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Measures to Reduce Emissions from Ships

A case study: An early evaluation of the potentials of digitalization and changed framework for port calls in the Port of Gävle.

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Summary

Many ports today want to improve the information flow in the logistics chain to be able to make port calls more efficient and thereby reduce the waiting times for ships, terminals and other operators in the logistics chain. The Port of Gävle is part of two ongoing projects, where digital tools to improve communication between the port and other actors in the logistic chain are being tested and evaluated. One of the projects also includes an improvement of the current regulatory and structural framework in the port. The new digital solutions in combination with a new framework also open the possibility for ports to improve planning and communication of time slots at quay for arriving ships. With less time spent in port and guaranteed time slots at arrival, the ships no longer must compete to get to the port first and can sail in reduced speed at sea. When the ships have shorter waiting times and slows down the fuel consumption also decreases. This study includes calculations of the emission reductions these possible reductions in fuel consumption would imply.

The example calculations made in this study show that the potential to reduce emissions at sea is great even at minor speed reductions. For example, the annual greenhouse gas emissions for all incoming vessels would decrease by 8 300 tonnes of CO_2-e if the ships would lower their speed at sea from last port by only 5%. This can be compared to effects from a shorter time at berth that not only can reduce emissions from ships quayside but also from ships at anchor, due to shorter waiting times. The potential reduction with 7% shorter times at berth is between 600 and 900 tonnes of CO_2-e/year and the reduction at anchor is estimated to be between 825 and 3 860 tonnes of CO_2-e/year. However, these calculations are theoretical and in order to calculate the actual reductions one needs to evaluate real time efficiency improvements of the measures applied.

To be able to calculate emission reductions, this study has developed improved methodology for emission calculations and calculations of times at anchor and sea, and quantified the uncertainties. The times at anchor have been extracted using Automatic Information System (AIS) data for the area around the port. These data show that 124 vessels that entered the port in 2017 anchored before they entered the port. The method used to quantify the uncertainties for emissions reductions at quay and anchor is to vary the assumed auxiliary power demand used by the ships while hoteling. The new assumptions are based on questionnaires and a literature study made in this project. The uncertainties at sea have been quantified by varying the assumed speed at sea and comparing these results with the emissions that some of the ships report to the EU in the Monitoring Reporting and Verification system. These results indicate that many container ships already slow steam and that the emission reduction potential calculated in this study probably is overestimated for these ships.

1 Introduction

Ports are facing several challenges with an increasing demand for better services and goods handling capacity. At the same time, they need to reduce the environmental burden associated with the port activities, such as air pollution and greenhouse gas emissions. Many ports are therefore trying to find solutions for improving their environmental performance, for example with installation of grid connections for visiting ships or environmentally differentiated port fees (Styhre, et al., 2019; Parsmo, et al., 2017). One other measure that several ports are adopting is to improve the information flow process with help of digitalization. It is hoped that improvements of the information flows will result in shorter times at berth. The Port of Gävle has started to implement such improvements. It is also hoped that the improvements in the information flow in combination with an updated framework for port operation will have more far reaching effects and reduce emissions also from ships at sea due to slow steaming , as a direct consequence of less fuel consumption (Johnson & Styhre, 2015). However, the emission models are not adapted to calculating emissions during idling condition or analyzing the environmental consequences of such improvements, so the emission model used in the port inventory therefore needs to be updated.

1.1 Emission inventory model

In recent years, IVL Swedish Environmental Research Institute has developed an emission calculation model for ships in ports. With this model it is possible to calculate emissions of carbon dioxide, nitrogen oxides, particles and sulfur dioxide, as well as fuel consumption for ships during port visits. It can also be used to do scenario analyzes for different policy measures. The model has been developed and used in several research projects, including analyzes of ship emissions in Sydney Ports, Port of Gothenburg, Port of Osaka, Port of Long Beach (Styhre, et al., 2017; Winnes, et al., 2015) and Halland harbors (Styhre & Winnes, 2016). There is also an interest in these types of analyzes from individual ports, and IVL has made emission inventories on assignment of the Port of Gothenburg, the Port of Stockholm, the Port of Gävle and Faxaflóahafnir (Iceland). Reducing uncertainties in important input parameters is important for accurate analyses of measures, such as for example the emission reduction potential of a more digital information flow.

1.2 Digitalization of information flows in the Port of Gävle

A main part of all communication between port- and ship actors is handled manually, mainly by phone calls, emails and radio communication. This type of communication implies inefficiencies, such as long waiting times. Also, since information is not shared between all actors at once, the same information needs to be shared several times. Instant sharing of information with all involved parties would enhance both communication efficiency and accuracy.

The Port of Gävle participates in an EU financed project called *EfficentFlow*. The general goal with the *EfficentFlow* project is to share information more efficiently. The information sharing occurs in the whole logistics chain, from route planning to port-hinterland logistics. With new communication tools, the aim of the project is to share the same information between port actors in real time. The project scope includes the implementation and evaluation of a new app called *Port Activity App*. In *Port Activity App*, port and ship actors can share information such as for example estimated time of arrival, berth slot times and cargo operation requests in real time (STM, 2017).

The *EfficientFlow* project only covers digital sharing of information between port actors. However, in order to allow for guaranteed slot times, the port also needs to update port regulations and improve interaction between port, terminals, goods and ownership. The *EfficeintFlow* project has therefore become a springboard for a new project called "*Development of port framework enabling energy efficient sea transport between ports*", which in this study is called the *Framework* project.

The *Framework* project is an implementation project that will entail regulatory and structural changes in the port so that it is synchronized with a recently launched international transport agreements for vessels (Sea Traffic Management, 2018; Port of Gävle, 2019; Bimco, 2018). Port actors and stakeholders, a good´s owner and a shipping company participate in the project. The *Framework* project will also include further development of the *Port Activity App*. It is important to note that container ships are already on schedule, and thereby have a guaranteed time slot at berth in general. However, the system and processes that shall guarantee container ships a time slot is not working optimally since other port actors and services are not included in that system, for example port authority, pilots and tugs.

One long-term goal of the projects is to accomplish fuel savings on ships and thereby improve environmental performance per transport work (tonne-kilometre). The fuel saving is expected to occur in three phases:

1. <u>At berth:</u> Reduced idling with shorter berthing times, since port operation will be more optimized, e.g. right equipment and personnel at the right place and time. One of the initial objectives of the Efficient flow project was that: "the project is expected to produce a time saving of 7%" (Ahlfors, 2018).

- <u>At sea</u>: The ships will use reduced speeds at sea, as ships will have the possibility to adopt their speeds to a known accessibility at quay i.e. slot-time. The principle in ports today is that the ship that arrives first is also served first. This implies that ships go faster than they need to, so they are not risking losing an available quay. In the new system, each ship can apply for a queue ticket to have a guaranteed berth slot time at the port if they arrive on agreed recommended time of arrival (RTA). By implementing the new queue system in the port, ships may adjust the speed in order to arrive on the RTA. BIMCO launched a new clause that may be added in a charter party contract (Bimco, 2018). The purpose of the clause is that the charterers shall be entitled to request the shipowner to adjust the ship's speed to meet an arrival time. The new BIMCO clause together with the new queue system in the port open-up the possibility for Just-In-Time port call. When the ships slow down their fuel consumption drop, since the drag (fluid resistance) decrease quadratically at slower speeds (Doudnikoff & Lacoste, 2014). This concept is generally referred to as slow steaming (Corbett, et al., 2009; Faber, et al., 2012; Meyer, et al., 2012), see section 1.3.

2. At anchor: Due to more efficient port operations, guaranteed slot time and improved flexibility, anchoring/waiting times are expected to decrease.

The real effects of the introduction of the digital information flows and the following efficiency improvement have not yet been evaluated. This study will therefore only investigate emissions reduction potential for some selected scenarios, which are further described in chapter 2. The method development used in this study can be used as an evaluation tool upon implementation of the measures developed in the *Efficientflow* project, the *Framework* project and the *Port Activity App*.

1.3 Slow steaming

The time saved from more efficient port activities may e.g. be used by ships to slow down speed during voyages. However, this is not necessarily the case; studies suggest that ships' speeds are very much related to the economic situation and that in good times, saved times in ports are rather used to perform more transport work (Lindstad & Eskeland, 2015). Nevertheless, the guaranteed time slot at berth will at least create the opportunity for ships to slow steam.

The environmental effect of slow steaming has been assessed in several studies (Corbett, et al., 2009; Faber, et al., 2012; Meyer, et al., 2012; Doudnikoff & Lacoste, 2014; Lindstad & Eskeland, 2015; Parsmo, et al., 2017). When a ship slows down, the fuel consumption is often significantly reduced due to the lesser need for propulsion power. However, the need for auxiliary power increases since the ship spend more time at sea for the same voyage. Also, if all ships would use slow steaming, the global fleet would need to be bigger in order to uphold the same amount of transport work (tonne km), which would imply an increase in upstream emissions associated with the transport, since more ships would be required. Such effects are not included in this study.

One important parameter in calculating the energy need for propulsion is the engine load factor. This tells how much of installed power that a ship needs during specific conditions. The propulsion engine load factor can be derived from information on actual speed and ship maximum speed, a value that can be found in ship databases. The actual speed of the ships can e.g. be derived from AIS data. AIS data includes signals on speed, direction, etc., and are transmitted with high frequency from all ships over 300 GT, globally. The power requirements for propulsion can thus be estimated using the following model (Port of Los Angles, 2014):

$$Propulsion\ engine\ load\ factor = \left(\frac{v_{actual}}{v_{max}}\right)^3 \quad (1.1)$$

Where v_{actual} is the ship´s real speed, and v_{max} is the ship´s speed when the engine is operating at maximum continuous rating (MCR), during average conditions. The relation is a highly simplified representation of reality and for example the actual speed may sometimes be higher than the speed in the denominator in equation 2.1, since e.g. winds and waves also influence the speed. The propulsion engine load factor when the ship is sailing at design speed are generally considered to be about 80% (i.e. $\frac{P_{"max"}}{P_{installed}} = 80\%$) (Jalkanen, et al., 2009).

1.4 Purpose

The study aims to theoretically investigate the potential of reducing emissions and fuel consumption in the Port of Gävle by an introduction of a more digital information flow and an updated port framework.

Another purpose of this case study is to improve the emissions calculation method for ship emissions. This includes a development of an existing IVL model for ship emissions in port involving the use of different data sets to calculate power requirements and fuel consumption of individual ships.

2 Data collection and methodology

This chapter describes what background information that have been used and how the emission calculations have been conducted. The analysis of the port call statistics builds upon the same methodology IVL uses for the emission calculation model.

2.1 Data collection

Six different data sets have been collected and used in this study, summerised in Table 2.1. These data are further decribed in the sections below.

Table 2.1. Data sources used in this study

Data type	Sources
Port call statistics	Port Autority in the port of Gävle and the Swedish Maritime Administration
AIS data	MarineTraffic
Ship data	Sea-web database – IHS Markit
Distances between ports	vesseltracker.com, searoutes.com
Questionnaire and literature reiview	Own work
Fuel consumption statistics	EU MRV

2.1.1 Port call statistics

The port authority collects information on all ships visiting the port. These statistics provide information about each ship's time of arrival and time of departure, ship identity, which quay it berths and the name of last port visited. Similar information is gathered by the Swedish Maritime Administration for all ships using Swedish fairways.

These data sets normally feed the IVL emission calculation model with information about time in different operational modes of individual ships, and also detailed information about visited quays. In this study the analyses is expanded to also involve an analysis of the distance between the port of Gävle and the last port visited, since this data is needed to calculate the time the ship spend at sea. When the information about the last port was missing in the data from the port authorities in Gävle, this infomation could be extracted from the statistics provided by the Swedish Maritime Administration.

2.1.2 AIS data

The speeds and the positions of ships have been analyzed with help of the ships' Automatic Identification System (AIS)- and satellite data from the sea surrounding the port of Gävle (MarineTraffic, 2019), the area is marked in Figure 2.1. The used AIS data cover signals from 298 ship that visited a quay in the port 2017. In total about 185 000 signals where extracted from the area. The AIS data contains information about IMO number, position, course, speed and a timestamp.

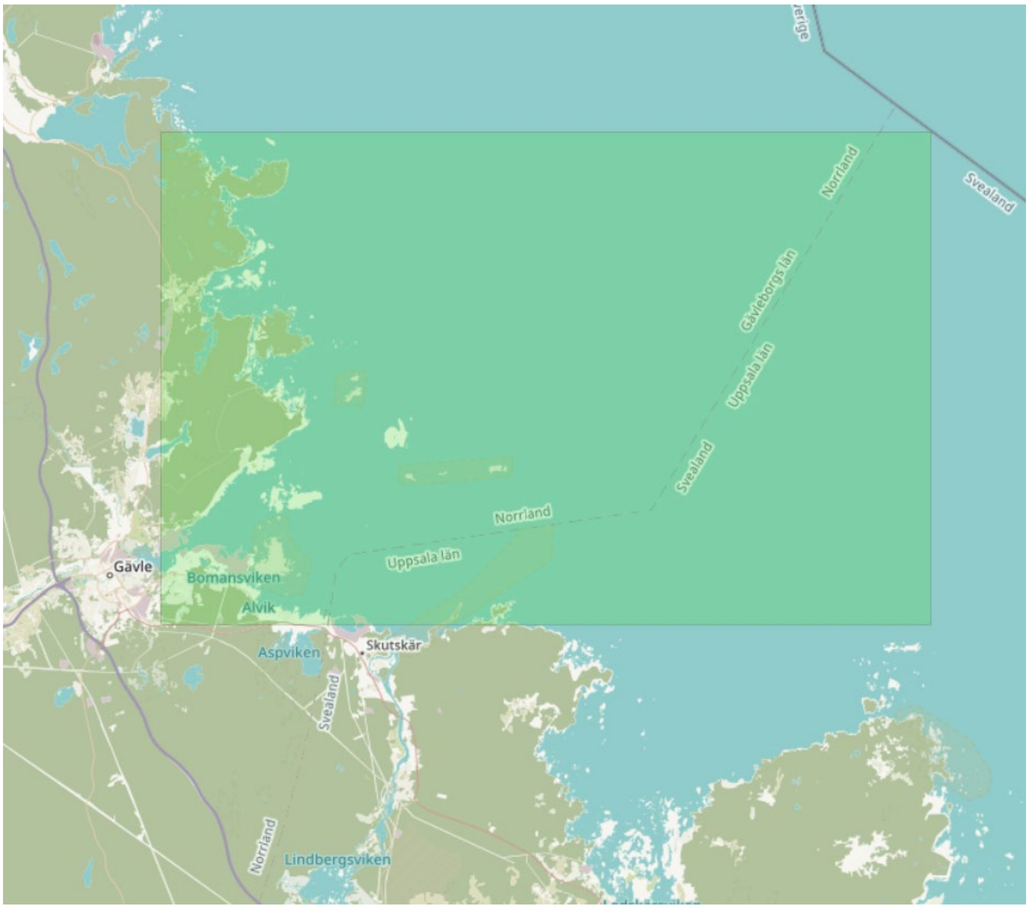

Figure 2.1. The area from which AIS signals were analyzed for this study.

The accuracy of the AIS data is high and for this analysis they have offered a possibility to validate the port call statistics, extract the anchoring times and the ship speeds in the area.

2.1.3 Distances between ports

Most information on distances is from a study in which the web based service "Vesseltracker" was used to estimate distances between ports (vesseltracker, 2019; Hult, et al., 2020). In some instances the distances have been extracted from another web based service called Searoutes (2019). All distances are presented in Appendix C.

The distances between ports have been used to analyse the full fuel saving potential from more efficient port operations. The distance is used to calculate how much fuel that is consumed at sea in the slow steaming scenarios. A development of the port framework, shorter time in ports and guaranteed slot times can for some ships for example facilitate slow steaming over larger distances, which may significantly reduce fuel consumption.

2.1.4 Questionnaire on ships' use of auxiliary power

The ships´ power needs at berth have been mapped partly through interviews with ship operators' technical staff and partly by means of technical data on the ships. A questionnaire was sent to shipping agencies whose ships called the Port of Gävle in 2017 or 2018. The template can be found in Appendix E. Similar studies have been carried out in for example the port of Rotterdam (Denier van der Gon & Hulskotte, 2009; Hulskotte & Denier van der Gon, 2010) and the Port of Los Angeles (The Air Resources Board, 2007; The Port of Los Angeles, 2010).

A large part of the emissions from ships in port areas are from the auxiliary engines on board. Direct information from crew and technical personnel at ship operator companies help avoid the use of generic values on power needs in ports. The results from the questionnaire is complemented with a literature review.

2.1.5 EU Monitoring reporting and Verification system (MRV)

European Union (EU) has a goal to reduce greenhouse gas emissions from ships and has therefore created a new monitoring program that collects data since the first of January 2018 (Erbach, 2019; EU, 2016). The monitoring program compiles fuel and cargo statistics from all ships larger than 5000 GT that enters a port within the EU (DNV-GL, 2019). The statistics are aggregated and presented at the MRV webpage (EMSA, 2020) and contained information about 11 000 ships in March 2020. The focus of the reporting is on the tailpipe[1] emissions of CO_2 only, since this is considered to be the most relevant greenhouse gas emission from ships. The data on emissions of other greenhouse gases was also expected to be more unreliable and unavailable. (EU, 2015)

In the comparison in this study we have used the statistics called "*Annual average CO_2 emission per distance [kg/nmile]*" in the MRV Database. If the ship that arrived at the Port of Gävle was a part of the statistics, the use the reported ship specific average. However, only 119 of the 299 ships where a part of the MRV-database. We therefor only compare the emissions for these ships. The total emissions are calculated by multiplying the *Annual average CO_2 emission per distance* with the distance, see section 2.1.3. These emissions are then compared with the emission calculated with the model used in the port inventories.

2.2 Methodology

IVL's previously mentioned calculation model for emissions from ships in port areas is constructed around the formula:

[1] Also called tank to propeller, i.e. emissions occurring due to the incineration in the combustion engine.

$$E = EF \cdot t \cdot P \ (2.1)$$

E is the resulting emissions, EF is emission factors that can depend on e.g. engine age, type of engine, fuel used and exhaust gas aftertreatment, t is time in an operational mode and P is the power needed in an operational mode. The power requirements are most often calculated as the product of installed engine power and an engine load factor - an assumed value. Many generic values are used, and by comparing results with alternative datasets for input on ships speeds, power requirements etc., inaccuracies can be removed and replaced. In the paragraphs below we explore the effects of complementing the port call statistics with other datasets and effects of replacing the previously used datasets with new ones.

It is the factors of time in different operational modes (t) and power need (P) that are modelled. For all scenarios the additional emissions associated with the boiler will also be added to the results. The case study includes analyses of emissions from ships at berth, emissions from ships at anchor and emissions from ships at sea.

2.2.1 Emission reduction from ships at berth

Emissions from ships at berth are calculated and described in the emission inventory report for Port of Gävle from 2018 (Jerksjö & Parsmo, 2018). A refinement of the calculations that is used in this study separate between ships idling at berth and ships in loading/unloading operation. Between the two, the power requirements onboard during idle condition are significantly lower.

The most likely scenario is that the "time saved" at berth, due to efficiency improvements, will occur when the ships are idling. During the idling-mode no extra power is required for loading or unloading. However, it is assumed that power could also be avoided during loading/unloading operation, e.g. due to better communication. For the tanker ships and the bulk/break-bulk ships the scenario results are therefore presented for two cases:

a) The loading/unloading condition: The value is the calculated values from the inventory report (Jerksjö & Parsmo, 2081).
b) The idling condition: Based on the percentage difference between idle condition and the unloading condition, derived from the literature review and the questionnaire

For container ships, savings are assumed to be the same for idling and loading/unloading conditions.

Further, this study assumes a small efficiency improvement – 7 % reduction of time at berth - corresponding to the objectives of the *EfficientFlow* project. The potential efficiency improvements are currently evaluated in the *EfficentFlow* project, see section 1.2. Since the project is still ongoing the efficiency improvements investigated in these calculations are not necessarily the same as those that *EfficentFlow* will conclude on.

2.2.2 Emission reductions from ships at anchor

The inventory from 2018 did not include emissions from ships at anchor, since most anchoring took place outside the port area (Jerksjö & Parsmo, 2018). In order to include these emissions in this analysis, AIS data have been used to extract the times at anchor.

At anchor the ships are often moving around slowly, which implies that AIS signals is saved in the AIS-dataset. When these positions are plotted on a map, these AIS-signals often take the shape of a circle instead of a line. In Figure 2.3 one can see this typical pattern appear in an area north of Skutskär. Based on these patterns two areas have been selected where the ships were considered to anchor. These anchoring sites correspond well (but not exactly) with the areas indicated in the maps provided by the Swedish Maritime Administration (SMA, 2020). The time at anchor has been assumed to occur when a ship arrived at the anchorages area until it left the area. However, ships that have been in the area for less than two hours are excluded from the sample, they are instead assumed to be ships that are passing the area.

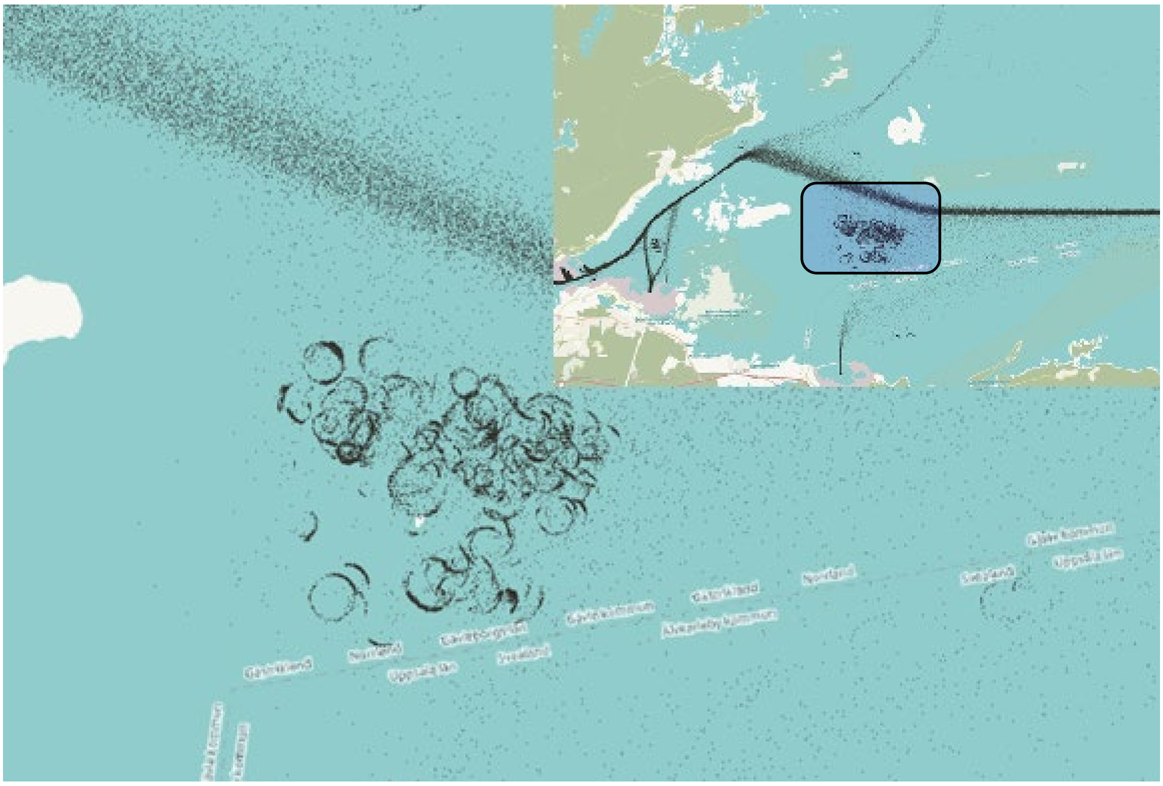

Figure 2.3. Each point represents one AIS signal from one of the 298 ships that entered the port of Gävle in 2017. The larger picture is the zoomed in version of the blue area indicated in the picture in upper right corner.

2.2.3 Emissions from ships at sea

Time at sea

In the previously reported emission inventory (Jerksjö & Parsmo, 2018) the time in port is calculated as the ratio of the distance travelled and the speed, available from the ship database Seaweb, used for the calculation model. However, in that study the time at sea was not included. Furthermore, in this analysis, we also calculate the time based on the extracted AIS signals outside the Port of Gävle. We will therefore use the average speed for each individual ship outside the port in the comparison in this study. Both the average inbound speed and the average outbound average speed will be used as a proxy for the actual speed.

Power requirements at sea

The previous inventory used tabulated values on main engine and auxiliary engine load factors, see table 2.3. For this study, we also use AIS data to calculate power requirements for the propulsion engine according to formula 1.1. This means we compare generic values from the previously used emission calculation model to those derived from AIS data on ships' speeds outside the Port of Gävle from 2017. Rated power is in both cases taken from Seaweb database (IHS Markit, 2019).

Tabell 2.3 Approximative load demand at different operational modes (Entec UK Ltd., 2002).

	At sea	In port area	Maneuvering	At Berth
Main Engine	80 %	20 %	20 %	0 %
Auxiliary engines*	30 %	40 %	50 %	40 %

*At sea the auxiliary engines also include auxiliary power demand of the shaft engine.

Emission reduction - Slow steaming scenarios

The emission reduction at sea is calculated by assuming slow steaming. Since the *Efficientflow* project has not yet been evaluated, the slow steaming potential for the ships is unknown. This study will instead exemplify the greenhouse gas emission reduction potential of slow steaming by calculating the emissions for different reductions of speed. Since the emission reduction potential for slow steaming is non-linear the speed reduction scenarios will be illustrated for a range of speed reduction between 5-15%.

We compare a scenario where all ships sail at service speed with a scenario where the entire fleet use slow steaming. The potential reduction will be calculated as the difference between the two scenarios:

$$Emission\ reduction = Emissions_{Service\ speed} - Emissions_{reduced\ speed} \quad (2.2)$$

Comparing emissions at sea

The emission reduction calculated with equation 2.2. depends on a lot of factors such as the speed assumed (in this case the service speed of the ship) and the power requirements of the propulsion and the auxiliary engines. The total emissions at sea will therefore be compared to the total emission at sea if one assumes that the speed is based on the inbound and outbound speed instead.

Parts of the results will also be compared with the calculated emission at sea based on the MRV-data, see section 2.1.5. MRV data are not available for all ships. This is done in order to evaluate if the results are in a reasonable range.

3 Analysis of methodology development

In the following paragraphs the use of the data sets is described in the context of the case study in the Port of Gävle. The influence of different source data and assumptions on estimates of time in different operational modes and power requirements are illustrated and explained.

3.1 Using AIS data to analyze ship movements in the port area

All individual shipping lanes are evaluated for each port call and categorized by analyzing the AIS-data. An individual shipping lane is an inbound and or and outbound path for each port call. This is a refinement to the model. This categorization has three different purposes:

1. to investigate if the ship is going into the port or if it is going out of the port.
2. to investigate which ships that are at quay and which are not, since some of the 298 ships that was in area sometimes didn't enter the port.
3. to investigate which ships that are anchoring and when.

The first step was to identify if the ship was arriving to the port or if it was leaving the port. Based on the AIS data a navigation channel was created for each ship´s individual arrival and departure at the traffic area. This navigation channel was based on the timestamp and the IMO number of the AIS-data. The data was then categorized into different geographical zones using GIS software. The zones were categorized into three different types:

1. anchor
2. navigation channels (at sea)
3. quay

The zones are illustrated in Figure 2.2. Each zone is also further categorized into several different zones for other purposes, these more detailed zones are further described in Appendix A.

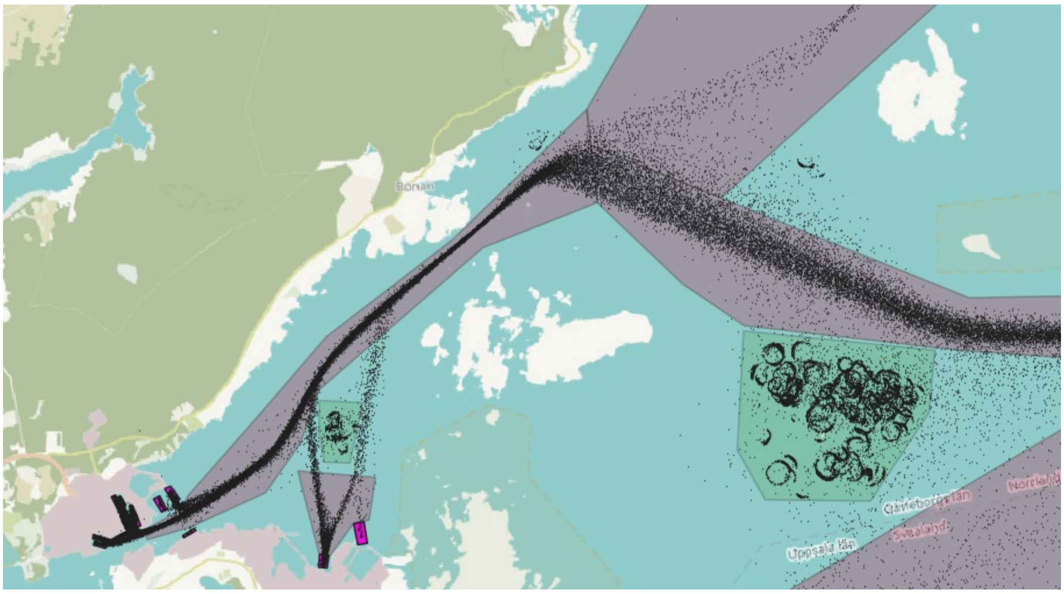

Figure 2.2 – Illustrating the joint between the AIS position data, the black dots, and the zones in the port of Gävle. The green zones are assumed to be anchoring places, the transparent purple zones are shipping lanes and the pink small zones are berth places.

The second step was to compare the timestamp of the AIS data with timestamp on the port call statistics. Based on this categorization it was possible to differentiate when the ship was leaving and when it was arriving at a specific area.

The AIS data and the port call statistics was also combined in order to evaluate which AIS data to use. It was possible to connect 845 of 896 port calls to the AIS data. There could be two possible explanations that it was not possible to connect all port call statistics with AIS data:

- There was some error in the timestamp either in the port call statistics or in the AIS-data.
- The AIS data for some port calls were missing.

845 calls are assumed to be a good representation of all port calls. The AIS analysis is used for ships at anchor and ships at sea. Of all 845 connected port calls it was possible to identify which ships that sailed into the port 832 times and out of the port 835 times, all paths are illustrated in Figure 3.1. For these paths it was possible to calculate average speed in different zones, see results in section 3.2.

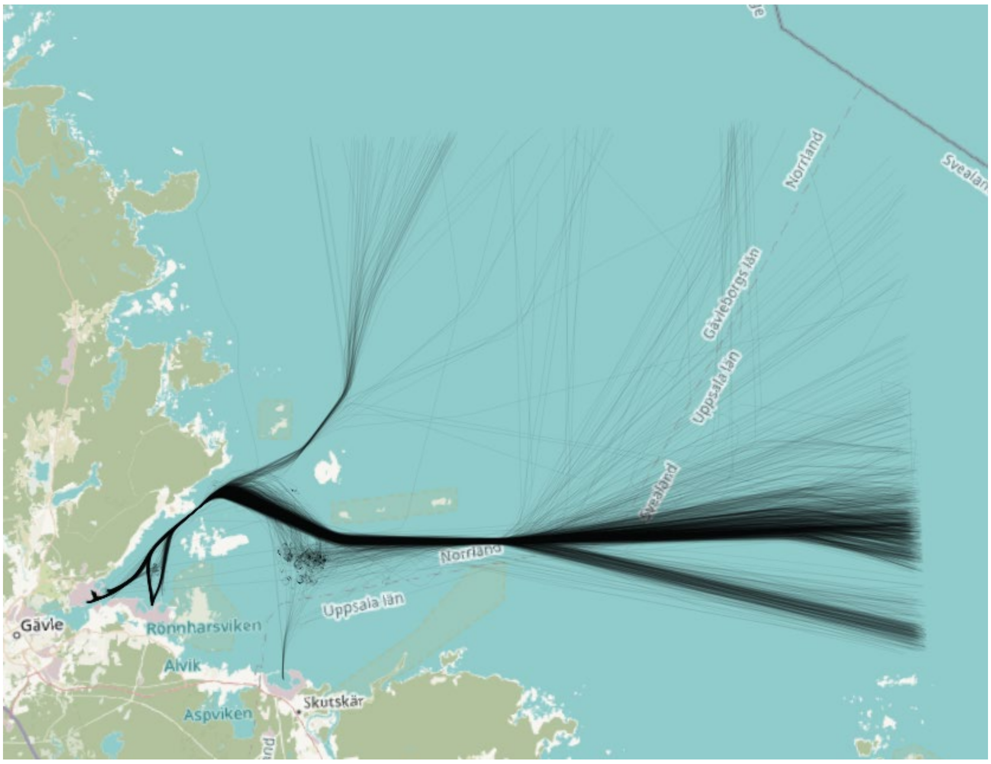

Figure 3.1. Illustrates all inbound and outbound navigation channels for port calls in 2017.

It was also possible to identify 124 anchoring's outside the port prior to port entry. Most of the anchoring's took place north of Skutskär instead of the anchorage just outside the port. According to the local port authority there are probably two explanations for this:

1. The depth is greater at the anchorages outside the dredged navigation channel.
2. Ships only need to call on the pilot one time if they decided to anchor at the outer anchoring area.

71 out of 124 times, a ship was at a specific quay the same time as another ship was anchoring, supposedly waiting for that quay, since the anchored ship later entered that specific quay. We assume that these ships were waiting for a time slot at that quay in the port. However, many of the 124 ships that where not waiting for a occupied quay, could as well have benefited from an improved information flow, since the anchoring could for example be a consequence of missing staff or equipment. We therefore estimate that between 71-124 of the all anchoring's outside the port, could have been avoided with a guaranteed time slot in 2017. This corresponds to about 2 900-4 600 hours of time at anchor.

3.2 Distance, speed and time spend at sea

The frequency distribution of the distances travelled by ships from the previous port to port arrival in Gävle is included in Figure 3.2. The average distance at sea was 590 NM. However, it was not possible to distinguish the last port for 24 of the port calls. For these ships, the average distance of 590 NM has been assumed and used in the calculations.

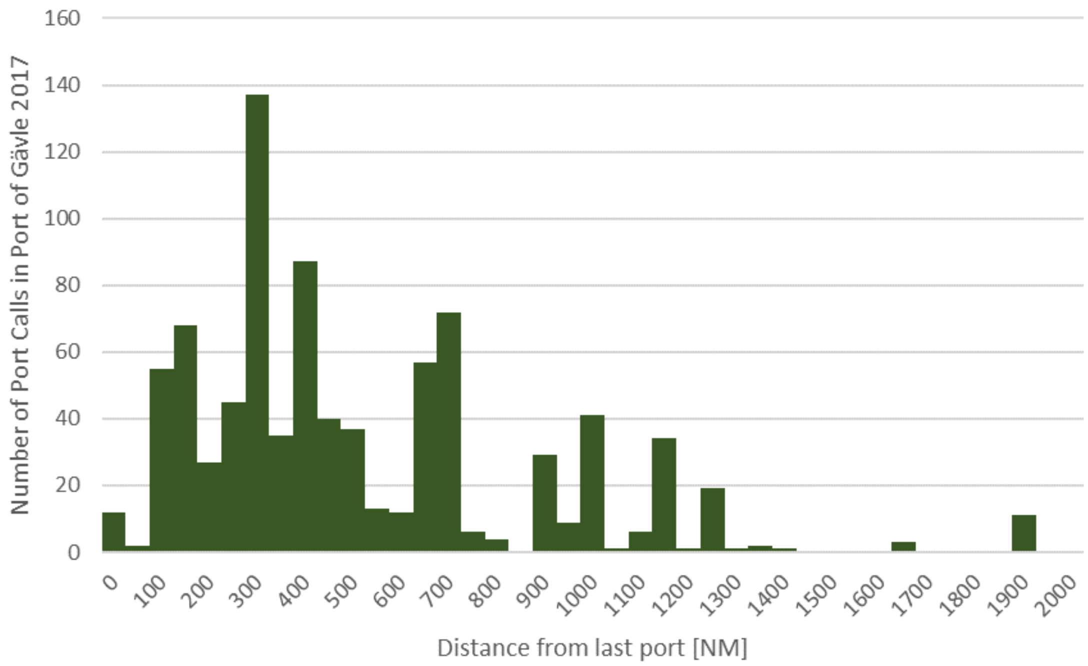

Figure 3.2. Frequency distribution of each inbound distance a ship has traveled in order to reach the Port of Gävle. Six port calls with longer distances (4 000-10 000 NM) have been excluded from the figure.

From the AIS data it was possible to extract the average speeds in the six studied zones for inbound and outbound ships. The average speed is then divided with each individual ship's services speed for each area in order to have an approximation on existing slow steaming. Aggregated data for the different ship categories and the areas are presented in Table 3.1. In Table 3.1 it is possible to see that the inbound cruise often is slower than the outbound. It is also possible to see that ships on average cruise slower than service speed also in the assumed full speed area. This seems to be more typical for the container ships than the other ship types.

Table 3.1 Comparison of the average speed and the service speed for different ship-categories in different areas outside the port of Gävle.

Zon	Ships transporting bulk- and other non-standardized cargo		Tanker ships		Container ships		AIS data points
	inbound	outbound	inbound	outbound	inbound	outbound	
1 – Reduced speed	60%	72%	48%	62%	36%	43%	15 006
2 – East	78%	87%	70%	79%	51%	64%	17 164
3 – North	74%	82%	60%	64%	47%	37%	1 247
4 – Karskär	21%	48%	12%	39%			1 266
6 – Full speed area	79%	87%	80%	86%	59%	72%	41 995
Total	**72%**	**85%**	**68%**	**81%**	**50%**	**66%**	**76 678**

The time each ship spends at sea have been calculated for three different speeds:

1. The service speed based on the ship data from the ship database.
2. The inbound speed at the assumed full speed area, based on the AIS data.

3. The outbound speed at the assumed full speed area, based on the AIS data.

If the average inbound or outbound speed was missing for a specific ship, an average sea speed for that ship segment has been applied.

As can be seen in Table 3.2 the total time spent at sea varies and depends if all ships cruise at service speed or with reduced speed. For example, total time spent at sea was 33 % higher when the inbound speed was used instead of the service speed, in the full speed area.

Table 3.2. Hours spent at sea for all inbound port calls in 2017, presented for different cargo segments and different speed assumptions.

Cargo segment	Inbound speed	Outbound speed	Service speed
Bulk or break-bulk	24 509	21 756	19 204
Container	8 702	7 138	5 199
Tanker	13 750	12 873	10 831
Total	**46 961**	**41 766**	**35 234**

3.3 Auxiliary power demand from questionnaire and literature

The auxiliary power of 35 ships was identified in this study: 10 tanker ships, 22 break-bulk cargo ships and 3 roro cargo ships. The average gross tonnage (GT) for these ships are plotted in Figure 3.3. and compared to the average fleet arriving to the port (2017-2018). Gross tonnage is a measure that describes the ship size, the internal volume, and in the literature GT is frequently linked to the power consumption of the auxiliary engines (Sjöbris, et al., 2005; Hulskotte & Denier van der Gon, 2010).

Three ships in the survey were of roro-type. However, since the sample was small and since roro-ships do not visit the port frequently, they were excluded from the analysis. Their specific power demand was still used in the port inventory calculations, see appendix D.

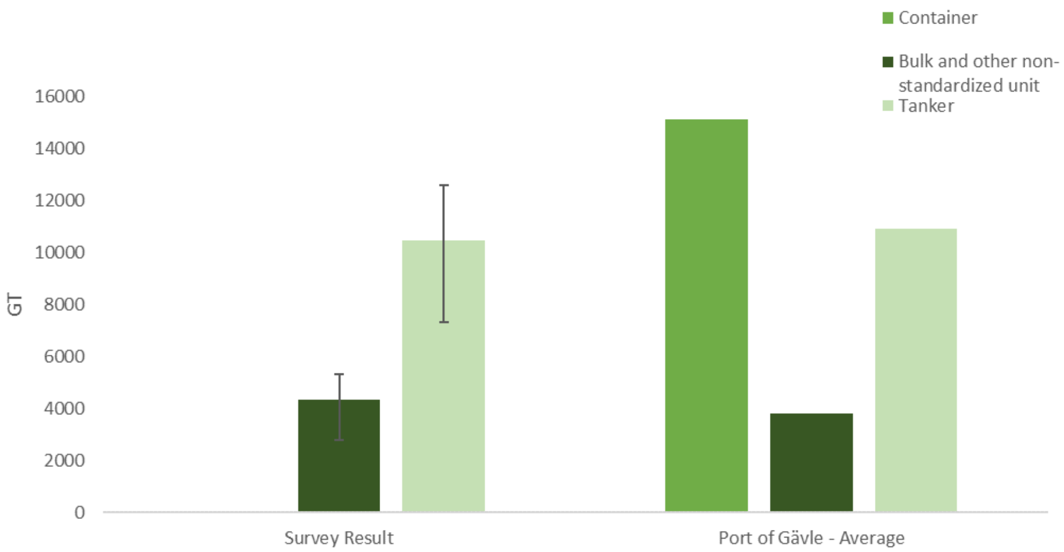

Figure 3.3. Average GT of the ships in the survey compared with the port call statistics in 2017 and 2018. The error bars on the surveyed ships corresponds to the maximal and minimal GT.

The average sized tanker and the average sized bulk ship is about the same in the questionnaire and in the port call statistics, Figure 3.3. However, there are also some calls with larger tanker ships in the port (>20000 GT), as illustrated in the frequency distribution in Figure 3.4. These large tanker ships were not included in the survey, so the results are not representative for these types of ships.

The results from the questionnaire are not conclusive. The sample for each ship category is small and only few shipping agencies answered the survey. The answers from the survey could therefore be unrepresentative. The results should accordingly be used as indications and additions to existing knowledge rather than stand-alone results that can be applied to a large number of ships.

There were no respondents representing container ships in the survey. However, as can be seen in Figure 3.4, container ships constitute a large and important fraction of all ships in the Port of Gävle. A literature review on the auxiliary engine power used onboard container ships has therefore been conducted, see section below. Table 3.3 is based on the survey and literature review and summarizes data which have been used in the calculations.

Table 3.3 – Summary of hoteling power demand compared to unloading power demand. The results are based on the results from the literature and the questionnaire, see section 3.3.1 to 3.3.3.

Cargo type	Hoteling power demand compared to unloading power demand	Source
Tanker	24%	questionnaire
Bulk and break-bulk	65%	questionnaire
Container	100%	Literature review

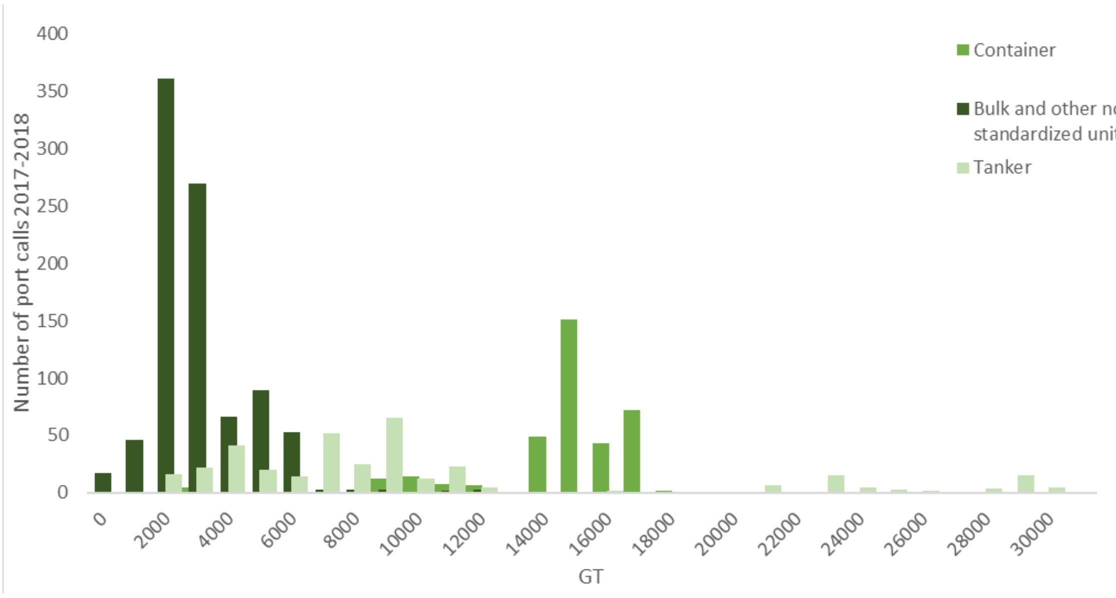

Figure 3.4. The number of calls made by ships depending on the size (GT).

The model used in the inventory reports, such as (Jerksjö & Parsmo, 2018), use a model to calculate the installed powers of the auxiliary engine (Sjöbris, et al., 2005), see figures 3.5., 3.6 and 3.8 in the sections below. The installed power is then multiplied with an average load demand of 40% (Entec UK Ltd., 2002):

$$auxilary\ engine\ power\ demand = k \cdot DWT^{n} \cdot engine\ load \quad (3.1)$$

Where DWT is dead weight tonnage and GT is Gross tonnage. The value of k and n can be found in Table 3.4.

Table 3.4 k- and n-values for different ship categories.

Ship Type Category	k	n
Bulk carrier	35.312	0.3603
Container ship	0.5504	0.8637
Chemical tanker	5.5294	0.5863
Oil tanker	9.6262	0.4891
Break-bulk cargo	0.7476	0.7796
Other	0.7476	0.7796

3.3.1 Tanker ships

The responses to the questionnaire show a large difference in power demand between idling, loading and unloading operations, see Table 3.5 and Figure 3.6. The hoteling power demand was only 24% of the power demand used at unloading condition, on average. This difference is partly covered in previously reported emission data: the auxiliary power model used in the inventory model includes additional power requirement during unloading operation of tankers. However, the results from the questionnaire indicate that difference between unloading operations and idling is larger than the difference in the inventory report.

Table 3.5. Average power demands for tanker ships at berth, results from questionnaire

	Power demand at berth			Hoteling power demand compared to unloading power demand
	Unloading	Loading	Hoteling	
Unit	[kW]	[kW]	[kW]	[%]
Average	1 040	338	211	24%
Sample standard deviation	583	84	57	10%

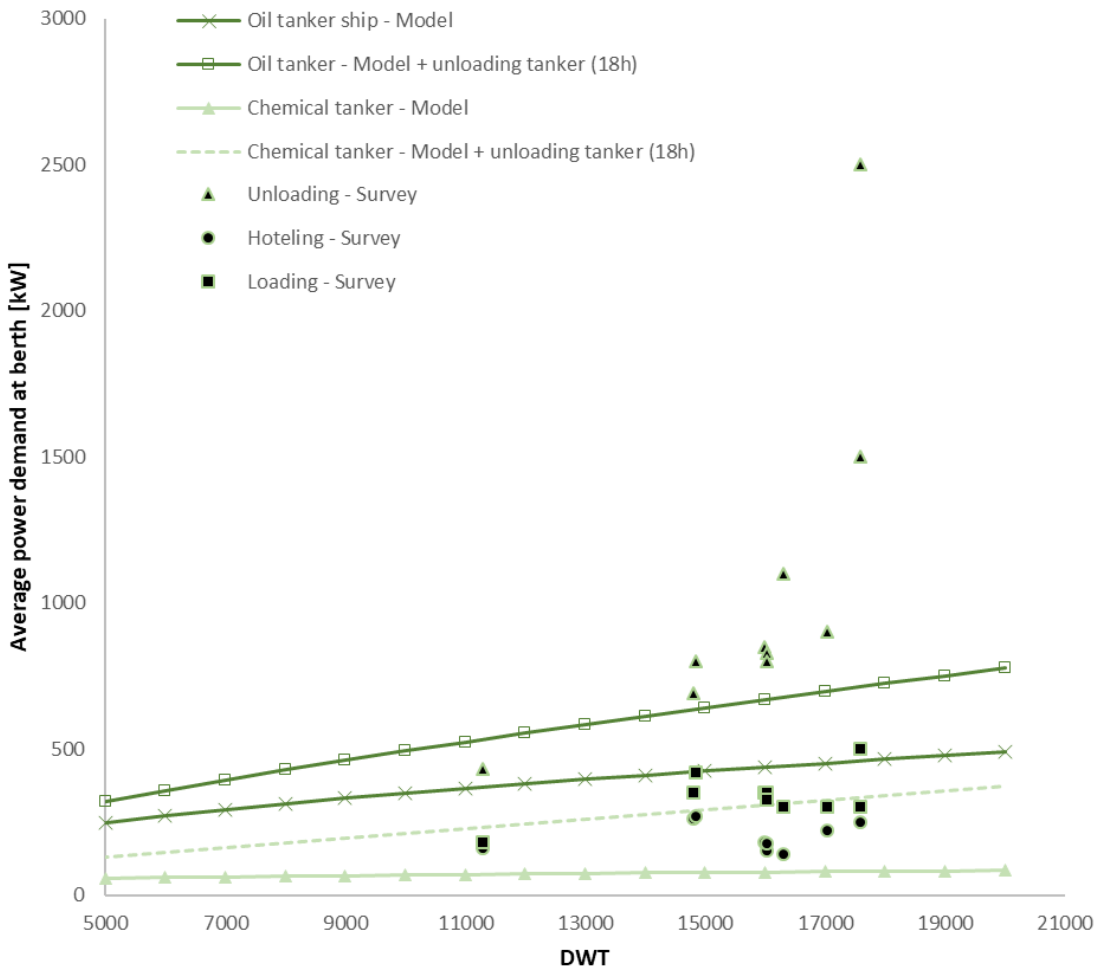

Figure 3.5 – Average questionnaire results of tanker ships. The additional power requirement in the port inventory is based on the number of hours a ship stays in port. In this comparison we assumed the number of hours based on the median number of hours that tankers where berthing in the Port of Gävle in 2017 and 2018.

All ships in the questionnaire are chemical tankers and should be compared with the two light green lines in Figure 3.5. It is worth noting that the results from the questionnaire seems to be higher than the calculated results also for the hoteling mode. According to statistics from the local port authorities the purpose of most calls by tankers in the port is unloading rather than loading oil products. e.g. only about 17 % in 2017 and 6 % in 2018 of the oil products handled by the port was loaded by tanker ships.

3.3.2 Ships transporting bulk or break-bulk cargo

The auxiliary engine power model for break-bulk is plotted in Figure 3.6, since all respondents in the questionnaire are defined as ships transporting break-bulk goods (also called general cargo), according to the ship database (IHS Markit, 2019). The port of Gävle handle both break-bulk and bulk goods. Break-bulk cargo could for example be construction equipment, wind turbines or timber while bulk cargo could be for example ore or clay. In other questionnaires the auxiliary engine power at berth and at anchor is differentiated between ships transporting bulk and break-bulk (The Air Resources Board, 2007; Denier van der Gon & Hulskotte, 2009).

Table 3.6. Average questionnaire results of break bulk ships

	Power demand at berth		Hoteling power demand compared to unloading power demand
	Loading/unloading	Hoteling	
Unit	[kW]	[kW]	[%]
Average	106	67	65%
Sample standard deviation	35	20	16%

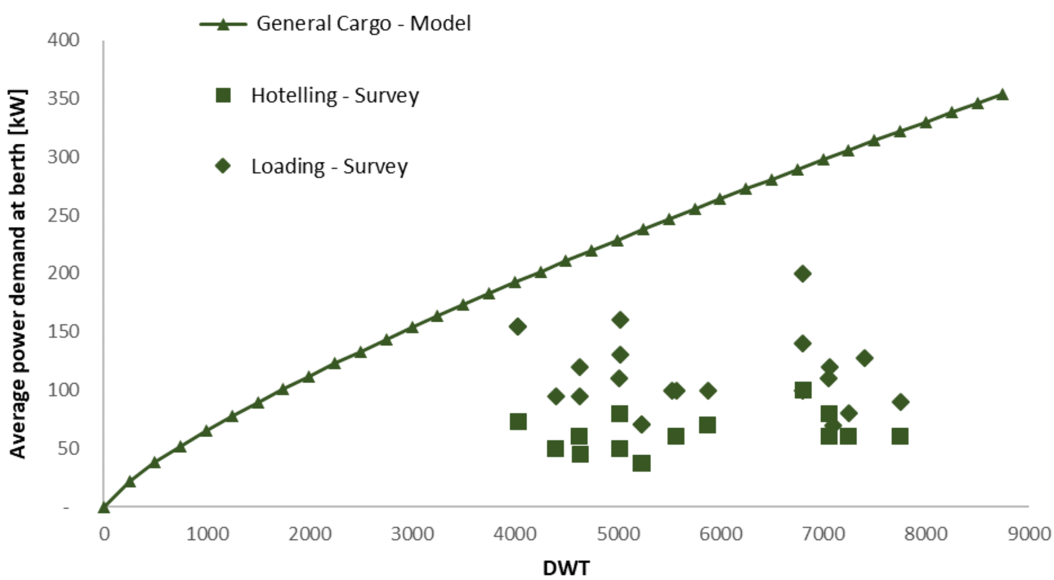

Figure 3.6. Comparison of modeled power use at berth and the results from the questionnaire.

3.3.3 Container ships

The auxiliary power demand at berth on container ships depends on several factors, such as the number of refrigerated containers and other cargo related activities (Doves, 2006). During loading and unloading, cranes could be used. Typically, smaller container ships use cranes onboard, while larger container ships rely on port assistance for loading and unloading operations (Ericsson & Fazlagic, 2008).

Modern container ships generally have the possibility to transport some refrigerated containers. The number of refrigerated containers will significantly influence the auxiliary power required. According to the container handbook a typical power demand for refrigerated containers at varying conditions is 3.6 kW/TEU (GDV, 2020). The power demand will depend on the type of cargo, the type of container and the ambient temperature. According to port call- and ship statistics all the container ships entering the Port of Gävle have reefer points (IHS Markit, 2019), see Figure 3.7. However, that doesn´t necessarily imply that these points are used, e.g. according to the port authorities the port only handled about 60 refrigerated containers last year.

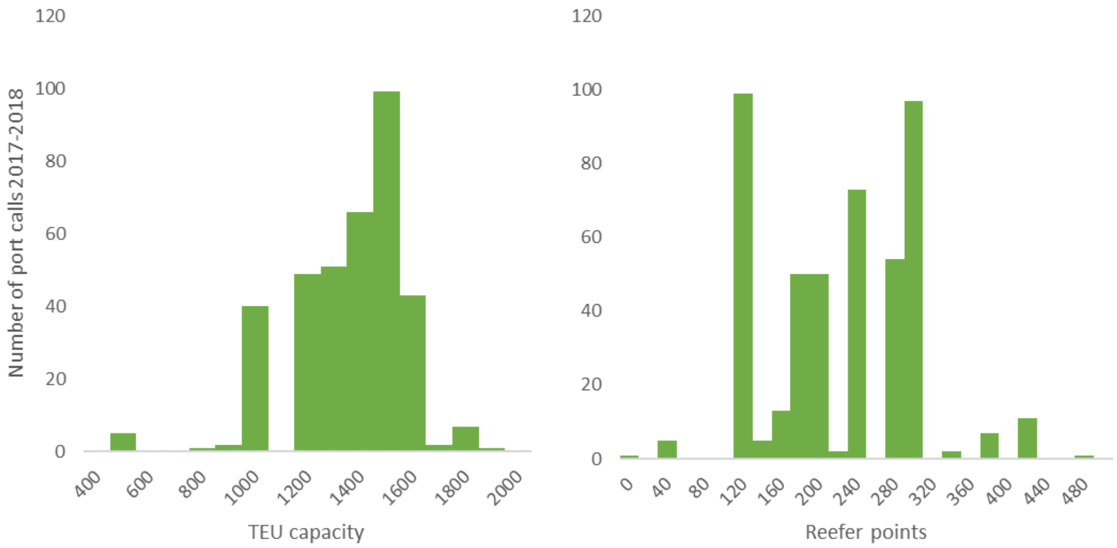

Figure 3.7. The frequency distributions of the containers ships TEU capacity (left) and of reefer point (right).

In figure 3.8, the yellow line represents the auxiliary engine power demands as calculated in the emission inventory model (e.g. Jerksjö & Parsmo 2018) according to the following formula:

$$k \cdot DWT^{n} \cdot engine\ load = 0.5504 \cdot DWT^{0.8637} \cdot 40\%$$

This is compared to values from the Port of Los Angles where several ship questionnaires have been collected, referred to as Vessel Boarding Program (VBP). The default auxiliary engine power used in the Port of Los Angeles emission inventories are represented by the black line in Figure 3.8. These default values are based on the survey results. In yet another survey, in the Port of Rotterdam, containers at berth where divided into two categories: feeders (<140m) and deep-sea containers (>140m) (Doves, 2006). In that survey the feeders had an average auxiliary power consumption of about 200 kW, while the deep-sea containers had an average power consumption of about 2000 kW. These are represented by the light green line in Figure 3.8 (Ericsson & Fazlagic, 2008). Denier van der Gon & Hulskotte also analyses a ship survey from the port of Rotterdam, and the results from that study is presented as a linear relation se green line in Figure 3.8.

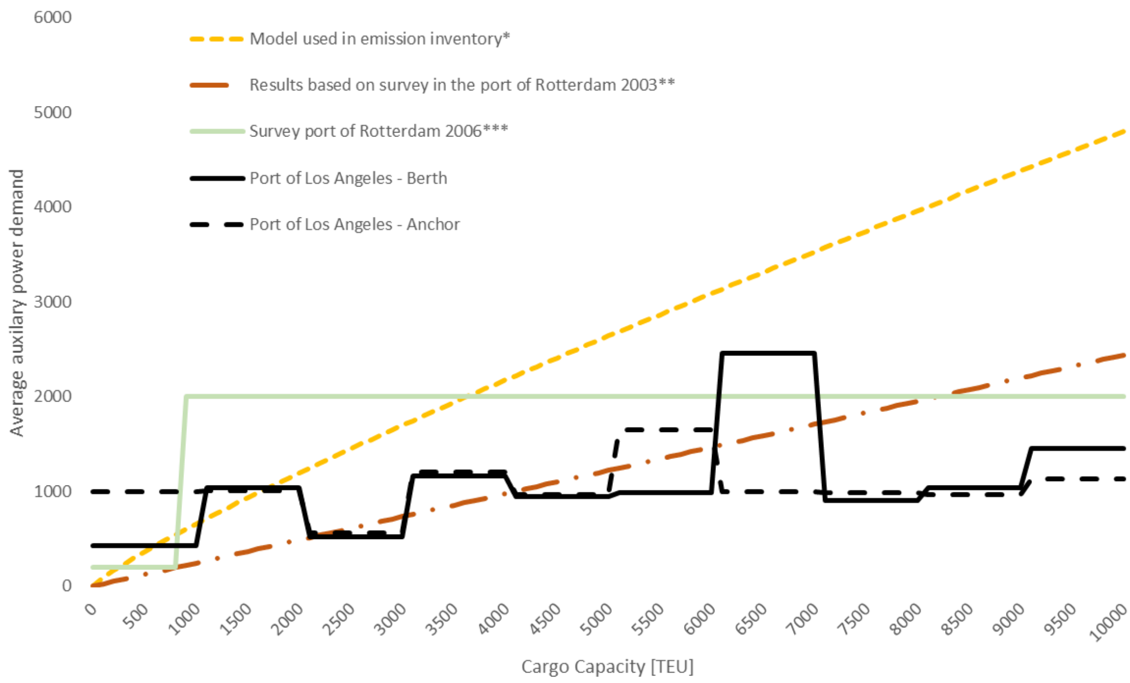

Figure 3.8 – Comparison of average power demand at berth between different studies. The inbound container ships at the Port of Gävle had a cargo capacity between 400 TEU and 1900 TEU.

* The model use DWT as ship characteristics, in order to compare the model with the other questionnaire a simple linear relation between TEU and DWT has been derived, see Appendix B (Entec UK Ltd., 2002; IHS Markit, 2019; Sjöbris, et al., 2005)
** The study compares power demand with the GT of the ship, in order to compare the study with the other questionnaires and models a simple linear relation between TEU and GT was derived, see Appendix B. SFOC is assumed to be 210 g/kWh (Hulskotte & Denier van der Gon, 2010)
*** In this study 140 meters containers ship are assumed to correspond to approximately a cargo capacity of 900 TEU, see Appendix B (Doves, 2006; Ericsson & Fazlagic, 2008).

As can be seen in Figure 3.8, the modeled and surveyed average auxiliary power demand for container ships at berth varies greatly between different sources. In all studies, the authors point out these variations that also are seen for ships with similar characteristics (Doves, 2006; Ericsson & Fazlagic, 2008; Hulskotte & Denier van der Gon, 2010; The Air Resources Board, 2007; The Port of Los Angeles, 2010; The Port of Los Angeles, 2018). This makes it hard to estimate the emissions for these types of ships at berth. In the LA study, which is the survey with most participants, they also compared ships' average power demands at berth and anchor. For container ships it seems like the average auxiliary power demand at berth and at anchor is not following any specific pattern, see black solid line and black dashed line in Figure 3.8. (The Air Resources Board, 2007; The Port of Los Angeles, 2010). It is therefore not possible to conclude that the power demand at berth and at anchor is different.

3.4 Evaluation of the ships fuel consumption in the MRV data.

119 of 299 of the ships the called the port of Gävle in 2017 were part of the MRV-statistics. The MRV data for all ships in the database, shows that fuel consumption per distance sailed varies a lot even within ship categories and for ships of similar size, see figure 3.9 to 3.11. Even though the variations are high, it is possible to see trends for all ship categories. For container ships the fuel consumption seems to vary more in the lower range while being more stable for larger ships, see the logarithmic trend line in Figure 3.9. It is also worth noting that there are very few ships in the MRV database which transport bulk or break-bulk cargo and are in the same size range as the ships entering the Port of Gävle, see upper right corner in Figure 3.10.

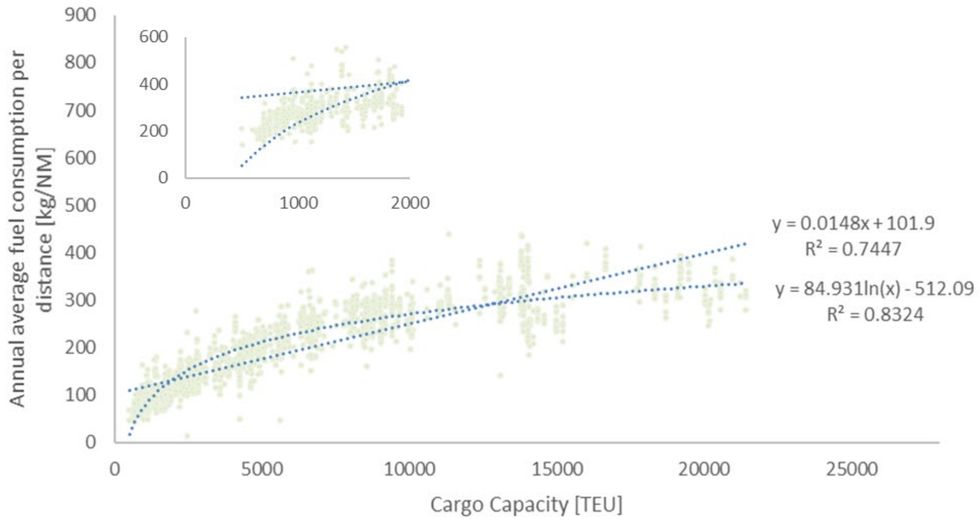

Figure 3.9. MRV fuel statistics compared to cargo capacity for container ships. Each point represents one ship. One extreme value has been excluded from the graph. The picture in the upper left corner illustrates the fuel consumption in the relevant range, i.e. the size range of ships that calls the Port of Gävle.

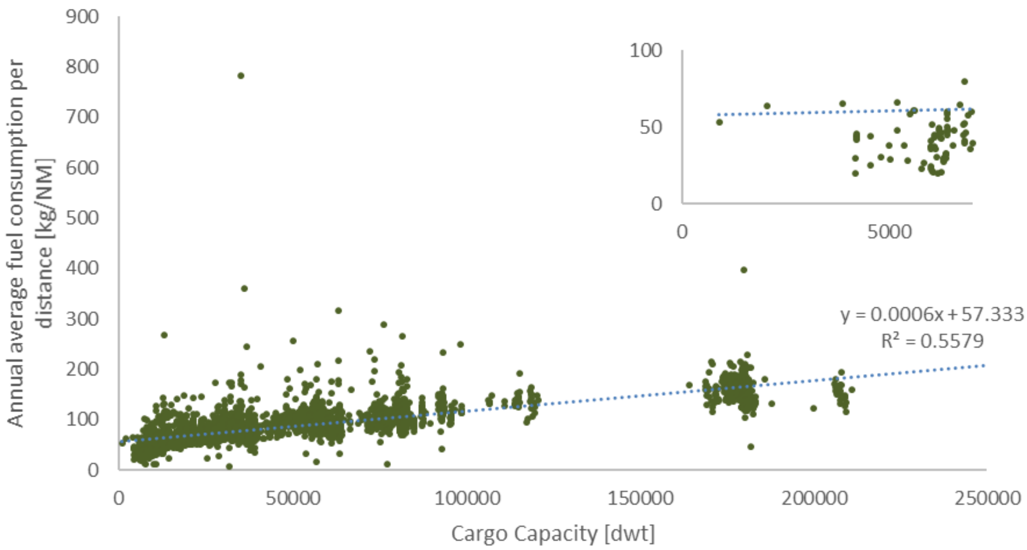

Figure 3.10. MRV fuel statistics compared to cargo capacity for ships transporting bulk or break-bulk cargo. A few extreme values have been excluded from the graph. The graph in the upper right corner illustrates the fuel consumption in the relevant range, i.e. the size range of ships that calls the Port of Gävle.

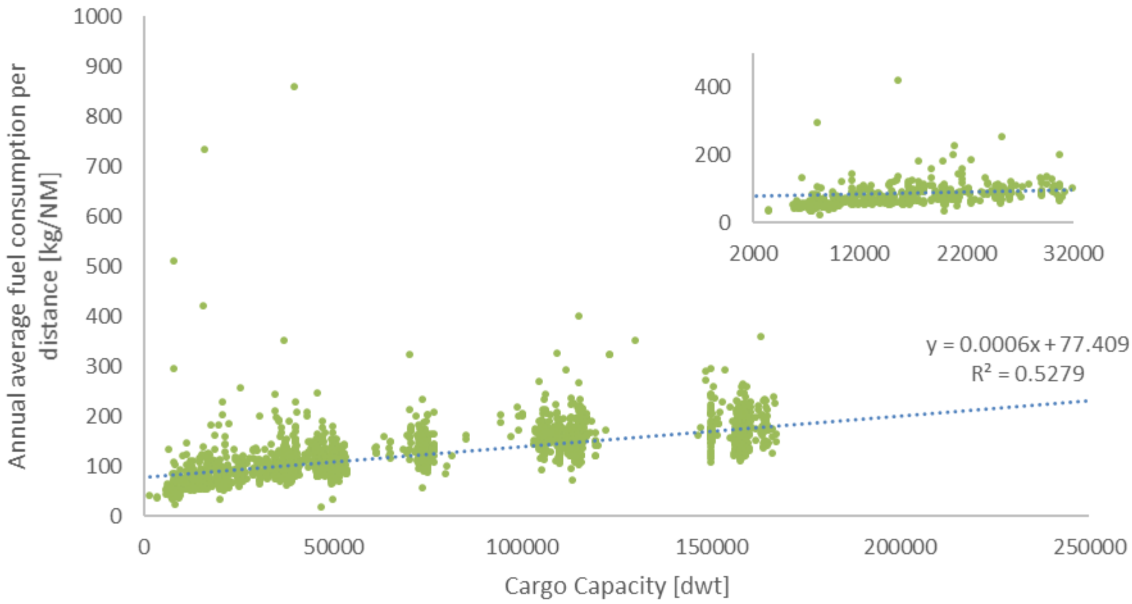

Figure 3.11. MRV fuel statistics compared to cargo capacity for a tanker ship. Each point represents one ship. Some few extreme values have been excluded from the graph. The graph in the upper right corner illustrates the fuel consumption in the relevant range, i.e. the size range of ships that calls the Port of Gävle.

It is also possible to identify some possible outliers from the statistics. These outliers have been excluded from the results in this study. These outliers could unproportionally influence on the results since only a third of the ships in the port of Gävle are a part of the MRV-statistics. After excluding the outliers, 113 unique ships remain representing about 40% of all port calls to the port in 2017.

4 Emission reduction potential

As described in Section 1.1, the digitalization of information flows in combination with an updated port framework is expected to impact the fuel consumption in three operational phases, at berth, at anchor and at sea.

As can be seen in Figure 4.1 the potential for emission reduction at sea is much greater than the potential at berth and anchor. However, the real effects of the digitalization have not yet been evaluated and this study exemplifies how much direct emission that could be avoided in different future scenarios, as an illustration of potential results. The presented results should not be aggregated, since the time a ship spend hoteling is not independent of the time a ship spends at sea. The focus in this study is on greenhouse gas emission (CO_2, CH_4 and N_2O). However, particulate-matter, NO_x and SO_2 emission will be presented for the reduction potential at berth.

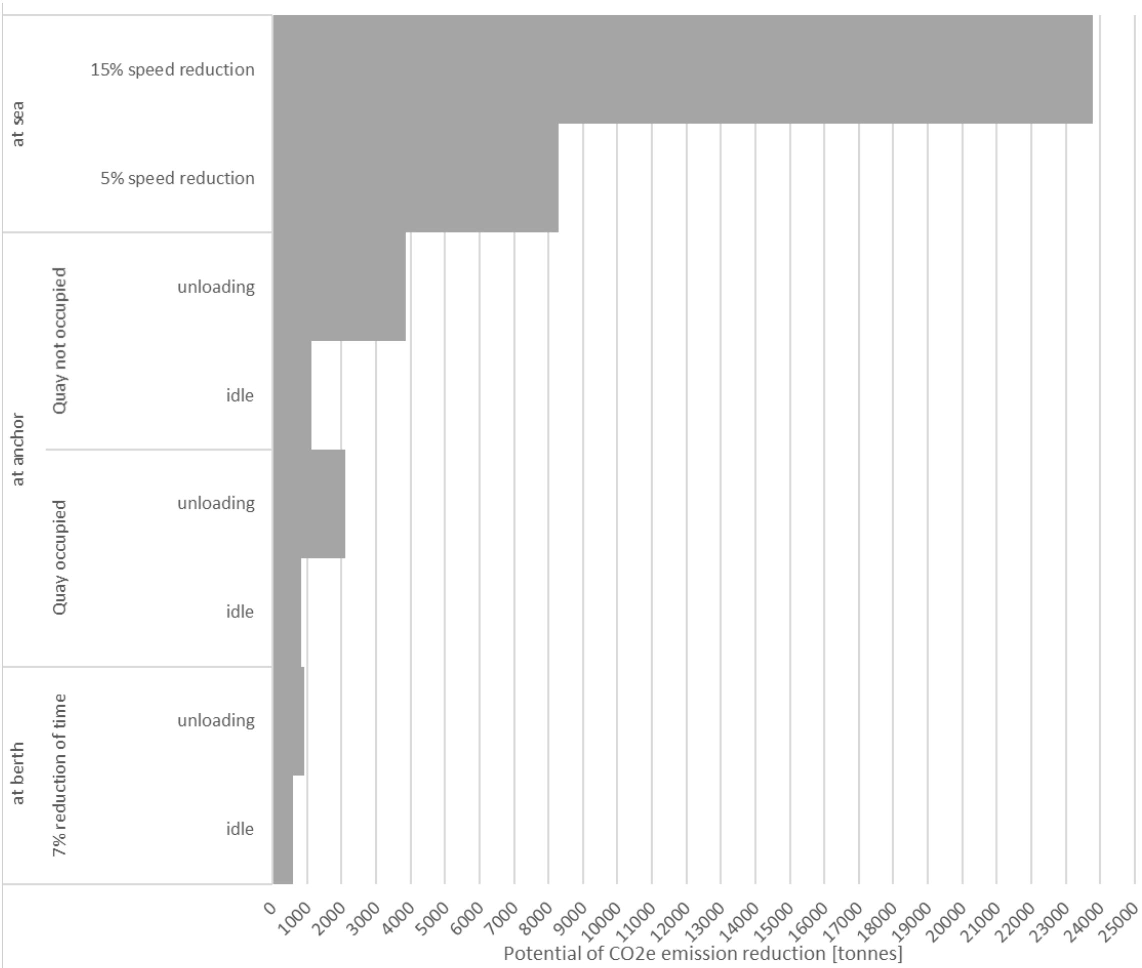

Figure 4.1. Summary of results on the calculated tailpipe emissions of greenhouse gases.

4.1 At berth

The emission in port would be reduced with about 600 CO_2-e per year in the idle scenario and 900 tonnes CO_2-e per year in the unloading scenario (2017), if one assumes that the efficient flow process would imply 7% more efficient port calls, see Table 4.2 and Table 4.3. The reduction depends both on less auxiliary power needs, and less fuel consumptions in the boiler per port call. Container ships are assumed to have similar average power consumption during unloading cargo and idling.

Table 4.2. Scenario 1: emission reduction potential per year at berth in tonnes under the assumption that the time saved would be when all ships are idling, the emissions are based on the port call statistics from 2017.

Scenario	Cargo type	CO2e	NOX	PM	SO2
Idle	Bulk and break-bulk	117	1.6	0.03	0.07
	Container	402	5.3	0.10	0.25
	Tanker	78	0.9	0.02	0.05
	Total	597	7.8	0.15	0.37

Table 4.3. Scenario 2: emission reduction potential per year at berth in tonnes under the assumption that the time saved would be when all ships are unloading, the emissions are based on the port call statistics from 2017.

Scenario	Cargo type	CO2e	NOX	PM	SO2
Unloading	Bulk and break-bulk	180	2.5	0.05	0.11
	Container	402	5.3	0.10	0.25
	Tanker	326	3.7	0.08	0.20
	Total	907	11.4	0.23	0.56

4.2 At anchor

Table 4.3. and Figure 4.2 describes the CO_2-e reduction potential if one assumes that the inbound ships, which where anchoring, could be avoided with a guaranteed time slot. The total reduction estimate varies between 825 and 3 860 tonnes of CO_2-e, depending on which assumptions are made. It seems like the potential for reducing CO_2-e emission for ships handling bulk and break-bulk cargo is limited. Both tanker- and container ships seems to have a higher reduction potential when at anchor. As described earlier, the power demand during anchoring is uncertain.

The two power modes, idle and unloading, can be considered as two different approaches of how to calculate the fuel consumption. The unloading power demand represents the calculations used in the emission inventories (Winnes & Parsmo, 2017; Winnes & Fridell, 2014), even though there is no actual unloading at anchor this scenario is used as a proxy for the “worst-case” power consumption at anchor, since some of the ships in the survey and the literature actually have the same power consumption, while anchoring as when at berth. The other scenario, called idle power mode, is probably more representative of a ship using less equipment onboard during anchoring. The idle power demand is calculated to have an emission reduction potential of between 825 and 1 134 tonnes of CO_2-e. However, more research is needed to confirm this, since the questionnaire conducted in this study only contains a few data points and the surveys presented in the literature is either old or mainly contains ships of a wider size range than hose calling the Port of Gävle.

Table 4.3. CO_2-e reduction potential at anchor. Quay occupied includes 74 anchoring prior to port entry while quay not occupied include 50 anchoring outside the port.

Cargo category	Assumed operational mode	CO_2-e reduction potential at anchor (tonnes)		
		Quay occupied	Quay not occupied	Total
Bulk and break-bulk	Unloading	37	97	134
	Idle	24	63	87
Tanker	Unloading	1 688	79	1 767
	Idle	405	19	424
Container	Unloading/idle	396	1 052	1 448
All	**Idle**	**825**	**1 134**	**2 093**
All	**Unloading**	**2 550**	**1 310**	**3 860**

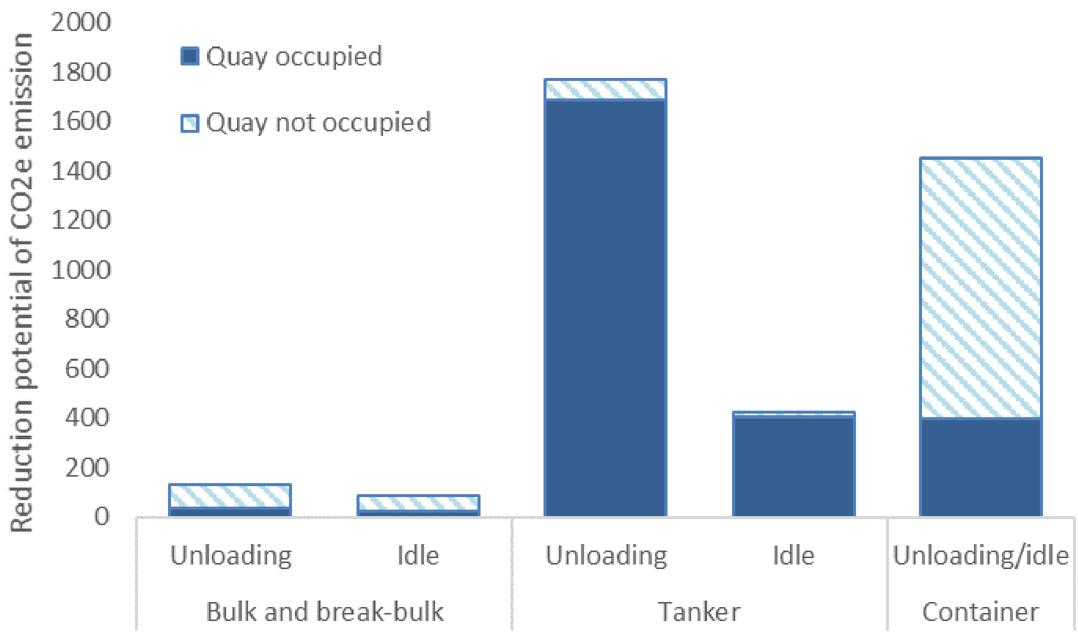

Figure 4.2. CO_{2e} reduction potential at anchor. Emissions in tonnes.

4.3 At sea

The total CO_2-e emissions from all inbound ships are presented in table 4.4. In the table it is possible to see that the choice of method on estimating propulsion power has a big influence on the calculated emissions. The emissions are for example 39% lower if the power requirements are calculated from the inbound speed, extracted from the AIS data, instead of the service speed and the generic 80% engine load factor. The emissions in the table comprise the calculated emissions from all ships entering the Port of Gävle 2017, the distance is the distance from last port to the port of Gävle.

Table 4.4. Ships' greenhouse gas emission expressed as CO_2 equivalents, based on different assumption of speeds. Only tail pipe emissions are included in the table.

Cargo type	No speed reduction, "service speed"	Engine load calculated from outbound speed		Engine load calculated from inbound speed	
	tonnes CO_2-e	tonnes CO_2-e	%	tonnes CO_2-e	%
Bulk and break-bulk	26 000	21 000	-19%	18 000	-32%
Container	36 000	21 000	-41%	17 000	-53%
Tanker	40 000	32 000	-21%	27 000	-32%
Total	**102 000**	**74 000**	**-27%**	**62 000**	**-39%**

In table 4.5. the emissions reduction potential for slow steaming is presented. This potential is rather big, compared to for example the efficiency improvements at berth. These results are in line with other studies such as Faber, et al. (2012) where they argue that 10% speed reduction would imply 19% reduction of emissions (here 10% speed reduction result in 16% reduction of emissions). However, if there is not a surplus cargo carrying capacity in the system one would also need to build new ships in order transport the same volume of goods. This effect is not included in Table 4.5.

Table 4.5. Results of the emission reduction (CO_2-e) if all inbound ships reduce their speed from the previous port. Based on the assumption that the ships previously cruised at service speed.

CO_2-e reduction	5% reduction		10% reduction		15% reduction	
	[tonnes]	[%]	[tonnes]	[%]	[tonnes]	[%]
Bulk and break-bulk	2 200	8.5%	4 300	16.4%	6 200	23.9%
Container	3 100	8.5%	6 000	16.6%	8 700	24.1%
Tanker	3 000	7.5%	6 00	15.2%	8 900	22.3%
Total	**8 300**	8.1%	**16 300**	16.0%	**23 800**	23.3%

The AIS data indicates that many of the ships does not cruise at service speed. This is also what the MRV data indicate in Figure 4.4. Please note that this figure only includes the emissions from 113 of the 299 ship that entered the port of Gävle 2017.

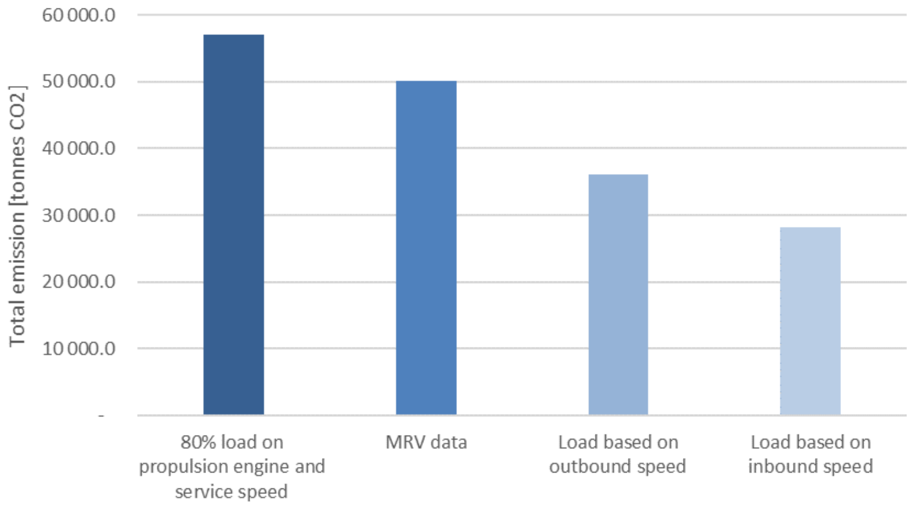

Figure 4.4. Direct CO_2 emission from 113 of the inbound ships (larger than 5000 GT). The MRV data is based on fuel statistics from the ships, while the other staples are calculated values.

The MRV data includes very few ships transporting bulk or break-bulk cargo as can be seen in figure 4.5. However, the ships in the MRV data seems to represent a large fraction of container and tanker ships. Considering the MRV data as the benchmark, the comparison of emission calculations using different source data in Figure 4.5. indicates that container ships in general:

1. do not cruise at service speed, or
2. that some ships cruise at service speed while other slow down more.

This is also what the results in section 3.2 indicates.

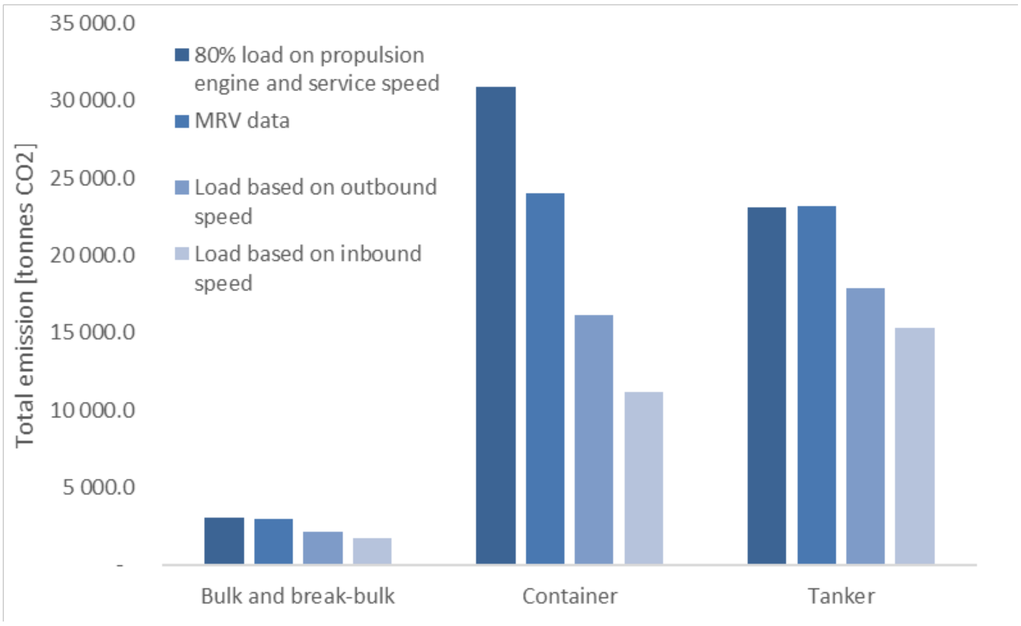

Figure 4.5 Direct CO_2 emission from 113 of the inbound ships (larger than 5000 GT), for different ship type categories. The MRV data is based on fuel statistics from the ships, while the other staples are calculated values.

5 Concluding remarks

Overall the results in this study show that there could be emission reductions in both the port area and at sea from more efficient port logistics and an improved port framework. The actual effects from the digital information flow and an improved framework has not been possible to investigate in this study, only plausible scenarios are exemplified and calculated. The results show that the potential of emission reduction at sea is much greater than the emission reduction potential at berth and at anchor. This demonstrates the importance to also include effects outside a geographical area, such as a port, since this type of action also impact the emission outside the port (Baumann & Tillman, 2004). It is also important to note that all figures presented in this study only indicate a potential corresponding to a pre-defined scenario. The real effects still need to be evaluated.

This study only evaluates the tailpipe emissions from ships and thus excludes any emissions from for example resource extraction and refinery processes associated with fuel used, so called upstream activities. This generalization is made since all ships are assumed to be driven with the same type of fossil fuels and we are focusing on the greenhouse gas emissions. Under this assumption the up-stream emissions will be in the same range for different scenarios. However, if one would use different types of fuels, such as biofuels or electricity it would also be important to include the up-stream emissions.

5.1 Potential of emission reduction due to reduced speed at sea

Both the MRV- and the AIS-data indicates that many container ships already slow steam, while tanker ships and bulk/break-bulk ships cruise closer to their service speed. This is probably because container ships already have guaranteed slot times. Bulk and tanker ships do not have guaranteed slot times today. It will therefore probably be small or no slow steaming effects by only introducing the *Port Activity App* for bulk and tanker ships. However, as a follow up initiative to the *EfficientFlow* project, the *F*ramework project will change port regulations, means of collaboration between ships-port-terminal and further development of the app in order to allow slot times also for these ship segments.

The emission reduction potential calculated in this study for speed reductions for container ship, due to digitalization and an improved port framework may be questioned. Since many container ships are already slow steaming, the emissions from container ships are probably lower than indicated in this study, resulting in a lower abatement potential. Furthermore, there are also other effects on the fuel consumption that will become more important when the ships are already slow steaming, as for example lower efficiency of the main engine, which are not included in this study. This should be further evaluated in a follow up study.

Another issue is that the calculations do not cover over-capacities in the system. However, if there is no over-capacity more ships would need to be built in order to maintain the same amount of transport-work. It is also important to note that this study doesn´t include any rebound effect, i.e. if the fuel consumption drops the transport-work will be cheaper, which could imply more transport. These are large scale effects and are not of high importance from the perspective of single ports.

5.2 The emission models

The results from the questionnaires and the literature review indicates that the auxiliary power model used in the inventory overestimate the power demand for container and break-bulk ships at berth (and thereby also the emissions). For tanker ships the auxiliary power model instead seems to underestimate the results. However, it is difficult to draw any conclusion about absolute values. The questionnaire could be biased, e.g. the number of respondents was small and could be unrepresentative for the whole population. In the future it would be better to increase the sample size, and to extract the data of power consumption onboard rather than interview technical staff.

However, three things were clear when comparing the results from the questionnaires and the literature with the auxiliary power model:

1. The variation in power demand at berth is large, also for ships with the same characteristics.
2. In general, power demands for unloading tankers and break-bulk cargo ships are much higher than the power demand during idling conditions, this is especially true for tanker ships. The model only partly includes this difference for tanker ships. This study therefore presents an alternative way to interpret the results.
3. The power demand at anchor and berth for large container ships is overestimated in the auxiliary power model (TEU<2000). However, the container ships arriving to the Port of Gävle are relatively small and the results in the emission inventory for the Port are not affected by the overestimations.

The MRV-data contains information about average fuel consumption for ships larger than 5 000 GT. Many of the calls in the Port of Gävle is made by ships that are smaller than 5 000 GT, which make it difficult to draw any conclusion from the comparison. Nevertheless, the results are still in the same range as the modeled results, which indicates that the large emission reduction potential for an improved information flow is at sea and not directly in the port.

One advantage of the MRV-data is that it contains the information about real fuel consumption for a specific ship. The model only assumes the fuel consumption based on the installed power. Another advantage of the MRV data is that they also include an approximation of the transport work (tonnes-km). However, the MRV-data are new, and some data need to be removed or modified in order to be used.

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Appendix A – Areas outside the port

The area outside the port has been divided into 6 different zones. Zone 1 and 4 represent the inlet channels to the ports, Gävle and Karskär. There is a speed restriction in these areas. Zone 2 and 3 and represents zones where the ship adopting their speed when arriving or leaving the port. Zone 6 is an area where the ships are expected to go cruise at their desired speed. Zone 5 is not a part of the port of Gävle, all paths from and to this port is therefore excluded from the results.

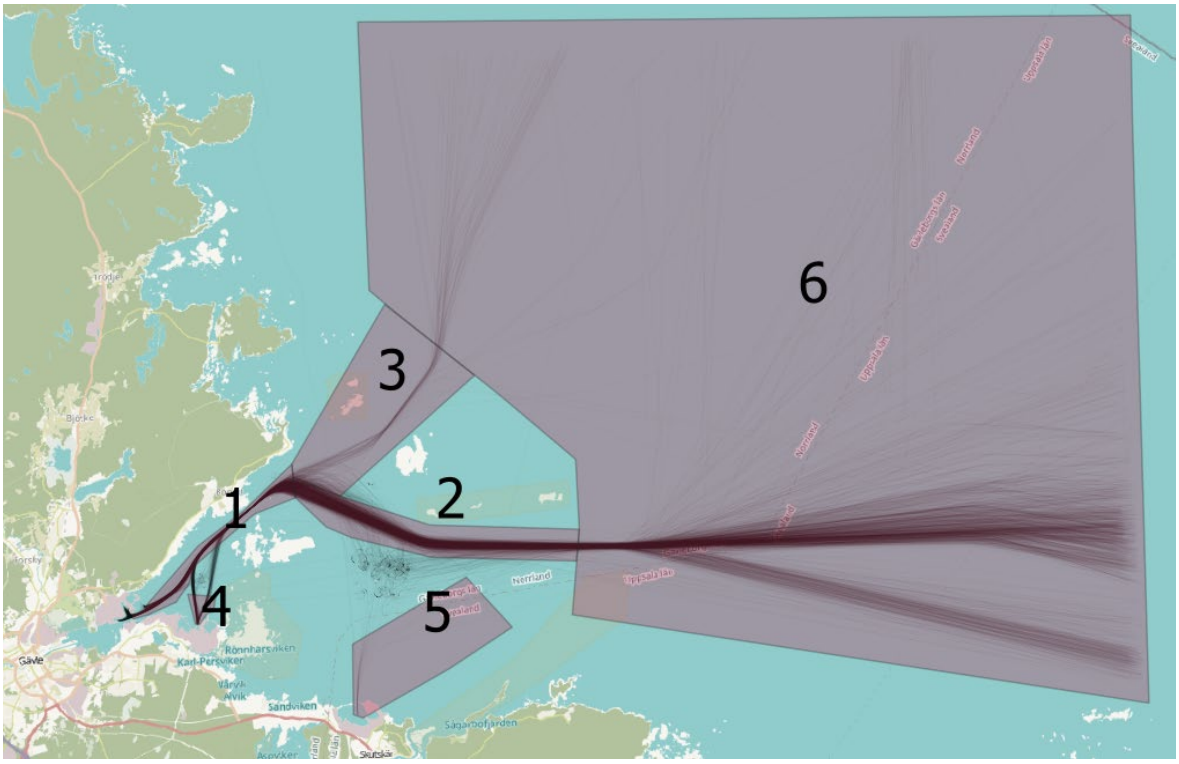

Figure A.1. Illustrating the categorization of the area outside the Port of Gävle.

Appendix B – Ship parameter relations

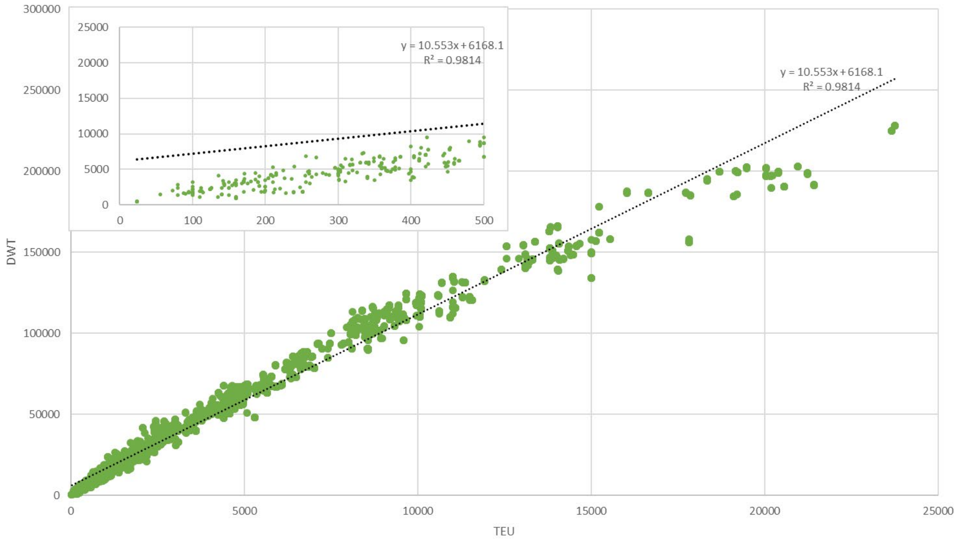

Figure B1 – Linear relation between deadweight tonnage (DWT) gross tonnage (GT) and twenty-foot equivalent unit (TEU), include all active container ships in the database (IHS Markit, 2019). In the upper left corner, it is possible to see that m-value in the linear equation is a bad estimate for the low range TEU.

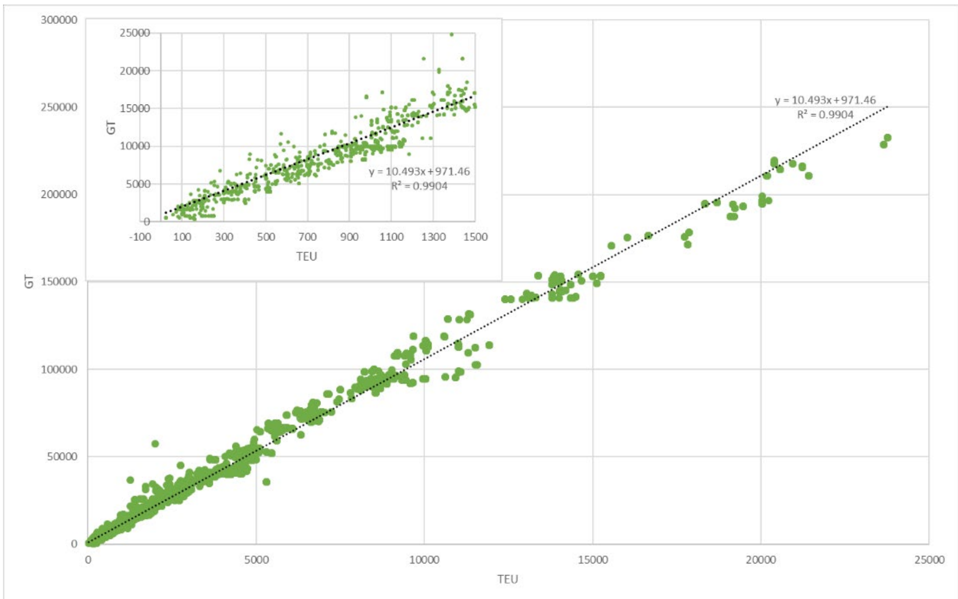

Figure B2 – Linear relation between gross tonnage (GT) and twenty-foot equivalent unit (TEU), include all active container ships in the database (IHS Markit, 2019).

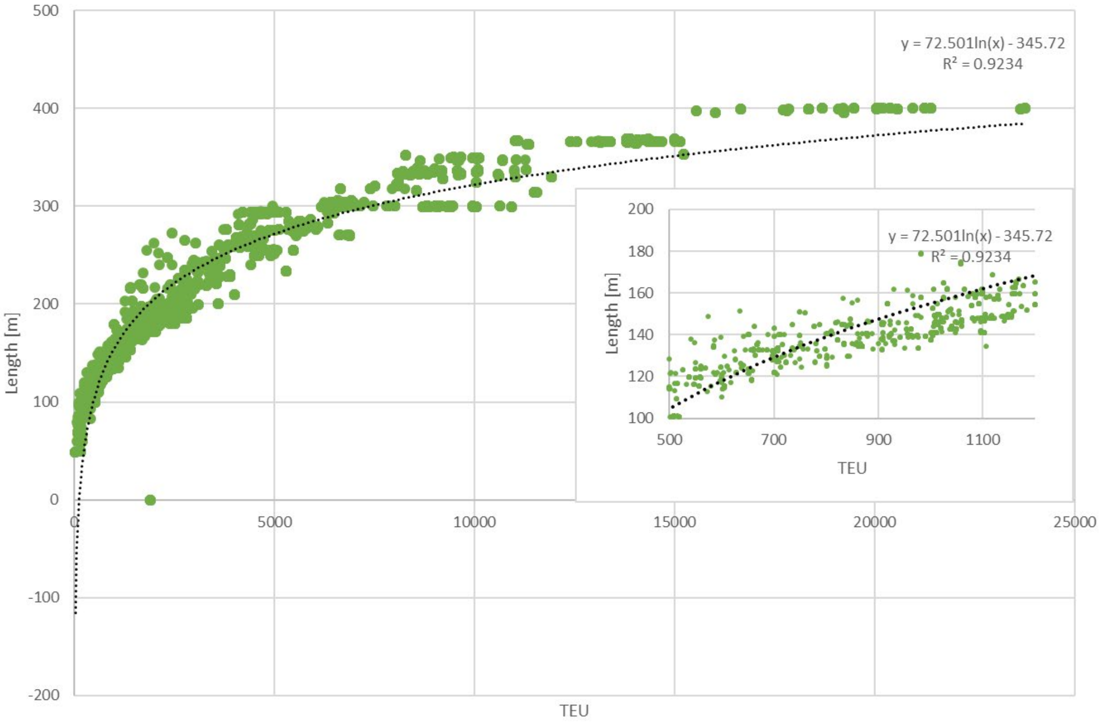

Figure B3 – Logarithmic relation between length (m) and twenty-foot equivalent unit (TEU), include all active container ships in the database (IHS Markit, 2019).

Appendix C – Sea distance table

Table C1. Assumed distances. A distance in the table is the distance from last port (see port code) to the Port of Gävle.

Port Code	Vesseltracker [NM]	Sea route NM [NM]	Distance used in this study [NM]
NLVLI	1 002		1 002
PLSZZ	550		550
FITKU	199		199
BEGNE	1 020		1 020
FIHMN	354		354
EEKND		340	340
PLSWI		510	510
FIHEL	284		284
FITOR	397		397
DKVEJ	663		663
LVRIX	344		344
SEOXE	240	229	240
FIUKI	127		127
SEKLI		303	303
LVLPX	316		316
EESLM	363		363
EERMS		278	278
SESSR		0	0
EEPRN		304	304
SEHAD		596	596
FIKOK	302		302
LVSKU	340		340
LVSAL		323	323
SESOL		420	420
DKKOG	521		521
DKSTP		519	519
SEKAN	418	409	418
NLMOE	974		974
PLGDN	450		450
NORAF	758		758
SEGVX	0		0
FIRAU	136		136
SESOR	139		139
LTKLJ	369		369
BEANR	1 038		1 038
NOFNE		1657	1 657
SESLI	251		251
DKAAB		642	642
NLRTM	941		941
RUULU	393		393

SEVBY		256	256
GBSOU		1 146	1 146
GBFOY		1 268	1 268
DKKOL	661		661
PLGDY	442		442
DEBRV	749		749
RUKGD	447		447
RULED	434		434
NLVLA		951	951
SEPIT	343		343
SEROR		283	283
SESAE	0		0
DEWIS	588		588
SELLA	375		375
FIPOR		136	136
EEMUG	274		274
PTFDF	1 916		1 916
SEAHU		425	425
FIKTK	341		341
SESDL	132		132
NLTNZ	1 011		1 011
SEOSK	300		300
SEBRO		699	699
FIPRV	311		311
SEGOT	661		661
FIOLK		131	131
SESOE	249		249
NOELN		1 159	1 159
GBKLN		1 032	1 032
LVVNT	269		269
DKGRE		609	609
NOBVK		754	754
SEIGG	86		86
SEHUS	212		212
FIKAS	182		182
SESTO	165		165
SEHLD		209	209
SEUME		217	217
NOHEY		1 385	1 385
FIOUL	398		398
NLDZL		808	808
SESTK		111	111
DEHAM	705		705
DKAAR	631		631
GBTHP	1 038		1 038
DEKEL	613		613
SENRK	265		265

SEHBV		165	165
AEFJR		6 981	6 981
SELYS		695	695
NLAMS		928	928
#N/A			0
GBFXT		995	995
SEDEG		349	349
DKCPH	525		525
DKFRC	658		658
FINLI		199	199
FRURO		1 219	1 219
GBGRG	1 148		1 148
GBTEE		1 040	1 040
DKKAL	631		631
GBLON		1 058	1 058
GRLRY		4 032	4 032
NORVK		1 311	1 311
EETLL	265		265
GBBLY		1 107	1 107
DKSKA	678		678
USSAV		4 573	4 573
SEOST	138		138
EEVEB		277	277
DERSK	557		557
SEUDD	703		703
GBMLF		1 428	1 428
SEHOG		558	558
NOFRK		749	749
DEBRB		663	663
USBTR		5 659	5 659
SEHAN		67	67
DENHA		10 286	10 286
SEOER	230		230
FIMHQ		110	110
EEPLA		246	246

Appendix D – Updated emission inventory results for 2017 and 2018

Table D1. Updated emission inventory results in tonnes (Jerksjö & Parsmo, 2018). The emissions are updated with some of the information archived from the questioner conducted in this study.

År	Hamnavsnitt	CO2	CH4	N2O	NOX	PM*	SO2
2017	Bulk	2 800	0.04	0.12	39	0.8	1.8
	Container	6 200	0.08	0.25	88	1.6	3.9
	Energi	3 500	0.12	0.13	39	0.8	2.2
	Karskär	750	0.01	0.03	10	0.2	0.5
	Kemi	1 100	0.01	0.04	15	0.3	0.7
	Alla	**14 400**	**0.26**	**0.57**	**191**	**3.7**	**9.0**
2018	Bulk	2 800	0.04	0.12	38	0.8	1.7
	Container	5 300	0.07	0.22	76	1.4	3.4
	Energi	2 500	0.11	0.10	29	0.6	1.6
	Karskär	1 200	0.01	0.05	16	0.3	0.7
	Kemi	900	0.01	0.03	12	0.2	0.5
	Alla	**12 700**	**0.24**	**0.51**	**170**	**3.3**	**8.0**

* Particulate matter emissions have change much compared to the results in (Jerksjö & Parsmo, 2018) since the emission factors at berth have been modified.

Appendix E – Outliers in the MRV data

Another way to identify the outliers is illustrated in Figure E.1. This figure compares the total emission in the MRV data with the emissions if one assumes that the ships use all engines, 100 % of the totally installed power for 8760 hours a year. This assumption is of course not reasonable. However, some ship emits more in the MRV data than they would have if they operated at "full power" the entire year (the values above 100% in the figure). This could of course also be a consequence of the fact that the specific fuel consumption or the installed power of the auxiliary engine is underestimated in the model. The total emissions in the MRV data are only based on the time when the ships are in EU.

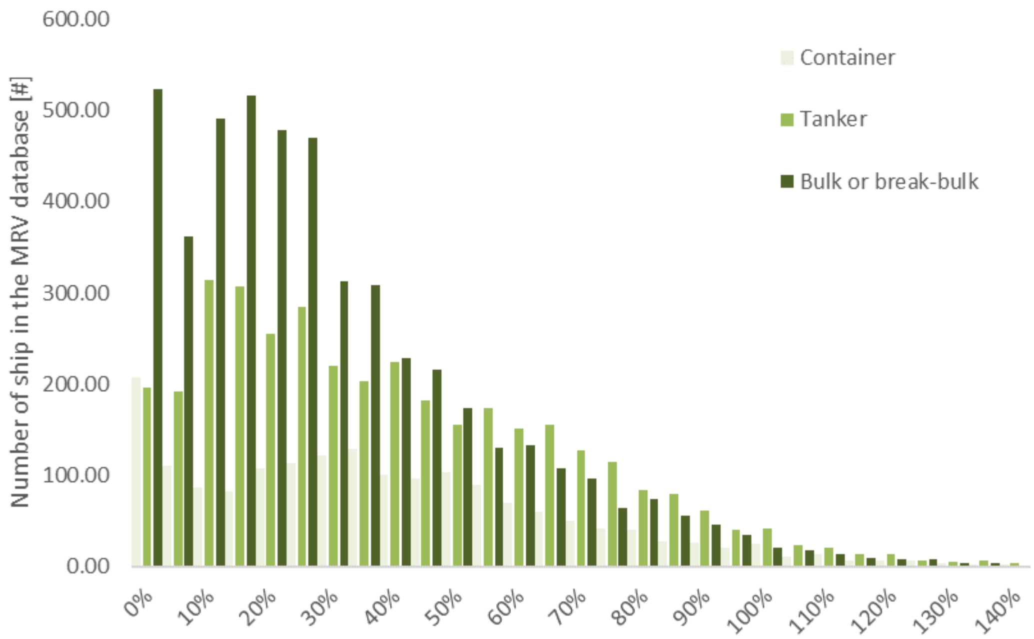

Figure E.1. Frequency distribution: The ship's total emission in the MRV database divided by CO2 emission when main and auxiliary engines operating at 100 %, 8760 hours a year.

Appendix E – Questionnaire templet

About this survey

We are working on increased knowledge and improved energy and emission models for ships. The work is a part of a research project made by IVL Swedish Environmental Research Institute on behalf of Port of Gävle. This survey has been sent to you since your organisation operates and/or takes care of the management of several vessels that has called Port of Gävle recently.

- We hope that either you or someone else in your organisation can enter ship specific data for one or several vessels in your fleet, preferably vessels calling Gävle. The data could either be actual data for a specific port call or typical data for a vessel or vessel type based on your experience. In case that you rather would like to send us the requested information in another form than below you are most welcome to send us information in other formats.

- The information gathered in this survey will only be used in aggregated form and/or anonymized form. Data for your specific organisation will not be published or made available to anyone outside IVL Swedish Environmental Research Institute. All information gathered will be handled in line with GDPR.

- We are gathering information on as many vessels as possible. So the more vessels you would like to add in below table the better statistics we would end up with. But we are of course also happy with one or two vessels.

Many thanks in advance!

Request for information - Research project related to auxiliary consumption

Organisation	
Name (of person submitting the information)	
E-mail	-

	Average figures during the specific activity	*Example*	Ship A	
	IMO Nr	*12345678*		
	Ship Name	*Sea Wind*		
	Number of similar sister vessels with the same characteristics	*2*		
A.E	Auxiliary engine capacity being used **sailing at sea during loaded** condition?	*-*		kW
Shaft power	How much power is produced from shaft power generator at sea during loaded condition?	*700*		kW
A.E	Auxiliary engine capacity being used **approaching port during loaded** condition?	*300*		kW
Shaft power	How much power is produced from shaft power generator at sea during loaded condition?	*400*		kW
A.E	Auxiliary engine capacity being used sailing at sea during **unloaded** (no cargo) condition?	*1 900*		kW
Shaft power	How much power is produced from shaft power generator at sea during unloaded condition?	*-*		kW
A.E	Auxiliary engine capacity being used during port **manouvering**?	*500*		kW
Shaft power	How much power is produced from shaft power generator during port manouvering?	*400*		kW

A.E	How much of installed auxiliary engine capacity being used at berth during **unloading** of cargo?	-		kW
Shaft power	How much power is produced from shaft power generator during unloading of cargo?	*2 500*		kW
A.E	Auxiliary engine capacity being used at berth during **loading** of cargo?	*300*		kW
Shaft power	How much power is produced from shaft power generator during loading of cargo?	-		kW
A.E	Auxiliary engine capacity being used at berth during **hotelling**?	*300*		kW

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