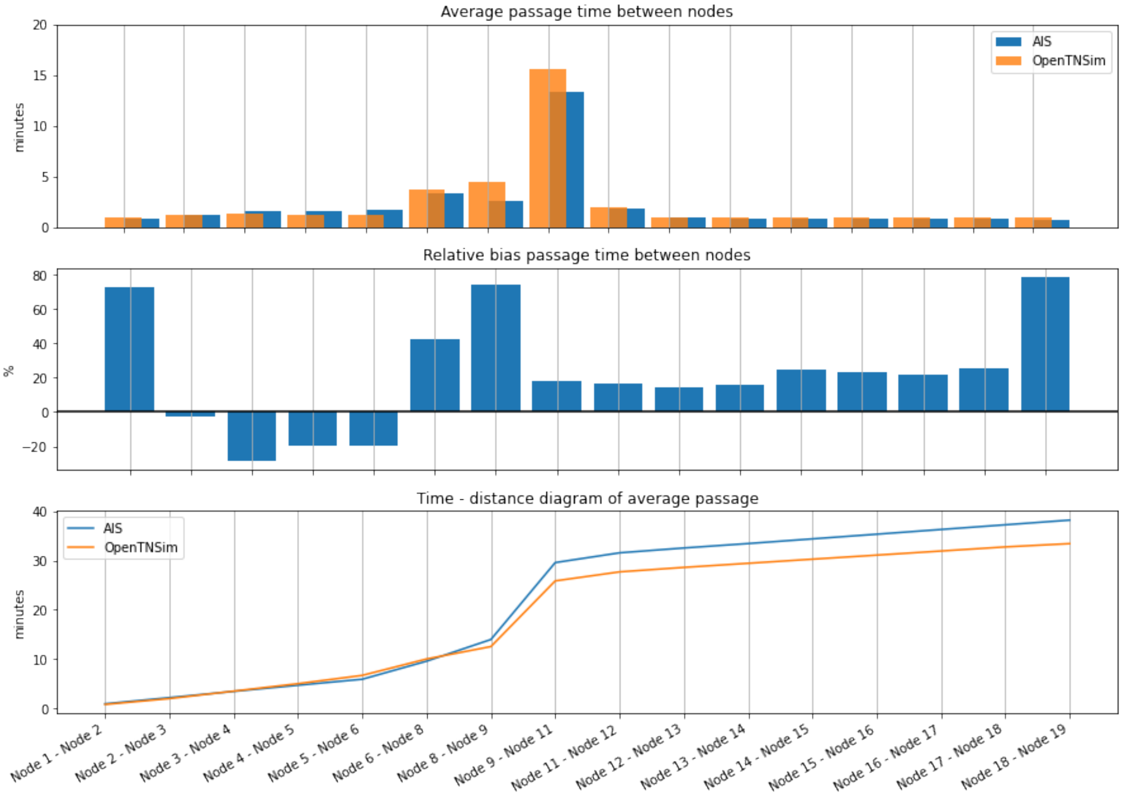

Figure 4.14: Passage time between nodes for OpenTNSim and AIS after validation, 1 vessel per locking with waiting

4.3.4. Case C: Two vessels, without waiting

The Figure B.4 shows the passage times for the same sections as mentioned with Figure 4.4, now for two vessels in a locking. The leading vessel is shown on the left graphs and the following vessel on the right. Both the entering and exiting times give a close approximation to the AIS data, with the following vessel having a longer entering time than the leading vessel. The time in the lock chamber, however, is much longer for the simulation compared to the AIS data. Figures 4.15 and 4.16 show the passage times between nodes for the leading and the following vessel.

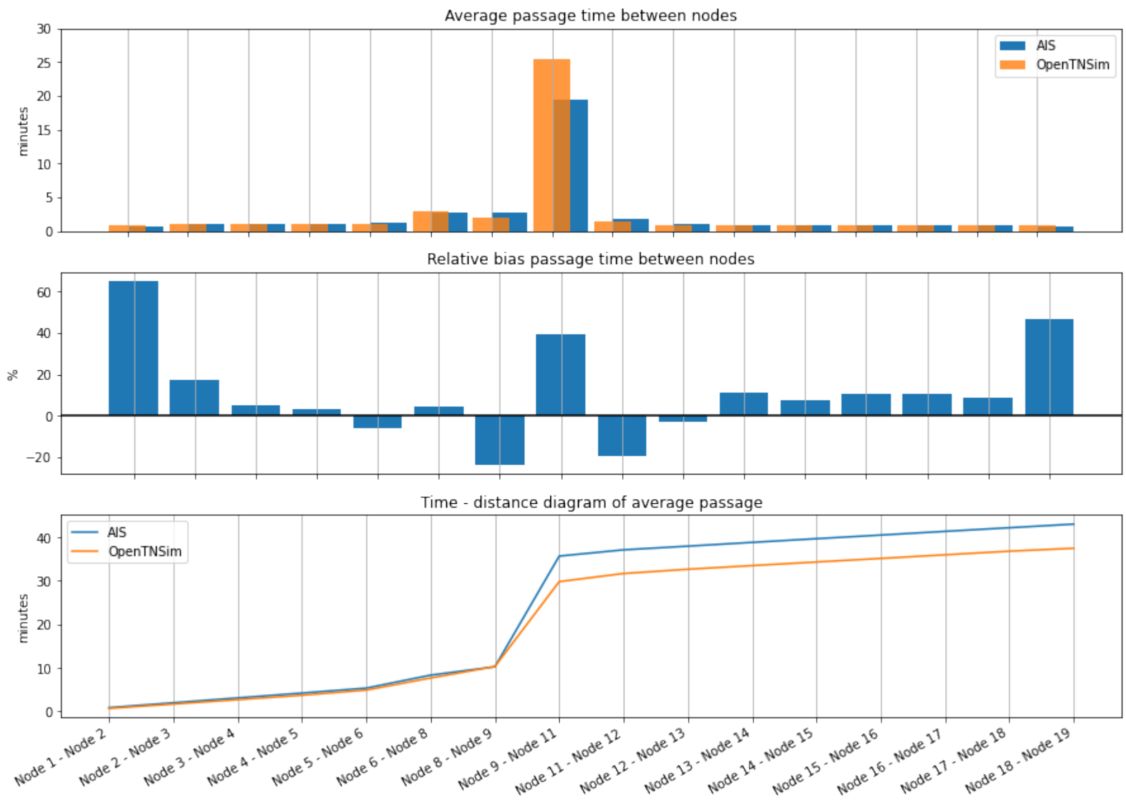

Figure 4.15: Passage time of validated OpenTNSim simulation and AIS data, 2 vessels per locking, leading vessel

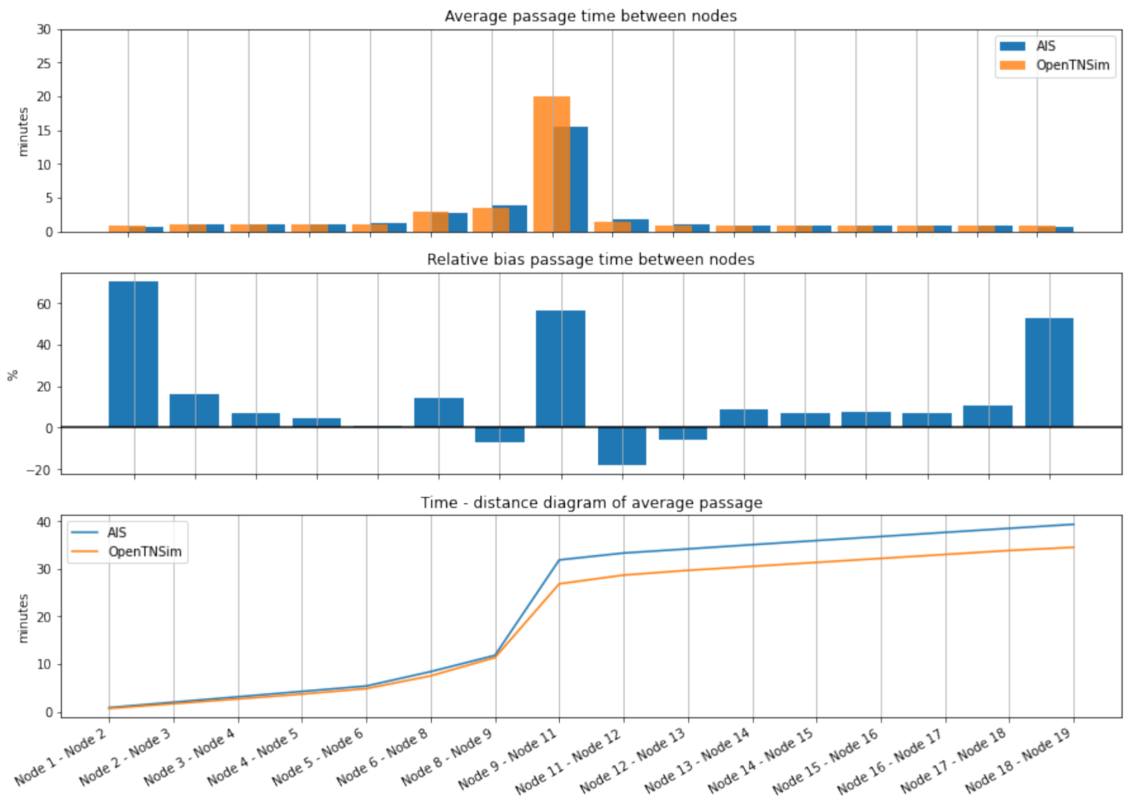

Figure 4.16: Passage time of validated OpenTNSim simulation and AIS data, 2 vessels per locking, following vessel

4.3.5. Overview

The relative biases of the three cases after calibration are combined in Table 4.4.

	Case A	Case B	Case C	
			Leading vessel	Following vessel
Node 1 - Node 2	68.2	72.8	65.2	70.6
Node 2 - Node 3	13.1	-2.9	17.0	16.1
Node 3 - Node 4	5.1	-36.8	5.0	7.0
Node 4 - Node 5	2.5	-35.0	2.5	4.5
Node 5 - Node 6	-1.7	-31.4	-6.3	1.2
Node 6 - Node 8	5.0	34.7	3.9	14.3
Node 8 - Node 9	36.2	74.0	-23.9	-6.8
Node 9 - Node 11	12.5	18.0	220.2	56.7
Node 11 - Node 12	-0.1	16.5	-19.2	-18.1
Node 12 - Node 13	-8.9	14.4	-3.0	-5.8
Node 13 - Node 14	4.3	14.6	10.8	8.9
Node 14 - Node 15	0.4	23.4	6.8	6.9
Node 15 - Node 16	2.2	23.1	7.9	7.4
Node 16 - Node 17	4.7	19.9	10.1	7.1
Node 17 - Node 18	5.9	25.6	8.4	10.6
Node 18 - Node 19	43.7	78.7	46.5	53.0

Table 4.4: Relative bias of the validated simulation for each case.

The mean error of the simulations after calibration was compared to the standard deviation of the observed data in the same way as for the base simulation (Figures 4.9, 4.10 and 4.11). The Figures 4.17, 4.18 and 4.19 show the mean error for all three cases.

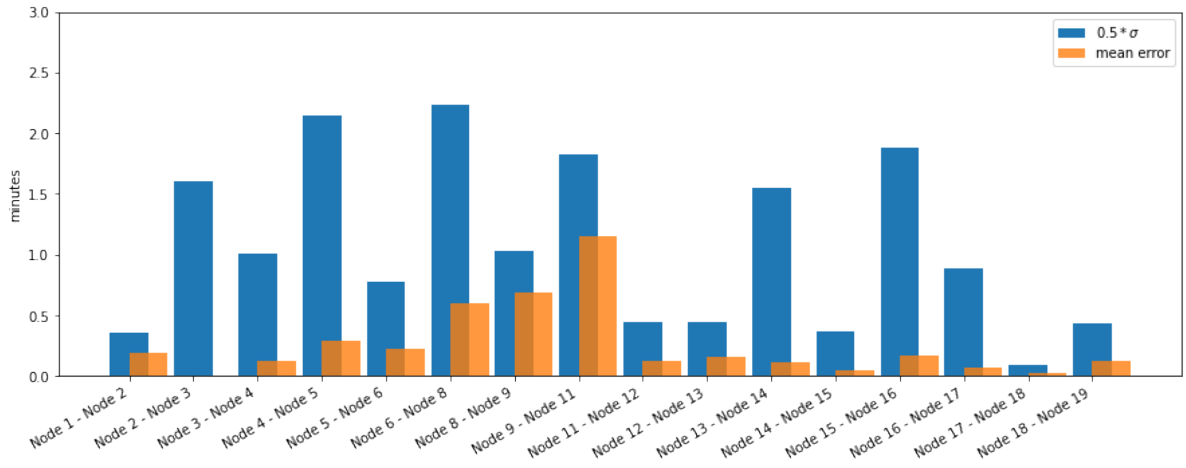

Figure 4.17: Mean error after calibration of simulations for case A: one vessel, without waiting

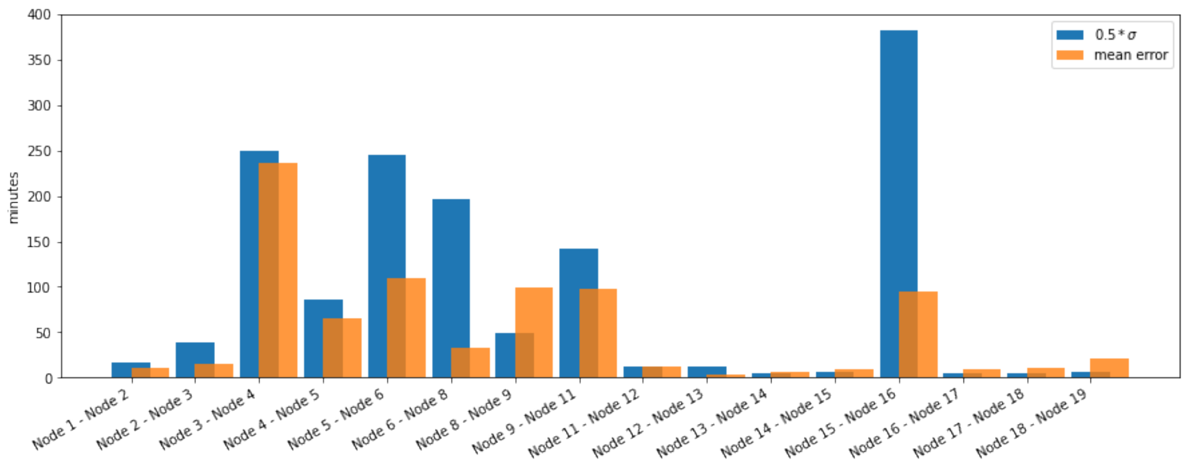

Figure 4.18: Mean error after calibration of simulations for case B: one vessel, with waiting

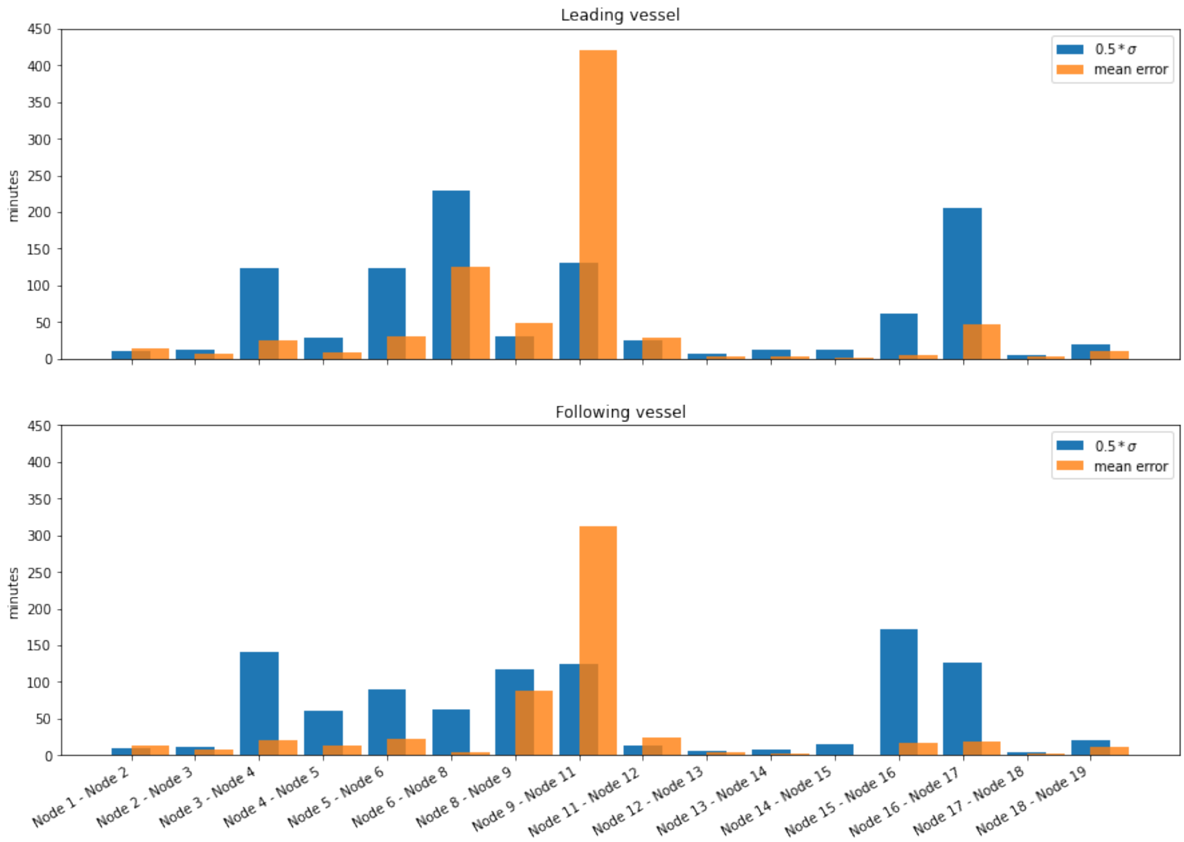

Figure 4.19: Mean error after calibration of simulations for case C: two vessels, without waiting

The mean error on the segment in the lock chamber has reduced when compared to the base simulation for all cases, where the error is lower than half of the standard deviation for Case A and B. Case C shows a large mean error for the segment in the lock chamber for both the leading and the following vessel. For the other segments, all values for the mean error are within half of the standard deviation except for the first segment before entering the lock chamber. The mean error is larger than halve the standard deviation for Case B and the leading vessel of Case C.

5
Discussion

This chapter, the method, materials and results are discussed. Firstly, the method for translating the AIS data to lock information. Followed by the application of this data by comparing it to a simulation model.
The method is applied using a case study on the Volkerak and the Kreekrak locks. Both lock complexes are used to AIS data translation method and the Volkerak locks were simulated with the package OpenTNSim and compared to the generated data.

5.1. AIS data translation

The method of using AIS data to create a data set of vessels passing a lock that can be used for the validation of a simulation model was described in chapter 3. The method resulted in a data set for the vessels passing a lock and the vessels were also combined into a data set of the lockings. AIS data is collected at any moment in The Netherlands and this means the method can create a data set for a desired lock and moment in time. However, the raw AIS data can quickly become a large file when the time span or the covered area increases. In the method, first all the AIS data is loaded and afterwards filtered on the coordinates of the lock area. This can lead to a high computational demand and might require an earlier filtering of the raw AIS data.
The AIS data gives an accurate representation of the vessels trajectory and speed on most of the times, but there are also deviating data points that are filtered and removed in the method. Some of these are incidental outliers of the GPS signal where the remaining data of a vessel is still accurate and there are some vessels that contain so many inaccurate data points that there are is not enough data of the vessel to proceed the method, this vessel in then discarded from the data set. With the case study of Section 3.3 64 vessels were discarded and 24.446 vessels remained.

5.2. Comparison and calibration of a lock simulation model

The calibration of the operation time and the vessel speed was described in Chapter 3 and the visualisation of the simulations (figures 4.12 and 4.13 for Case A) can be compared to the initial simulations (figures 4.4 and 4.5 for Case A). The total passage time after calibration is equal for the OpenTNSim simulation and the AIS data for Case A, this does not mean that all sections of the lock passage equal the AIS data.

5.2.1. Three cases for comparison

The three cases that were used gave boundaries for the calibration process. The large sample sizes for Cases A and C, of 943 and 561 samples respectively, gave a confident representation of the case for the Volkerak locks. Case B had a much smaller sample size of 89 samples of lockings with a single vessel that had to wait to enter the lock. An explanation for this small sample size is that waiting times only occur when the arrival rate at the lock is higher than the capacity of the lock. In a situation of high arrival rate, it is likely that multiple vessels are waiting to pass the lock. The Table 5.1 shows the possible sample sizes for the case study of the Volkerak locks, a case with waiting and with two or three vessels per locking would result in a larger sample size than for one vessel per locking.

Number of vessels in both direction	Without waiting	With waiting
1	969	89
2	561	152
3	304	184
4	111	93
5	23	60
6	6	11
7	0	0

Table 5.1: Possible sample sizes for Volkerak case study with and without waiting.

5.2.2. Vessel speed during passage

The vessel speed defines the passage time between two nodes of the simulation and, with a discrete event simulation, this vessel speed is constant on the transit from one node to the next. Speed reduction factors are assigned to specific nodes to meet the gradual deceleration and acceleration of the vessel during the approach and leaving of a lock. On comparing the passage time between nodes before and after the validation are notable deviations found on the sections closest to the lock chamber and the two outermost sections. An explanation for the outer sections is the absence of data points, the outer nodes are placed on the edge of the filtered areas. This means that the AIS data point closest to the node is always on one side of the node. Resulting in a structurally shorter distance of the first and last segment found with AIS.
The deviations of the passage times close to the lock chamber are also the sections of the largest variations in vessel speed. While the speed reductions are useful to get a close estimation of the entering and exiting times overall, this is not always accurate for the vessel speed close to the lock chamber. When addressing the bias of the segment Node 8 - Node 9, the bias improved for all cases. The mean error for this segment after calibration is lower than half the standard deviation for Case A. For Case B and C the mean error is still too large for the simulation to be considered accurate.

Location of the waiting vessels

With the simulations of case B, one vessel with waiting time, can be seen in Figure 4.14 that the passage times of the nodes prior to the lock chamber do not correspond to the AIS data. Also, the mean error in Figure 4.10 is large on the nodes connected to the waiting area and line-up area. An explanation for this is the location where a vessel is waiting, for OpenTNSim this is the line-up area if there is enough space there. The capacity of the line-up area is the distance to the node in front of the node assigned to the line-up area. The longer passage times of the nodes prior to the line-up area suggest that in reality vessels do not wait at the start point of the line-up area but in the area in front.

5.2.3. Time in the lock

The Figures 4.12, B.3 and B.4 show histograms of the passage time of the lock chamber on the second graph and the passage time of the lock chamber and the loop distances combined on the third graph. The passage time of the lock chamber consists of the operating time of the lock and the movement of the vessel in the chamber, the exact starting point of the operating time cannot be derived from the AIS data. The variables that make up the operating time of the lock, following equation 2.2, are validated to meet the lock passage time found with AIS. This resulted in an average time spent in the chamber of 14.8 minutes with the simulation, compared to 13.7 minutes found with the AIS data, for a single vessel passing the lock. With this configuration of the operating time, the case of two vessels passing the lock, Case C, shows larger differences in the passage time. The Table 5.2 shows the average times spent in the lock chamber for both vessels found with the simulation and with AIS.

	AIS	OpenTNSim
Leading vessel	19.4	25.7
Following vessel	15.5	20.0

Table 5.2: Time in chamber for two vessel passing the lock, in minutes

The large operating times for Case C in OpenTNSim can be explained with the right of entering and exiting the lock chamber in the model. In the model, the following vessel is allowed to pass the line-up area when the leading vessel has passed the chamber doors. On leaving the chamber, the following vessel is allowed to start sailing when the leading vessel passed the line-up area on the opposing side. These rules the model is based on lead to longer entering and exiting intervals than found with the AIS data. This is indicated by the large mean error found for the following vessel on Node 8 in Figure 4.11. The entering and exiting intervals are part of the total entering and exiting times as explained in Figure 2.2. The large intervals result that the leading vessel is waiting longer in the chamber for the levelling to start and the following vessel in waiting in the chamber longer to leave.
There are two ways to improve the accuracy of the model on this. The rule that gives the right for approaching the chamber can be based on the entering interval found in the AIS data, this way the data is used to calibrate the model. Another way is by adding another node between the line-up area and the lock doors. The right of leaving the line-up area can be given when the leading vessel has passed this node.

5.2.4. Limitations of the method

Limitations were found on various stages of this study. There are limitation in the choice of data source, in the method for translating the AIS data and in comparison to the OpenTNSim simulation model.

AIS data

The legal obligation of using AIS for professional vessels in the Netherlands makes AIS a complete data source. The assumption can be made that all professional vessels are included. The obligation stands only for professional vessels and not for recreational shipping. Situations can occur when there are many recreational vessel interfering with the locking cycle. These vessels will not be accounted in the AIS data.
While AIS is used and collected in the Netherlands, it is not a publicly available data source. For this study at the TU Delft, the data was provided by Rijkswaterstaat. The provided data set was also on forehand anonymised, which was another limitation of the data. In Section 5.2.2 was explained that the entering times vary for laden and unladen vessels, this information is not present in the anonymised data.
AIS can only provide data of the vessels in and around a lock, the validation method is therefore only based on vessel data. The data can provide an accurate indication of most of the locking process, but there are some phases that cannot be found using this data. Most uncertainties occur during the lock operation, since the start of the lock operating is based on the vessels laying in the lock chamber. The results show that the method can give an indication of the total operating time, but the operating time consists of opening and closing the gates and the levelling. When these phases of the lock operation are a focus point in a study, this method might be insufficient.

OpenTNSim

Some limitations were found with the calibration of the locking module of OpenTNSim. Firstly, the development of the model was limited during this study. The locking module cannot place vessels in a two-dimensional order in the locking chamber, so the capacity is based on the length of the chamber. It has a maximum capacity of 3 or 4 vessels, dependent on the vessel length, with a lock chamber length of 330 meters. Figure 4.2 shows that there are lockings with 6 vessels in the chamber.
Next, OpenTNSim is a discrete event simulation model. Besides the advantaged of this type of simulation, it can only match the vessel's deceleration and acceleration to a certain point. The speed of the vessel is fixed between two nodes on the network. Multiple nodes on the approach of the lock chamber are used to match the vessel speed.

5.2.5. Use of additional data

The need for additional data when validating the lock module is dependent on the intended use of the OpenTNSim module. When the particular lock is part of a network, containing other locks or other features, then an accurate operating, entering and exiting time might be sufficient. However, when the lock has a more prominent role in the simulation, this method might not be accurate enough. For example when the simulation is used to analyse and improve the operation of a lock. In this case a more precise understanding of the gate opening and closing times can be necessary, which cannot be found using ship data. A source of additional data can be the Object Data Services (ODS), this is a standardised data set of the operation of objects like bridges, tunnels and locks (TriOpSys, 2022). The ODS data logs all operations of the lock, such as gate times, and can also provide data of a bridge or other structures that might interact with the lock.

In the case of seagoing locks, or locks connecting to a large volume of water, the wave conditions can have an influence on the arrival and exiting of a ship. The Section 2.2.2 already shows the combination of AIS data with hydrological and meteorological data by Zhou et al. (2020). This can be useful for the approach of a seagoing lock.

6 Conclusions and recommendations

This report leads to the answer to the research question:
How can the calibration of simulation models for locks be improved using AIS data?

6.1. Conclusion

To decrease the dependency on historical data for the validation of lock simulation models, a method is developed that creates relevant information of a lock from Automatic Identification Systems (AIS) data. The use of AIS is mandatory for all professional inland shipping and is therefore available on the waterway network in The Netherlands. Rijkswaterstaat collects this data and an anonymised set is used and translated to relevant lock data. In this study a time period of three months is used for the validation of the OpenTNSim simulation model, but other time periods can also be used. The availability of AIS data at any time gives an opportunity to validate a simulation model with data of a long time span or with data of different situations. Some of these situation can be high or low water levels or during periods of construction or maintenance in the waterway. The use of AIS data can result in a more extensive validation of locks and for varying situations.
The translation of the AIS data, that is vessel specific data, to data that is relevant to a lock uses the timestamps and the location of each data point of a vessel. The trajectory of a vessel tells the lock and lock chamber it passes and whether the vessel is moving or not. By combining each vessel's trajectory at the same point in time, the locking cycles can be defined. The method is used at a case study of the Volkerak locks for a period of three months, during which 24.446 vessels passed the locks. A filtering of the data points is needed to find outliers of the coordinates. However, for most vessels these are incidental outliers. With the considered case study 0.26% of the vessels is discarded for the inaccurate AIS data.
Using the data derived from the case study at the Volkerak locks, a calibration is done of the discrete event simulation OpenTNSim. After the calibration, the average total passage time of the simulation matched the passage time found with the AIS data. This is reached by adjusting the operating time of the lock in the simulation to the time the vessels are in the lock chamber based on the data and by adjusting the vessel speed between nodes of the simulation network to the vessel speed found with the data. The simulation can match the vessel movement for a large section of the entering and exiting the lock, the vessel movement close to and in the lock chamber are more difficult to match in a discrete event simulation. The overall entering and exiting times however can accurately be validated using this method, both the entering and exiting times had a deviation within 0.4 minutes relative to the AIS data when a single vessel passes the lock. Differences in the operating time were found with the simulation of two vessels passing the lock. Further development of the lock module of OpenTNSim can reduce these time differences. In the case when waiting was required, the location of the vessel while waiting showed differences. The simulation model has an assigned node for waiting, while the AIS data showed that the location of waiting was more spread out. This resulted in differences in the passage times of segments in front of the lock chamber. However, the total entering time was accurate.
To answer the research question, the results of a lock simulation can be compared to data retrieved

from AIS. This comparison indicate the phases of a locking cycle with a large deviation to the data. The simulation model can be calibrated for a specific lock or period, knowing the phases that show the largest deviations to the data.

6.2. Recommendations

There are recommendations to be made for the development of the method and for an extension of the application of the method. Some recommendations follow from limitations of the method and the materials. Others are suggestions on applications of the method that were not considered in this study.

6.2.1. Method development

First of all, the method could be further generalised. In an ideal situation with a direct link to an AIS database. To create a tool that can deliver a data set of a given lock at a given time to anyone that wants to use the data and does not know the working process of the method. In the current state, manual adjustments of the data and the process are still necessary.
The method does have a high computational demand, especially for large time period, that could be improved in a simple way by using a powerful computer or by optimising the code.
The OpenTNSim simulation uses a one dimensional lock chamber, so all vessels are in line in the chamber. When this method is used for the validation of a simulation with a two dimensional lock chamber, the location of the vessels in the lock derived from AIS data can be used to validate the vessel arrangement of the simulation.

6.2.2. Further research

A limitation in this study was the anonymised AIS data. Information on the deadweight tonnage of the vessel, if the vessel is laden or unladen or the type of vessel can benefit the method. The data is compared to the simulation model without these distinctions. While SIVAK, for example, does make a distinction for vessel type and laden or unladen vessels when determining the entering and exiting times of the vessel.
The method of obtaining lock relevant data is in this study used as for the calibration of a lock simulation, this is not necessarily the only application. The method can be used to obtain data for statistical analyses of a lock or a lock system, possibly for locks with historical data that is outdated or limited in size.
This study had a focus on the lock passage times, but the method can also be used to obtain information about arrival rates and arrival velocities. For the simulation model is the arrival speed of the vessel at the first node of the network considered as the initial vessel speed, a useful additional research would be to find the distance on which a lock influences the speed of a vessel. Not only is the method limited to locks. The method can be applied to find waiting times for bridges, possibly in combination with road traffic data. Another example can be to find bottlenecks in a port system.

A

AIS data example

This table gives a view of the AIS database used for the case study on the Volkerak and Kreekrak locks. The table shows 5 data points of different vessels. The vessels in the data set are anonymised for the sake of privacy, this is visible in the shipname and the various identification numbers such as *callsign, eni, imo* and *mmsi*. The dimensions of the vessel (*width, length, draught*) and the location of the AIS transponder on the vessel (*tobow, toport, tostern, tostarboard*) are specified by the vessels captain. This means that uncertainties can occur for these values, for example the *NaN* values in the third column or a value for *draughtInland* of 13 meters.

newtimestamp	2019-08-02 03:19:34	2019-08-01 16:52:49	2019-10-23 17:55:48	2019-10-23 00:31:16	2019-09-21 05:50:53
oldindex	0	0	0	0	0
sog	6.4	0.0	10.2	0.0	6.8
headingValid	511	511	511	511	511
callsign	PH34000	PH70800	PH15000	PH25710	PH74000
vesseltype	89	80	89	79	79
rot	0.0	0.0	0.0	0.0	0.0
hazardous cargo	1	5	5	5	5
eni	2034000	2070800	2015000	2025710	2074000
imo	3400000	7080000	1500000	2571000	7400000
latitude	51.696846	51.691235	51.697220	51.682674	51.692936
maneuver	0	0	0	0	0
seconds	35	49	49	16	53
mmsi	340000000	708000000	150000000	257100000	740000000
nationality	Duitsland (Bondsrepubliek)	Nederland (Koninkrijk der Nederlanden)	Nederland (Koninkrijk der Nederlanden)	Belgie	Nederland (Koninkrijk der Nederlanden)
shipname	testschip-340	testschip-708	testschip-1500	testschip-2571	testschip-7400
vesseltypeERI	8020	8310	8020	8010	8010
longitude	4.422218	4.410875	4.424017	4.396727	4.415652
eta	–12-13T23:55	–12-30T12:44	–08-29T17:05	–00-00T00:00	–12-31T11:00
cog	47.000000	266.600006	53.299999	0.000000	49.000000
heading	0	0	0	0	0
tobow	98.0	120.0	NaN	93.0	5.0
width	12.0	13.0	NaN	9.0	11.0
toport	8.0	7.0	NaN	6.0	6.0
tostern	12.0	15.0	NaN	12.0	105.0
length	110.0	135.0	NaN	105.0	110.0
tostarboard	4.0	6.0	NaN	3.0	5.0
draughtMarine	2.0	1.8	4.2	1.4	1.0
draughtInland	2.0	1.8	4.3	13.0	1.0
geometry	POINT (51.69685 4.42222)	POINT (51.69123 4.41087)	POINT (51.69722 4.42402)	POINT (51.68267 4.39673)	POINT (51.69294 4.41565)

Table A.1: Example of AIS input data

B

Passage times case study

This appendix shows histograms of passage times for the Volkerak case study.

B.1. Base simulation

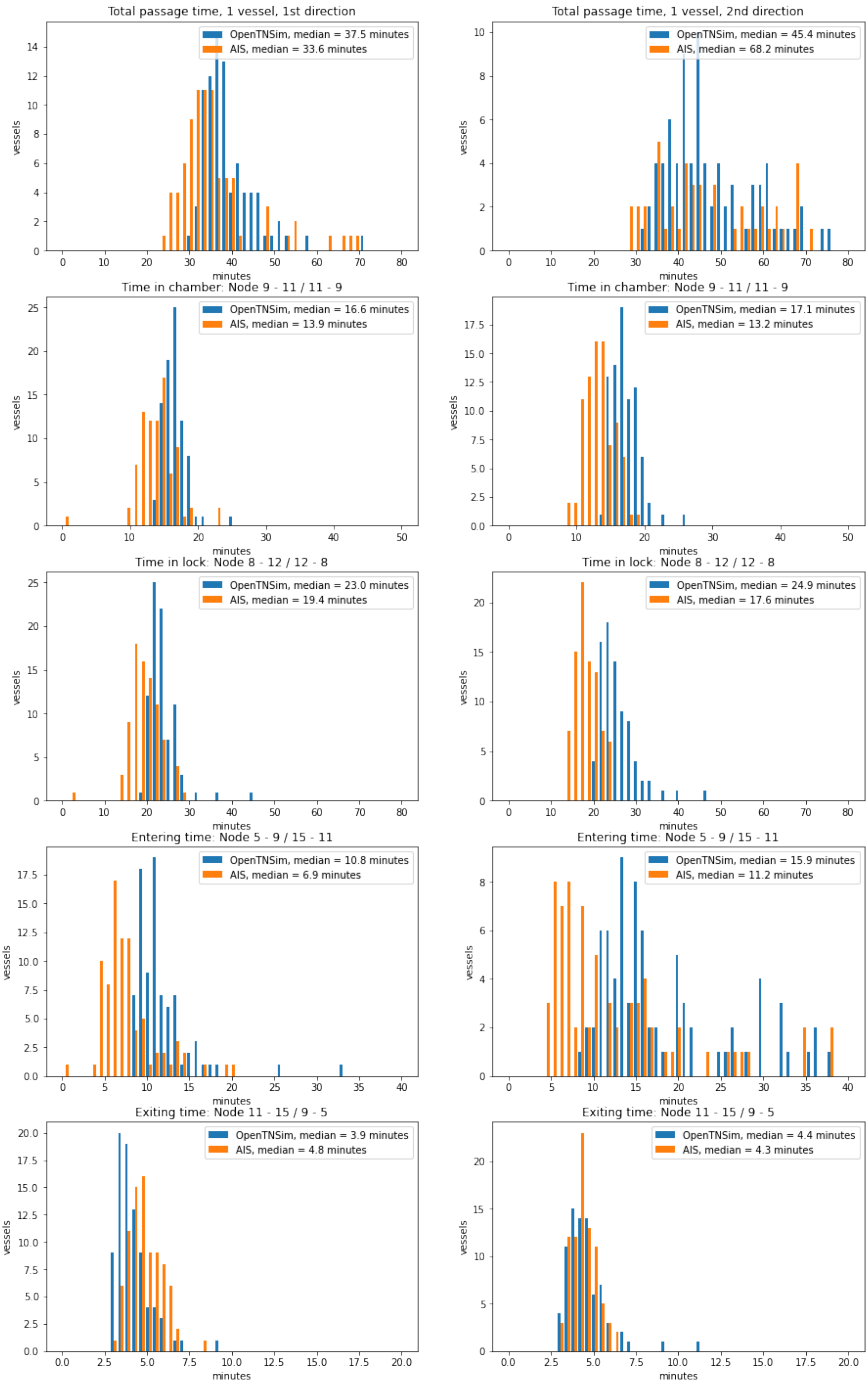

Figure B.1: Passage time of OpenTNSim simulation and AIS data, Case B: 1 vessel per locking with waiting time

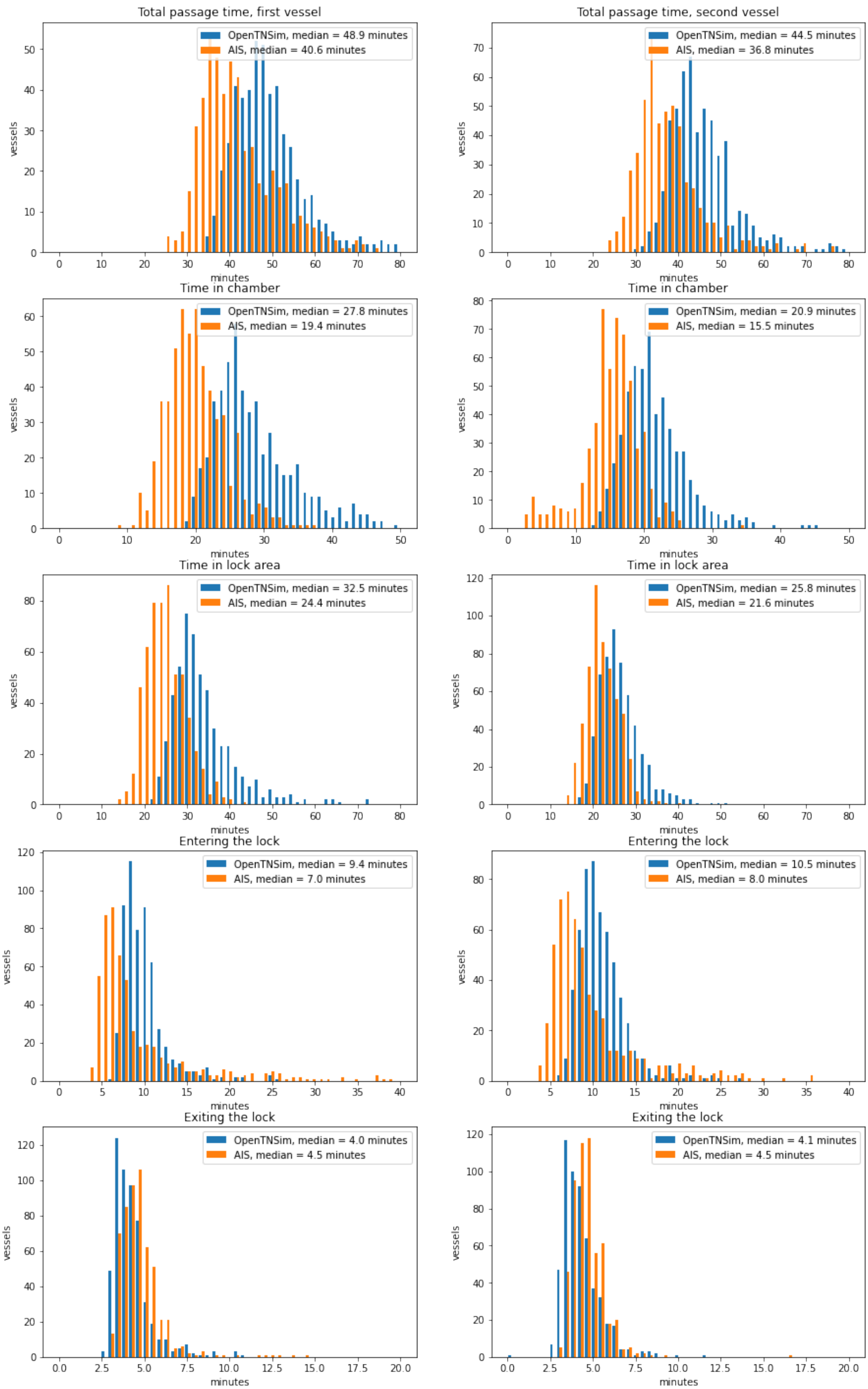

Figure B.2: Passage time of OpenTNSim simulation and AIS data, Case C: 2 vessels per locking

B.2. After calibration

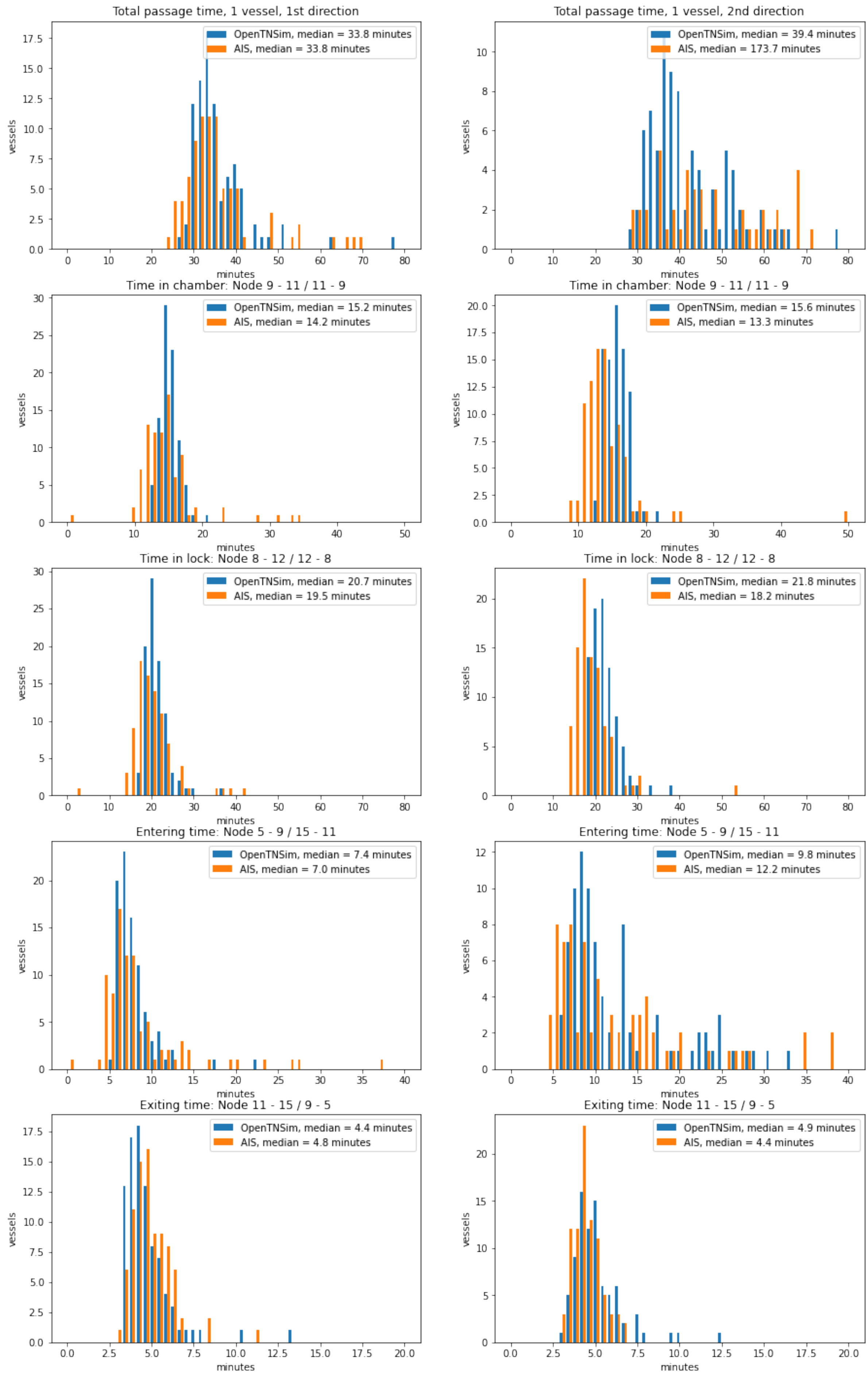

Figure B.3: Passage time between nodes for OpenTNSim and AIS after validation, Case B: 1 vessel per locking with waiting

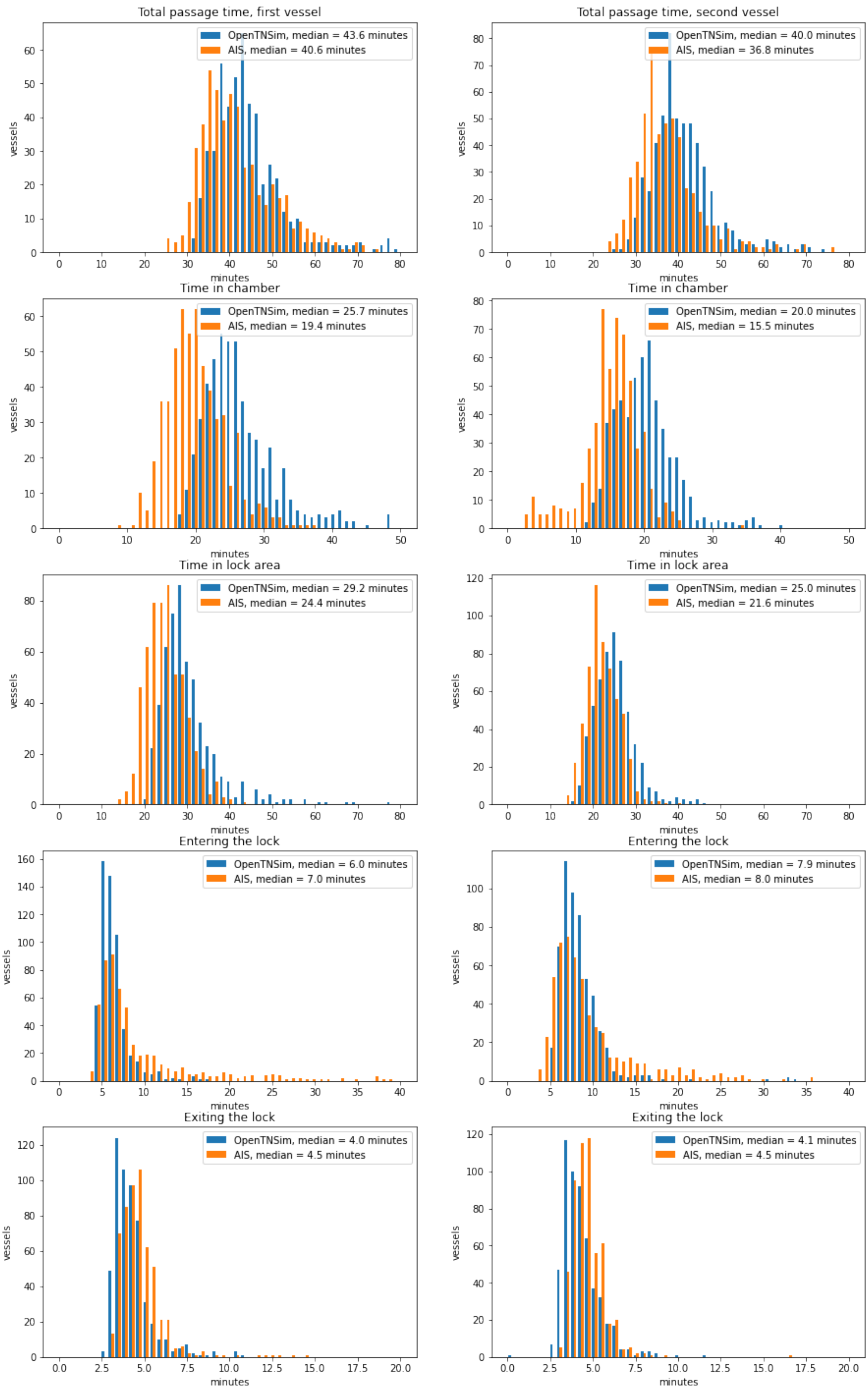

Figure B.4: Passage time of OpenTNSim simulation and AIS data, Case C: 2 vessels per locking

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