METEOROLOGY No. 153, 2013

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Adaptation of Airviro and application in the Baltic Sea

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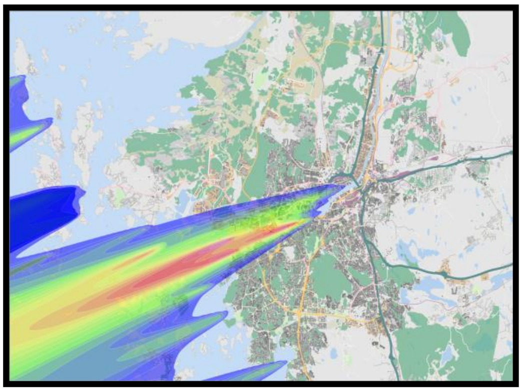

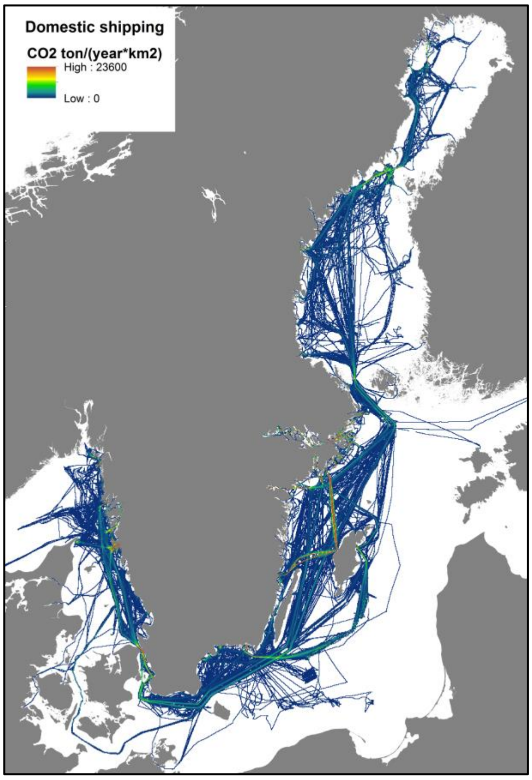

Front page
Right: Emission of CO_2 from Swedish domestic shipping year 2011.
Top left: Dispersion of NO_x from shipping 18 Aug 2010, 04-05
Bottom left: Chimney, © Sjöfartsverket

ISSN: 0283-7730

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Preface

This project was managed by SMHI (Swedish Meteorological and Hydrological Institute) in cooperation with SMA (Swedish Maritime Administration). Also, PhD students and researchers at Chalmers Lighthouse research centre have contributed to the project. The consultancy firm APERTUM IT AB has been responsible for large parts of the software development. The Swedish Environmental Protection Agency has financed the work of SMHI and has also been part of the project steering committee.

Summary

In many countries, shipping is an important contributor to emissions of air pollutants. For sulphur, shipping is nowadays often considered the most important source of emissions. Shipping also emits significant amounts of nitric oxides, particles and volatile organic compounds. From a climate change perspective, shipping is an important source of green house gases, and also contributes significantly to emissions of short lived climate pollutants, such as soot. Emissions to air from shipping have impact on air quality, climate change and acidification.

To understand the impact of shipping emissions on the environment, human health and the climate, it is necessary to quantify, map and describe the emissions. Due to lack of data and knowledge, estimates of emissions from shipping have always been very uncertain. One reason to the uncertainties has been difficulties to locate the large number of ships travelling at sea, another reason has been uncertainties regarding emission factors. Since year 2007 AIS (Automatic Identification System) has been a standard for positioning and identification of ships at sea. AIS is complementary to radar and describes location, speed and identity of ships with high precision. This development creates new possibilities to improve information regarding emissions.

A system that makes use of data from AIS to estimate emissions from shipping has been developed. The system allows emissions to be calculated for shipping based on the latest knowledge regarding emission factors and makes use of ship specific data as far as possible. The general motivation is to improve the quality of estimations of emissions of air pollutants, green house gases and SLCP (Short Lived Climate Pollutants) as well as to provide a flexible tool to be used for related questions. The system is an integrated part of the Air Quality Management system Airviro.

The developed system has been applied for the Baltic Sea. This application of the system is called Shipair. Shipair contains AIS information for the whole Baltic Sea, and the North Sea up to the southern coast of Norway. The AIS information comes from the international AIS database operated by HELCOM. Besides AIS, the Shipair application also makes use of a web service operated by Swedish Maritime Administration to acquire and estimate ship specific parameters needed for emission calculations.

The Shipair application of Airviro has been validated by comparing calculated and measured fuel consumption for a small number of ships. The differences between measured and calculated fuel consumption are below 10 % for the individual ships, which is considered well within what could be expected. Comparisons have also been made with results from other ship emission inventories. The results are similar to those of the STEAM2 model published by FMI (Finnish Meteorological Institute), which are based on a similar methodology. Emissions used by from EMEP (Environmental Monitoring and Evaluation Programme) on the other hand can be seen to give significantly higher emissions than both Shipair and STEAM2. Finally, indirect verification has been made by comparing results from dispersion models with concentrations measured in ambient air. Due to a large number of other emission sources that dominate the concentrations in ambient air, these results can confirm that the Shipair calculations are reasonable, but does not provide any closer evaluation of the quality of the results.

To investigate if estimates based on fuel statistics, currently used in international reporting of Swedish shipping emissions, are reasonable, a comparison has also been made with estimations based on national fuel statistics. The results indicate that estimations based on the fuel statistics could be underestimating the emissions of CO_2 from domestic shipping with approximately 50 %.

Sammanfattning

I många länder så är sjöfarten en viktig källa till emissioner av luftföroreningar. Nuförtiden anses sjöfarten ofta vara den viktigaste källan till utsläpp av svavel. Sjöfarten släpper även ut betydande mängder av kväveoxider, partiklar och flyktiga organiska ämnen. Ur klimatperspektiv så är sjöfarten en viktig utsläppakälla för växthusgaser och bidrar även till utsläppen av kortlivade klimatpåverkande ämnen, såsom sot. Utsläpp till luft från sjöfart har påverkan på luftkvalitet, klimatet och försurningen av våra vattendrag.

För att förstå vilken påverkan sjöfarten har på miljö, människors hälsa och klimatet, så är det nödvändigt att kvantifiera, kartlägga och beskriva dess emissioner. På grund av avsaknad av data och kunskap så har beräkningar av sjöfartens emissioner alltid varit mycket osäkra. En orsak till osäkerheterna har varit svårigheten att lokalisera och identifiera det stora antal fartyg som rör sig på våra vatten. En annan orsak har varit svårigheter och brist på kunskap kring emissionsfaktorer för fartygsmotorer. Sedan år 2007 har AIS (Automatic Identification System) varit en standard för att positionera och identifiera fartyg till sjöss. AIS är ett komplement till radar och beskriver enskilda fartygs position, fart och identitetmed hög precision. Denna utveckling har öppnat upp nya möjligheter att förbättra information om sjöfartens emissioner.

Ett system som använder AIS för att beräkna fartygsemissioner har utvecklats. Systemet möjliggör beräkning av emissioner från fartyg utifrån den senaste kunskapen kring emissionsfaktorer och tar hänsyn till fartygsspecifika uppgifter så långt som möjligt. Drivkraften för denna utveckling är att förbättra kunskapen om sjöfartens påverkan på miljö, människors hälsa och klimatet, samt att erbjuda ett flexibelt verktyg för frågor relaterade till utsläpp av luftföroreningar, växthusgaser och kortlivade klimatpåverkande ämnen. Det utvecklade systemet är en integrerad del i luftvårdssystemet Airviro.

Det utvecklade systemet har använts för Östersjön. Denna applikation av systemet kallas för Shipair, vilket avser såväl Airviro som de datakällor som används i denna uppsättning av systemet. Område som täcks in omfattar Östersjön och Nordsjön upp till Norges södra kust. AIS-data hämtas från den databas med alla Östersjöländers AIS information som administreras av HELCOM. Vid sidan av AIS-data använder applikationen Shipair även en webbtjänst från Sjöfarsverket för att inhämta och uppskatta fartygsspecifika uppgifter som behövs för emissionsberäkningarna.

Systemet har validerats genom att jämföra beräknad och uppmätt bränsleförbrukning för ett mindre antal fartyg. Jämförelsen visar på god överensstämmelse mellan beräknad och uppmätt bränsleförbrukning, med skillnader under 10 % för individuella fartyg. Jämförelser har även gjorts mot resultat från andra inventeringar av sjöfartens emissioner inom Östersjön. Resultaten överensstämmer väl med publicerade resultat från modellen STEAM2 utförda av FMI (Finska Meteorologiska Institutet). Denna inventering baseras på en liknande metod som Shipair. Större skillnader ses vid en jämförelse med de emissioner som används inom EMEP (Environmental Monitoring and Evaluation Programme), där EMEPs emissioner är betydligt högre än de som beräknas med Shipair. Slutligen genomfördes även indirekt verifiering av resultaten från Shipair genom att jämföra resultat från spridningsmodeller med uppmätta halter i omgivningsluft. På grund av ett stort bidrag från andra källor, vilka döljer signalen från sjöfarten, kunde inga mer detaljerade slutsatser dras rörande resultatens kvalitet. Jämförelsen bekräftade endast att de beräknade emissionerna inte är signifikant överskattade.

En jämförelse har även gjorts för att undersöka om emissioner för Svensk inrikes sjöfart beräknade utifrån bränslestatistik är rimliga. Resultaten indikerar att utsläppen från inrikes sjöfart beräknade utifrån bränslestatistik kan vara underskattade med ca 50 %.

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1 Background

Shipping is an important contributor to emissions of air pollutants. Significant amounts of sulphuric oxides, nitric oxides, particles and volatile organic compounds are emitted. From a climate change perspective, shipping is an important source of green house gases. Lately there has also been a lot of focus on short lived climate pollutants, such as soot, for which shipping is considered one of the most important sources. It is recognized that air pollutants, especially soot, have an impact on the climate change. Black soot particles have a positive green house gas potential, while e.g. sulphate particles partly reflect the incoming sunlight and thus reduce the solar radiation reaching earth surface, causing a cooling effect. Besides providing input to describe air pollution and its impact on environment and health, a detailed description of emissions from shipping can therefore also contribute to more detailed scenarios from climate models, including short term forcing from air pollutants.

Currently being the main source of sulphur emissions, shipping is an important cause to the acidification problems in northern Europe. While sulphur content in fuel used by land-based emission sources has been strictly regulated for a long time, shipping is first now beginning to catch up. IMO (International Maritime Organisation) has introduced new regulations limiting the sulphur content gradually all over the world. The Baltic Sea has been identified as a SECA (Sulphur Emission Control Area), making the regulation regarding fuel content especially strict. It is of interest for environmental authorities to monitor the reduction in SOx emissions and evaluate if the expected reduction in sulphate particles can be observed in ambient air.

The health impact caused by shipping emissions mainly relates to particles. While the emissions of sulphate particles can be expected to drop as sulphur content in fuel is reduced, the soot particles and other particle fractions generated in the combustion process will still cause a health impact. The impact from shipping is relevant both on regional scale, as a contributor to background concentrations of particles, and on local scale in port areas where shipping can cause a significant impact on nearby population.

Since shipping is one of the main emitters of nitrogen oxides around the Baltic Sea, it can also be regarded as a significant contributor to the eutrophication problems.

To understand the impact of shipping on the environment, human health and the climate, it is necessary to quantify, map and describe the emissions to air. Historically, there have been large uncertainties when trying to quantify the emissions. This has been caused by lack of information regarding the extent of traffic, the fuel used, and emission factors of the ship engines. It has also been difficult to describe the spatial distribution of the emissions and their variation in time.

During the last years the AIS system (Automatic Identification System) has been developed and taken into operation. The system constitutes a standard for positioning of ships in Europe, and is a complement to RADAR. The AIS system makes use of IMO-numbers (identity), position, speed etc. being sent with short intervals over VHF radio. The AIS system provides a vast amount of ship specific information. Besides the information directly provided by AIS, the identity of the ships can be used to match with other sources of information.

2 Aim

The general objectives of this project are to:

- Improve the basis for regular follow-up and evaluation of the impact from ship emissions on air quality.
- Improve the estimations of green house gas emissions from shipping.
- Improve the tools available for planning and evaluation of measures to reduce the impact of shipping on air quality.

More specifically, these objective is to develop a technical infrastructure for estimating shipping emissions using bottom-up methodology based on AIS-data and known properties for individual ships.

3 Methodology

The methodology to calculate ship emissions has been integrated as a new component in the EDB-module (Emission DataBase) of the air quality management system Airviro[1]. The Airviro system is owned by SMHI together with Apertum IT AB, and has been used for air quality management in Sweden and in several other countries since the early nineties. By using the Airviro system as basis for the development, the new methods for ship emissions are set in a context that provides a wider functionality than would be possible otherwise. For example, the methods for ship emissions are fully integrated into the Airviro web framework making it possible to administrate the ship inventory, perform emission calculations, present results on maps etc. This report will not cover the whole range of functionality provided by the Airviro system, but will focus on the more scientific side of ship emission calculations and how ship emission sources are managed in the system.

Ship emission calculation using Airviro is dependent on access to positioning data from AIS (Automatic Ship Identification System), as well as technical properties for the ships. AIS-data can be collected directly from receivers, or from other sources such as databases or networks of AIS-receivers. Ship properties can for example be transferred from databases maintained by national authorities or commercial companies. In Figure 1, the different components necessary to perform calculations of emissions from shipping are shown. It can be seen in the figure that ship properties are acquired from external sources. The framework is not restricted to any special source of information and can also make combined use of multiple source of information. An important part of the logic connected to estimation of shipping emissions is connected to the estimation emission factors and assumptions related to how the ships are operated. Currently, emission factors are included in the external database of ship properties that is used (Ship Emission Information, operated by Swedish Maritime Administration). This data-source also includes basic assumptions regarding for example the expected load on auxiliary engines during different operational modes.

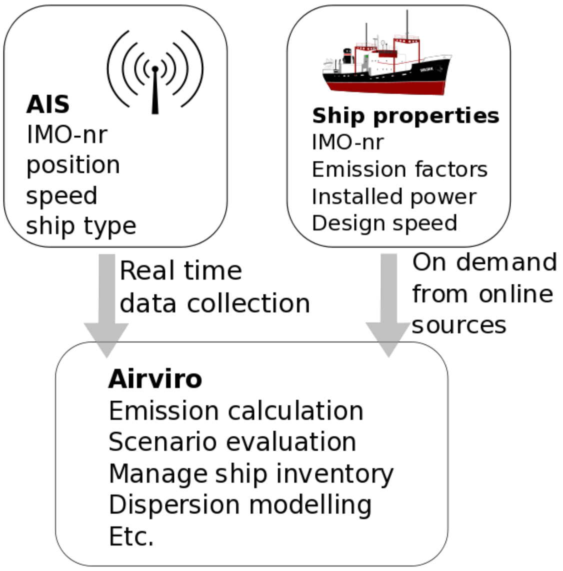

Figure 1. The different components necessary to calculate emissions from shipping.

[1] www.airviro.smhi.se

3.1 Tracing of ships using AIS

3.1.1 What is AIS?

AIS (Automatic Identification System) serves as a complement to radar at sea. It uses VHF-radio to transmit positions for ships equipped with AIS-transponders. Positions are transmitted with very short intervals (seconds), and static ship properties are sent containing information on MMSI (AIS transponder identity), IMO, name, ship type, destination, origin etc. Anyone using a VHF-receiver can listen to the AIS-messages. To use the data and for example plot the ship trajectories on a map, it is necessary to interpret the messages.

3.1.2 AIS Coverage

Not all ships have AIS-transponders installed. Since 2007 the following vessels are obliged by law to have AIS-transponders:

- All passenger ships in international traffic
- Other ships > 300 GT in international or domestic traffic

Ships with more than 12 passengers are defined as passenger ships. Many smaller ships such as tug boats, guide boats, police, fishing and some leisure boats, have installed AIS-transponders voluntarily. It could be assumed that today, all ships that are relevant for estimations of emissions are found in AIS.

Due to radio shadow and reach of the AIS-system, it is not possible to receive all AIS-messages using a single receiver. To get a complete picture of all shipping, networks of receivers are used. Such networks can for example be found in many countries, and even along the coasts of India and China. In the Baltic, there is also an international network organized through HELCOM[2] that contains AIS-data from national networks in the different member countries. This data is stored by HELCOM and made available to the maritime administrations of the HELCOM countries. The whole Baltic and the North Sea along the coasts of Denmark and Sweden are covered by the HELCOM AIS-network. A detailed presentation of the coverage is given in Figure 2, where the extent is visualized by emissions of nitrogen oxides during April year 2010. As can bee seen from the scattered emissions along the coast of Norway, the AIS coverage in this area is incomplete.

[2] HELCOM (Helsinki Commission), is an organization for countries around the Baltic Sea to cooperate for an improved environment.

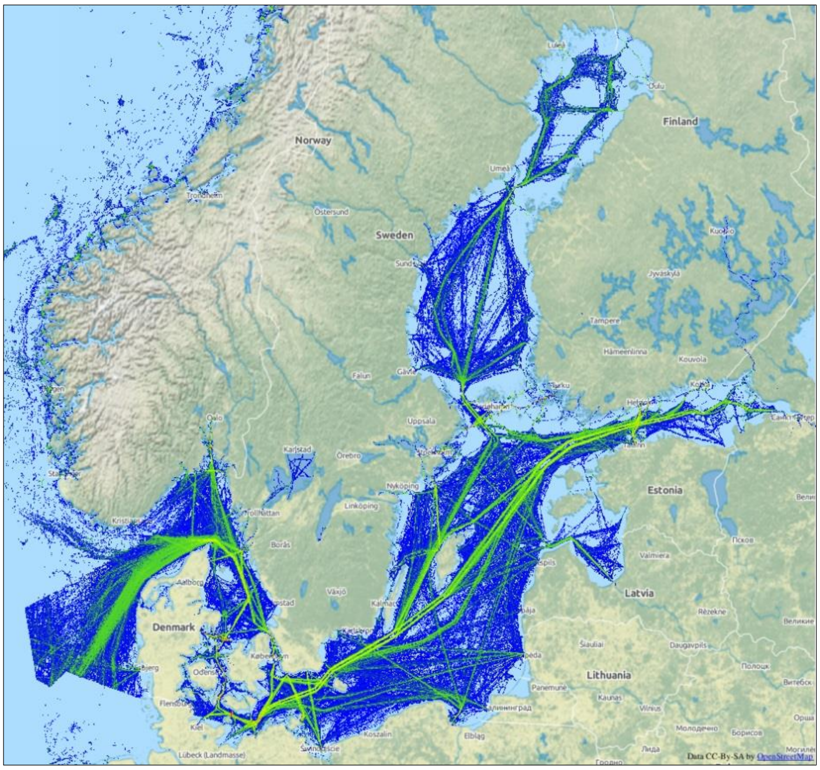

Figure 2. Coverage of the HELCOM AIS network.

3.1.3 Representation of ship trajectories

The coordinates sent out by AIS are latitude, longitude in the geographical coordinate system WGS84. Airviro needs a metric coordinate system to store the positions and therefore the coordinates are transformed into a chosen spatial reference system. For the application of Airviro in the Baltic Sea, the Swedish projection RT90 2.5 gon V has been chosen and gives a good representation of the whole area.

Ships positions are stored as time-series using a high performance time-series database. This is of vital importance when performing calculations since the extremely large number of ships and the high temporal resolutions make the amount of computations considerable.

All positions are not stored in the time-series database. At the time being, the resolution is limited to 5 minutes. Between the stored positions the ship trajectory is interpolated linearly. This resolution was chosen to limit the amount of data, and thereby the time needed to perform a calculation, but at the same time allow usage of the emissions when performing e.g. dispersion modelling on urban or even local scale. Considering that most air quality models use a time resolution of 1 hour, this should be sufficient.

Besides the X and Y coordinate of the ship a third time-series is stored representing the travel status. This parameter includes information regarding operational mode, as well as route origin and route destination. Further explanations are given in sections 3.2.2 and 3.2.3.

3.2 Processing of AIS-data

3.2.1 Pre-processing

Positions from AIS often contain errors and it is therefore necessary to validate that they are reasonable before using them for emission calculations. An example of this is frequent reports at coordinate 0º, 0º, which could possibly be caused by the GPS-equipment not having contact with satellites. Another example is rapid changes in position that imply an unreasonably high travelling speed. Such errors are quite easy to identify, and all unreasonable positions are eliminated by a pre-processing routine.

In theory, the intervals with which AIS positions should be reported are very short. However, it is quite common that messages are missing which may cause gaps of several minutes or even more. In Airviro, positions are stored at even 5 minute intervals. Since it is possible that no message is available for that exact time, an interpolation between the messages closest in time is performed before storing positions in the database.

3.2.2 Operational mode

The emission rate for a ship depends heavily on the power output. The power output in turn, depends on how the ship is operated. For cruising ships, there is a direct relationship between power output and speed, while for manoeuvring ships (i.e. accelerating or decelerating) this is not the case. Other modes of operation that can be distinguished are hoteling (i.e. berthed) and when the ship is connected to on-shore power supply.

The operational mode for a ship is decided from the ship's speed and position. The criteria for each operational mode are presented in Table 1. The ship speed is calculated based on the positions from the AIS, i.e. the speed given directly in the AIS-signal is not used.

Due to uncertainty in the GPS equipment on-board the ship, the positions in the AIS signal will indicate small movements also when the ship is moored. Because of this, if a ship moves less than 10 m between two consecutive positions (given each 5 minutes), the ships is considered not to be moving.

Besides the speed, the location is also used to determine the operational mode. It is assumed that all ships need to manoeuvre before entering or leaving port. Therefore, manoeuvring areas have been defined for all known ports. The manoeuvring areas are represented by polygons and saved in a standard GIS format. Manoeuvre areas can be defined for any areas where it is known that ships use a lower speed, accelerate and decelerate. For ships at berth connected to on-shore power supply, the auxiliary engines are assumed to be switched of completely, and no emissions are generated. To distinguish ships at berthed with on-shore power supply from berthed ships that are using the auxiliary engines, so called OPS areas have been defined. They are represented by polygons similar to the manoeuvring areas, but are stored separately. Examples of manoeuvring and OPS areas can be seen in Figure 3.

A code for the operational mode is stored as part of the status time-series that is assigned for all ships. The assignment of operational mode is run automatically as a post-processing route. The post-processing is scheduled to run with short intervals with some overlap in order to capture all ship tracks. The operational mode can be retrieved from the status time-series for historical data, and conditions can be set for the operational mode in algorithms used for the emission calculations, as well as in the conditions set for when to calculate emissions (i.e. a calculation can be done that only includes emissions during a specific operational mode).

Table 1. Criteria for operational modes.

Operational mode	***Criteria***
Manoeuvring	The ship is moving and is located within a manoeuvring area.
Hoteling	The ship is not moving and is not within an OPS area, i.e. the ship is anchored or at quay.
OPS	On-shore Power Supply. The ship is not moving and is located within an OPS area.
Cruise	Default. The ship is moving and not located within a manoeuvring area.

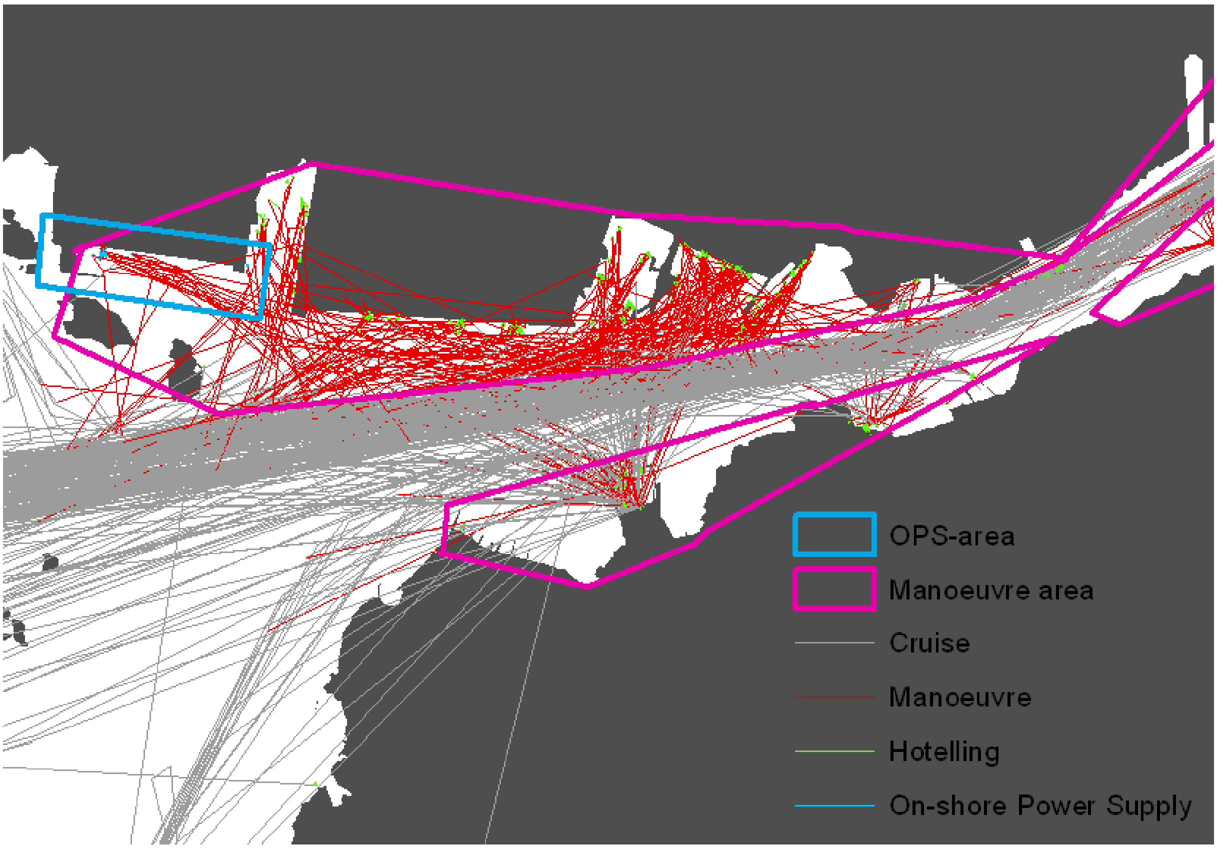

Figure 3.Different operational modes in the Gothenburg port area. The modes are represented by different colours on the ship trajectories. The manoeuvre areas are defined to allow the ships passing by in the middle of the port inlet to be classified as cruising. The trajectories that cross the border of a manoeuvre area polygon are classified according to the position of the midpoint of the trajectory, i.e. if the trajectory midpoint is inside the manoeuvre area the operational mode is set to manoeuvre otherwise it is set to cruise.

3.2.3 International and domestic traffic

For some purposes it is interesting to distinguish emissions caused by ships on specific routes. One such example is to distinguish between international and domestic traffic which is necessary when reporting of emissions under CLRTAP[3] and UNFCCC[4].

In Airviro, a route, i.e. the voyage between two stops in port, is classified according to codes representing the origin and the destination. In the case when it is desired to distinguish between international and domestic shipping, separate codes are used for each country. It would also be possible to use codes for different ports or regions or to separate emissions from ships passing by from ships actually calling at a specific port.

To be able to specify the origin and destination for a specific route, all origin and destination areas have to be defined by polygons. If a ship stops inside a destination polygon, it is interpreted as if it has reached the destination. In case the route destination and the route origin points out the same country, the route is interpreted as domestic, otherwise the route can be interpreted as international traffic.

The country codes for the route origin and destination are, just as the operational mode, stored as part of the status time-series that is assigned for each ship. The processing is scheduled to run automatically with an overlap in the time intervals that assures that all routes will reach

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[3] Convention on Long-Range Trans-boundary Air Pollution

[4] United Nations Framework Convention on Climate Change

their destinations during the processing interval. The country codes can be used as search keys when calculating emissions. This makes possible to, for example, calculate emissions from domestic shipping in different countries, as well as to distinguish international traffic or traffic just passing by.

There are a number of possible cases that needs to be treated when assigning route origins and destinations. The first step involves the definition of routes. A route is defined as the voyage between two stops in port. In Figure 4 the definition of a route is illustrated. As shown in the figure, the time in port is evenly divided between the route before and after the stop.

The processing is constructed as a so called “state-machine”. The rules for the processing are illustrated in Figure 5 and some special cases are listed in Table 2. An example of ship tracks sorted out to represent Swedish domestic traffic is given in Figure 6.

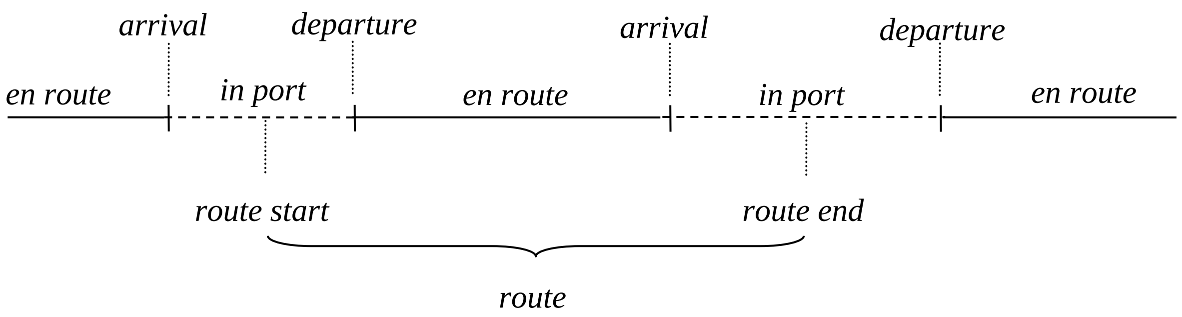

Figure 4. Definition of routes used when determining the type of traffic. Half of the time in port is added to the route after, and half is added to the route before.

Table 2. Special cases to be treated when setting country of origin and destination.

Situation	***Action***
A new ship appear inside a destination polygon	It is assumed that the ship is put into operation. Route origin is set to the country code of the destination polygon.
A new ship appear and is not located inside any destination polygon	It is assumed that the ship enters the AIS domain. Route origin set to country code representing countries outside the AIS-domain.

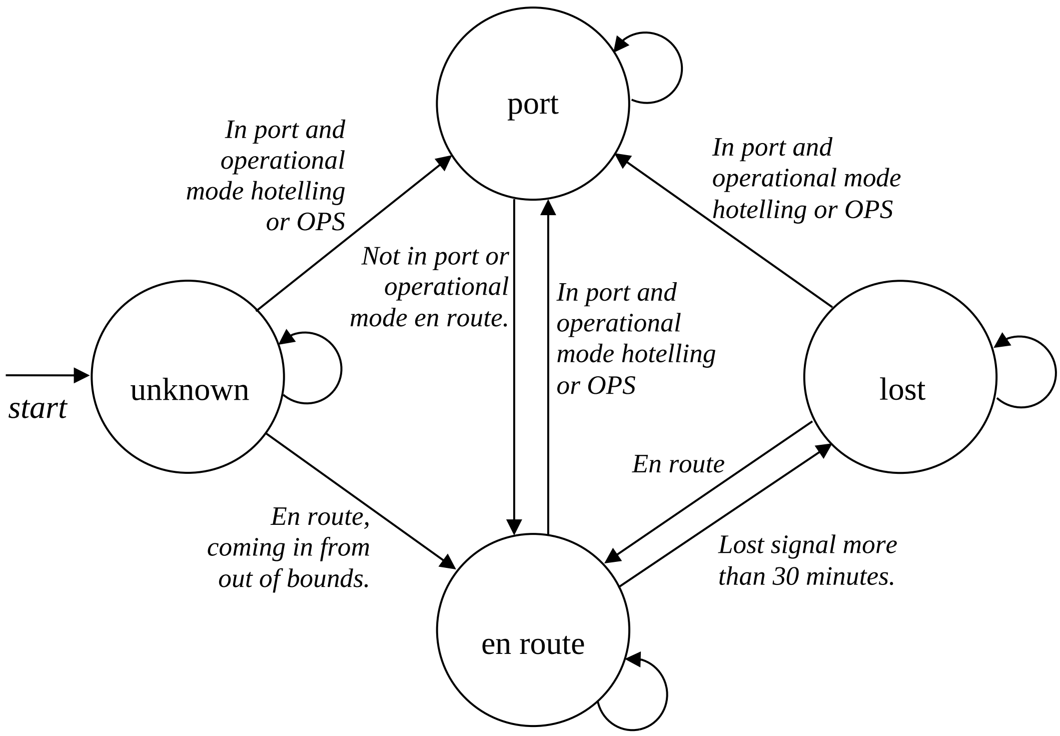

Figure 5. Rules for states used to define routes and to set country code for origin and destination. The state "en route" refers to moving ships. The initial state is always "unknown", the state is then shifted according to the paths in the graph.

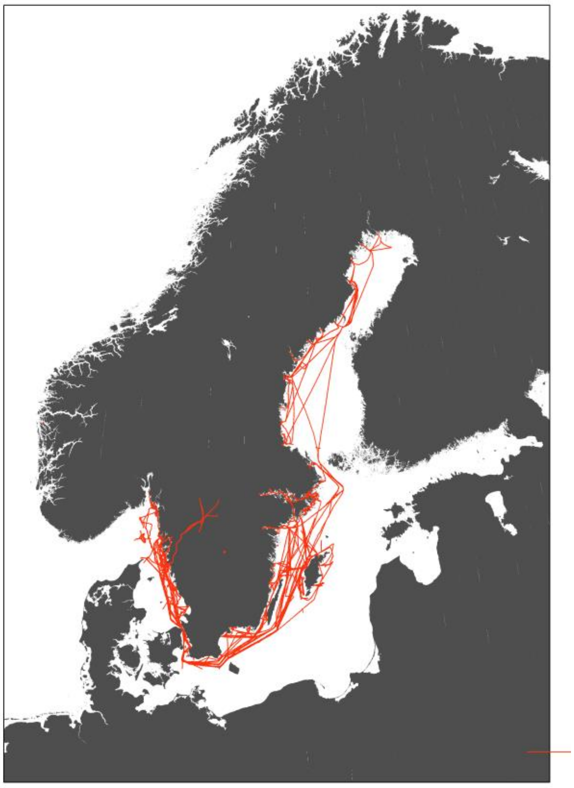

Figure 6. Example of ship tracks for 2 days marked as Swedish domestic shipping, i.e. both origin and destination is set to Sweden's country index in the status time series.

3.3 Ship properties

Using ship properties generally available from existing databases, it is not possible to guarantee a high precision in estimates of emissions for single voyages of individual ships. Such an estimate would require more detailed knowledge regarding hull parameters, conditions at sea and operation of the ship that cannot be extracted from AIS in a reliable way. The focus of the described system is instead to produce a good aggregated description of ship emissions, i.e. estimates for a number of ships and over longer time-periods. Even though the system does provide information for individual ships with high resolution, the emissions calculated for single ships during short time-periods should be considered as relatively uncertain. Ship properties are available from different sources. Examples of these are:

- Static parameters in AIS-messages
- National ship registries. Contain ships registered in the country. Also ships registered in other countries are normally obliged to provide information when visiting a port.
- Commercial databases, such as those of IHS Fairplay (formerly known as Lloyd's register)
- Free online databases. There are a number of free sources of ship information. Most of them have restrictions regarding how the data can be used. One example is the MARS database of the International Telecommunications Union5.

3.3.1 Identification of ships

Each transponder is given an MMSI-number by the national radio communication authorities. In Sweden the registration is handled by The Swedish Post and Telecom Agency (PTS). The MMSI is unique for a specific transponder, but can be changed e.g. if the ship changes flag or owner. To identify a ship the IMO-number is more suitable since it follows the ship during the

[5] www.itu.int

whole lifetime. The IMO-number is part of the static information in the AIS-messages, but it is voluntarily and manually entered into the transponder. Quite often the IMO number is either invalid or missing completely. Moreover, smaller ships, e.g. leisure boats, do not have IMO-numbers. Because of these shortcomings, the IMO-number by itself is not suited for identification of ships in AIS.

The solution in Airviro is to use MMSI as the primary identification number for the ships in the system. However, IMO number is collected for as many ships as possible, and can be used when necessary to match data from other databases.

3.3.2 Ship categories

There are a large number of ship category definitions used among shipping authorities. Some examples are:

- Lloyd's ship categories, which are the codes used by IHS Fairplay to categorize ships.
- SITS-codes, which are used by the Swedish Maritime Administration
- AIS ship categories, which are sent by the AIS-signal.
- Categories used by ITU (International Telecommunications Union)

Multiple ship categories can be specified for each ship. Emission calculations can then be made for a selected category definition separately, resulting in a table of all combinations

The ship category specified in the AIS messages is set automatically when new ship sources are created. These can then be corrected if more reliable information is available from other sources. In the application of the developed system for the HELCOM AIS network, ship classifications are primarily corrected using data from the ITU and secondarily using classifications from the Swedish Maritime Administration.

A list of ship categories used by the Swedish Maritime Administration is given in Appendix 1.

3.3.3 Ship source templates

Since several thousands of ships are found in AIS, there will always be gaps in the information. Also, when performing dispersion simulations, information regarding stack and the characteristics of the exhaust itself are necessary. These parameters can not to the authors knowledge be found in any complete register today.

In order to ensure that all parameters necessary to perform an emission calculation are found, templates are used for each ship category. These templates should be ideally be specified using the finest (most specific) ship category available. The templates are stored in a separate edb (emission database), which is the term used for emission inventories in Airviro. Before doing any calculations, the ship sources are completed by matching each ship with a ship source template of the same category.

This way it will be possible to perform calculations even if AIS is the sole source of ship information. However, the quality of such a calculation would be questionable.

3.3.4 Automatic completion of ship data

Ship source inventories in Airviro can automatically be loaded with data from data sources available online. So far, data can be fetched from two different data sources:

- SEI (Ship Emission Information) which is a web service operated by the Swedish Maritime Administration
- Mars database of the International Telecommunications Union.

SEI was developed specifically to serve as a data source for Airviro and its application in the Baltic Sea. This system is described further in section 4.1. The Mars database contains data from the authorities responsible for registration of AIS transponders. The completeness of the register varies depending on the ambitions of the authority that have gathered the information.

The most important parameters provided by the MARS database are IMO-number, ship category and ship name. Although this information should already be present in AIS, the MARS database can be used to fill gaps in the data and also provides a finer classification of ship categories.

There are also commercial services that with small changes could be used to complete the data needed for emission calculations automatically.

3.3.5 Ship inventory structure

Ships are stored as point sources in an edb using the EDB module of Airviro. The edb:s are stored separately for each user. There is no limit set on the number of edb:s that a user can store and typically a new edb is created for each project or for each scenario to be calculated. Different privileges are set to decide which edb:s a specific user should be able to read and edit.

To facilitate maintenance and updates of the ship inventory, one edb is created that contains the all ships sighted in AIS. This edb is automatically updated when new ships appear in the AIS stream. When a new ship source is created it only contains the data available in AIS, i.e. name, MMSI, IMO ship category and call-sign. Also, a parameter is set that specifies that the data source is AIS. Data that is missing in AIS the moment a new ship is sighted might appear later. As long as the data source is set to “AIS”, data is therefore updated in this edb if changed in AIS. If the data source parameter is set to something else than “AIS”, parameters are only automatically updated if currently no value is given.

The “live edb” containing all ships can easily become very large, and thus difficult to work with. A good practice is therefore to create copies that contain only ships sighted during a specific year. All these general edb:s can be write protected for most users, but readable, so that they can be copied and completed with emission factors and other data to describe different scenarios.

When preparing an edb for a specific project, the first step is to make a copy of an edb containing all ships for the specific time period. The next step is to complete all ship sources using a template edb as described in section 3.3.3, and then to apply emission factors and other necessary parameters as described in section 3.3.4. All these steps can be made using the Airviro web interface. In Figure 7, the preparation of an edb for ship sources is visualized.

Since the complete ship inventory is maintained in the so called “live edb”, it is practical to add all general static ship information to this edb. The information will then be included when creating copies for specific projects or scenarios.

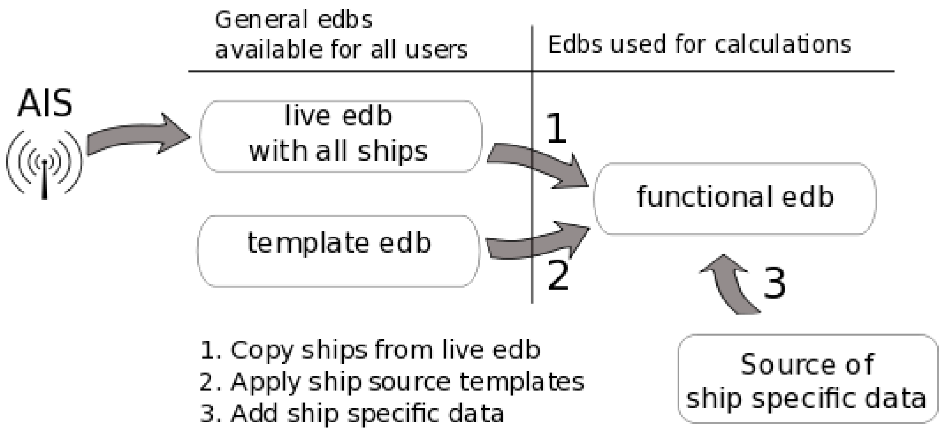

Figure 7. Preparation of an edb with ship sources. New ships sighted in AIS are added as ship sources in the live edb. To create an edb for a specific project, the user extracts relevant ships from the live edb and copies them to e new edb. Ship source templates are applied to the new edb in order to ensure that default values are set for all parameters. Finally, ship specific data is transferred from available sources such as commercial databases or national ship registers.

3.4 Emission calculation

The evaluation of power output, fuel consumption and emissions from ship sources is configurable by the user in Airviro. For each emission source a number of emission activities are specified. An emission activity is defined by an algebraic/logical expression. When evaluated, the expression returns the emission of a specific substance.

The variables used in the expression can be constants representing e.g. installed power or specific fuel consumption but they can also represent time-series. The time-series variables available to be used for shipping emissions are ship speed (knots) and operational mode. The operational mode is then given by an integer corresponding to each mode (1=cruise,2=manoeuvring,3=hoteling and 4 = on-shore power supply).

The use of configurable expressions to control the logic for emission calculations makes the emission calculations very flexible. It should be understood though, that specifying new expressions require care and validation of the results. For most users, the expressions already provided in the system will be the ones used for emission calculations. It should also be noted that the methods currently used have been chosen based on the available input data. If more detailed ship properties are available it is straight forward to implement more specific expressions that make use of these to improve the calculations. An example of this could be to include dependency on engine load in emission factors for particulate matter, CO and specific fuel consumption following Jalkanen (2011). If the number of main engines is known for a ship, the current load could be estimated by:

$$n_{op}^{ME} = ceil\left(\frac{P^{ME}}{0.85*P_{inst}^{ME}/n^{ME}}\right) \qquad [1]$$

$$P_{inst}^{MEi} = \frac{P_{inst}^{ME}}{n^{ME}} \qquad [2]$$

$$EL = \frac{P^{ME}/n_{op}^{ME}}{P_{inst}^{MEi}} \quad [3]$$

Where:

n_{op}^{ME} is the number of engines in operation

P^{ME} is the current power output from main engines

P_{inst}^{ME} is the installed power on main engines

P_{inst}^{MEi} is the size of each individual main engine (all engines are assumed to be of equal size)

$n^{ME}$is the number of main engines

EL is the engine load (fraction of installed power on an individual engine that is currently used)

Also following J-P Jalkanen (2011), specific fuel consumption can then be estimated according to:

$$SFC = SFC_{rel} * SFC_{base} \quad [4]$$

$$SFC_{rel} = 0.563 * EL^2 - 0.857 * EL + 1.33 \quad [5]$$

Where *SFC* is the specific fuel consumption

SFC_{base} is an engine specific base value for SFC

SFC_{rel} is the actual SFC relative to SFC_{base}. The polynomial given in equation 5 is not identical to that of Jalkanen (2011) but has been fitted using the original data referenced in the same publication.

For auxiliary engines, SFC_{base} can be approximated to 260 g/kWh, while main engines SFC_{base} can either be acquired from engine manufacturers or from Bauhaug et al (2009).

In a similar manner, emission factors for particulate matter and CO which are dependent on engine load can be adopted.

3.4.1 Power prediction

3.4.1.1 Power output when cruising

For the main engines the power output is dependent on the propelling speed of the ship. Following Jalkanen et al. (2009) a method to predict the power output originally published in ITTC, 1999, is used. According to comparisons performed during the project this rather simple method appears to describe the power output just as well or even better than what can be achieved using more advanced methods such as those is suggested by Holtrop & Mennen, (1982). The more advanced methods require detailed knowledge of ship characteristics that are usually not known. It is concluded that when default values are used for several of these characteristics, the possible advantages of the more advanced method are lost.

The currently used method uses a simplified version of the method found in ITTC (1999). Under the assumption that friction parameters are ship specific constants, the following relation is used:

$$P_{cruise}^{ME} = k * V^3 \quad [6]$$

where P_{cruise}^{ME}represents the power output from the main engines, *k* is an empirical constant and *V* is the current speed of the ship. In reality this parameter to some extent also depends on the ship speed.

By assuming that 80% of the main engines are used at design speed, the factor k can be calculated as:

$$k = 0.8 * P_{inst}^{ME}/V_{design}^3 \quad [7]$$

Where P_{inst}^{ME} is the total installed power of the main engines, and V_{design} is the design speed of the ship. It should be noted that this method only requires knowledge of two parameters, P_{inst}^{ME} and V_{design}. For speeds close to design speed, the assumption that k is constant should be less uncertain. Jalkanen et al. (2009) also introduces a safety margin of 0.5 knots to account for ship speeds seen in AIS that exceed the expected maximum speed. This reasoning behind this in not clear to the author and this safety margin is not used in current application of Airviro when estimating shipping emissions.

The design speed can often be estimated from the speed distribution available by processing AIS-data for a specific ship, leaving only P_{inst}^{ME} as an absolute minimum requirement. Comparisons for ships with known design speed has shown that the 90-percentileof the registered speeds corresponds reasonably well to design speed in most cases. For ships that are operated outside of design criteria for longer periods of time, an estimate based on AIS-positions can be relatively far from the real design speed. In Figure 8, an example of a speed distribution for a ship is given. Actual design speed (registered) is marked by a red line in the figure, while design speed estimated (measured) from AIS is marked by a black line.

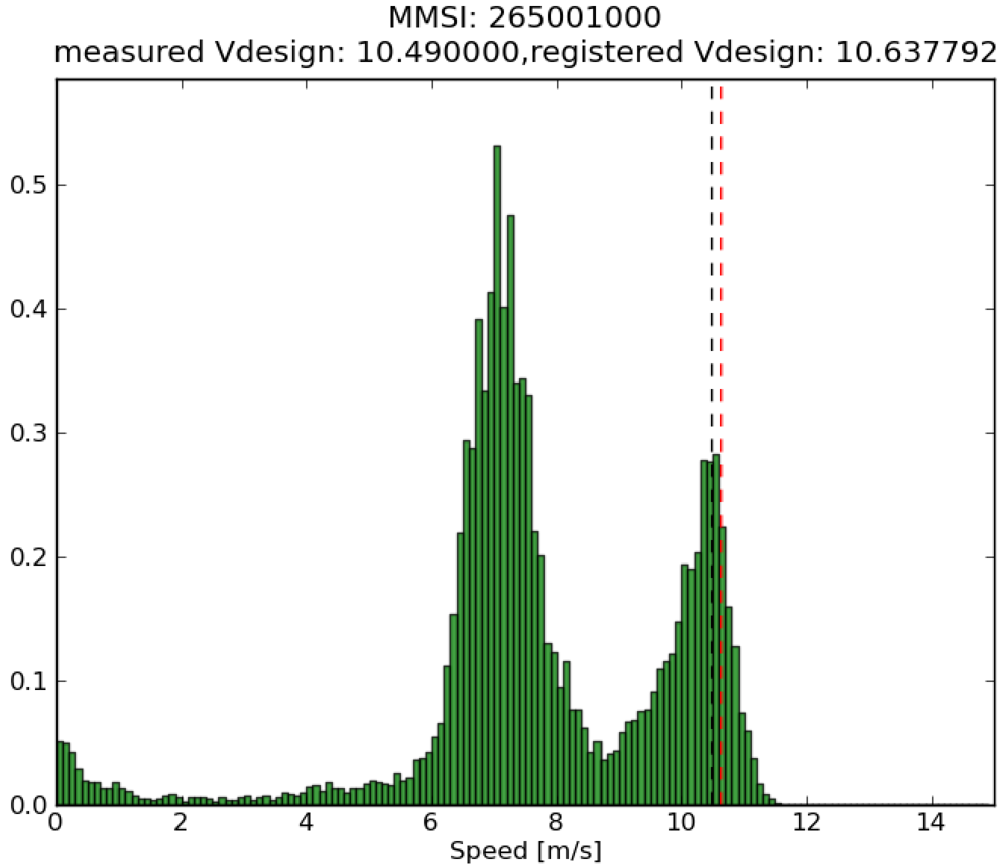

Figure 8. Normalized distribution of ship speed estimated from AIS-positions. The actual design speed is marked as a red line, while the estimated design speed is marked in black.

3.4.1.2 Power output for other operational modes

When the ship is manoeuvring, a prescribed percentage of the auxiliary engines and main engines are used. When the ship is hoteling, only the auxiliary engines are used. How large percentage of the engines that are used when manoeuvring and hoteling is set depending on ship type. For example, the power output for auxiliary engines of a passenger ship is assumed to be larger for a cargo ship of the same size. All parameters can be set individually for ships, but specific values for these parameters are generally not found in available ship databases.

3.5 Dispersion modelling

Emission inventories in the Airviro AQM-system are integrated with a number of dispersion models. Dispersion models are typically run using a time-step of one hour. The emissions from the inventory are served automatically to the dispersion model in a suitable format.

Ship sources can be stored together with other types of emission sources in the same emission database. This makes it possible to include ships, road transport, point sources, area sources and gridded emissions in a single dispersion model run. This makes it possible get a complete picture of the emissions and their contribution to concentrations of pollutants in ambient air.

3.5.1.1 Emission source representation

There are two alternatives ways implemented regarding how to include ship emissions in dispersion models:

- Point sources - representation by a number of point sources along the ships path.
- Grid sources - Sorting emissions along the path into a grid

For local or urban scale dispersion modelling, each ship movement is discretized into a number of point sources. The point sources are distributed with a user-specified distance interval, e.g. one point source per 50 m or 100 m. When running the dispersion model, a new set of point sources will be generated for each hour corresponding to the ships within the modelling domain during that specific hour. The density of point sources can be set such that the dispersion field is continuous and follows that which would be expected by an hourly average of concentrations from a passing ship. An example of a dispersion field for a specific is shown in Figure 9.

To represent the ship emissions in gridded format is mainly suited for large scale modelling. A reason for this is that emissions from the whole grid are released at the same height in the dispersion model, making it impossible to consider different chimney heights for different ships. For large scale applications this can be seen as a reasonable simplification. An advantage with gridded emission is that it largely simplifies the exchange with different models. For example, in order to use dispersion models offline (outside of the Airviro system), it would be possible to export hourly emission grids for the whole period and feed these to the dispersion model. It is also possible to accumulate monthly or weekly emissions in order to limit the amount of data.

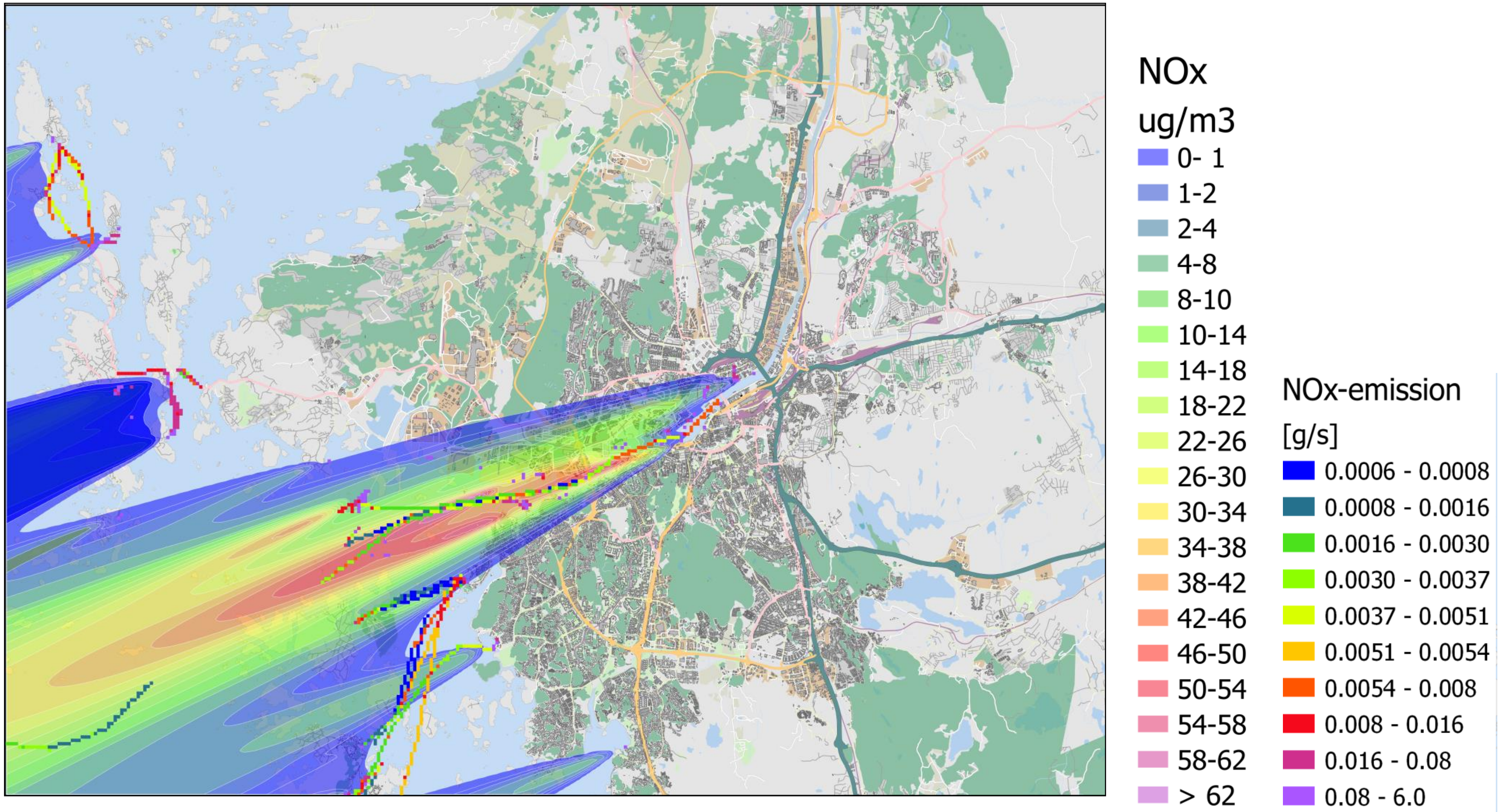

Figure 9. Hourly average concentration of NO_x caused by shipping during one hour, 2011-08-18 04-05. On top of the concentration field, gridded emissions from the ships are presented in g/s. Different colour maps are used for concentrations and emissions.

4 Shipair – a large scale application

On behalf of the Swedish Environmental Protection Agency, Airviro is used to estimate shipping emissions using data from the HELCOM AIS network. The purpose of the application is to improve the basis for decisions and environmental studies related to shipping emissions around Sweden. The application has been developed in cooperation with the Swedish Maritime Administration.

Currently, the system is used for the Baltic Sea and the eastern parts of the North Sea along the coast of Denmark up to the southern coast of Norway.

4.1 SEI (Ship Emission Information)

Besides AIS-information, the most critical input information is ship properties (including emission factors). For this purpose the Swedish Maritime Administration has developed a web service that can be used to automatically transfer ship information for ships found in AIS. The web service is called SEI (Ship Emission Information).

The user can send requests to SEI using the Airviro interface. The request is a list of ships defined by MMSI, IMO and ship category. The user also specifies which set of emission factors that should be fetched from SEI. SEI returns a list of ships and a number of ship specific parameters. The expressions currently used to estimate emissions and the parameters fetched from SEI are given in Appendix 1.

The parameters, assumptions and routines used in SEI are outside the scope of this report and are therefore not described in detail.

4.2 Verification

4.2.1 Uncertainties

There are a number of uncertainties introduced through model assumptions and uncertainties in data. Below, the most important uncertainties are listed.

- *Incomplete AIS-data.*
  All ships do not carry AIS-transponders. Also, there are some gaps in the AIS-data caused by downtime in the HELCOM AIS network. For specific ships, there might be shorter periods missing due to malfunction of the transponder.

- *Incorrect or incomplete ship information*
  Installed power and design speed affect the calculations of power output, and are therefore critical for the overall performance of the calculations. There are also uncertainties in the emission factors, which for some substances can be very large.

- *Effects from waves and currents*
  Ice, waves, wind and currents have influence on the resistance in the water and the air for moving ships. Even though these effects can be significant at certain times, this is neglected in the calculations. To some extent, it is assumed that the effects cancel each other for a ship moving in areas with different conditions. It is also noted that these effects are largest at sea and less prominent in port areas or close to shore.

- *Assumptions regarding operation*
  During manoeuvring and hoteling, it is difficult to estimate power output from engines. For example, the loading and off-loading of cargo usually requires additional motor power. This mainly increases the uncertainties in ports. In general, the largest emissions adhere from the main engines during cruise. When estimating the power output from main engines at cruise, the main assumptions regard the power output at design speed and how much the auxiliary engines are used.

- *Model assumptions*
  One basic modelling assumption is the relation between power output from main engines and the speed: $P=k*V^3$. Although there are more detailed relations, there is often not enough data available to use these. Validation of the used model shows that it is reasonably accurate during operation close to design speed, but less accurate at higher load.

4.2.2 Comparison with measured fuel consumption

A comparison between calculated and measured fuel consumption during 2009 is given for six of the ship owner Stena Line's ships in Figure 10. The ships are passenger ferries and freight ferries, and have been in traffic during the whole year. The results represent a test of the data available for the ships, as well as the calculation method.

It should be noted that the quality of the results depend heavily on knowledge regarding ship properties such as, for example, design speed and total installed power. For a ship where these parameters are unknown and need to be estimated, the performance of the calculations can be expected to be worse.

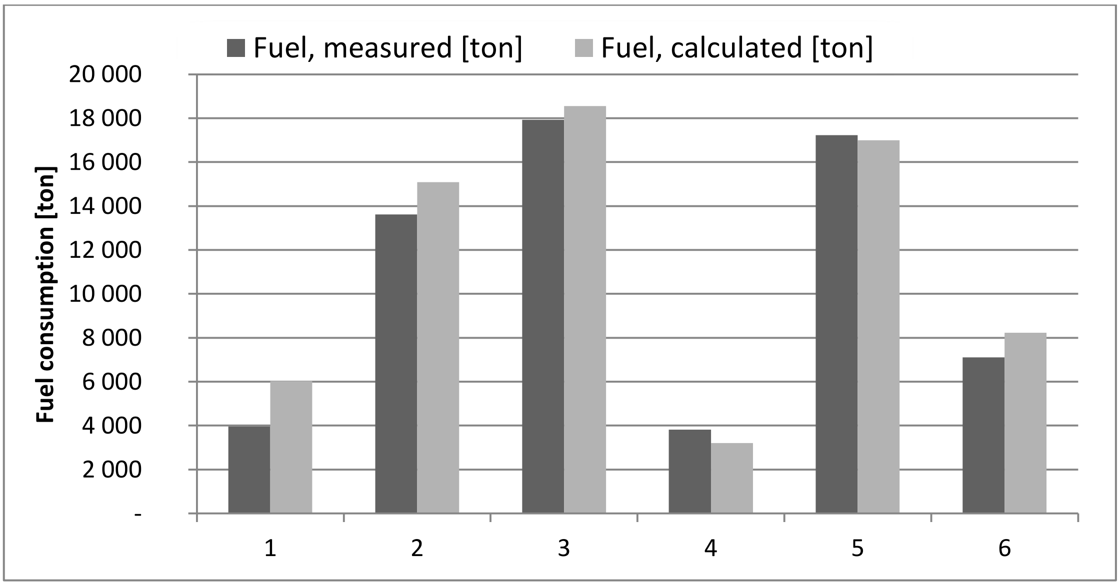

Figure 10. Comparison between measured and calculated fuel consumption during 2009 for six large passenger ships.

4.2.3 Validation using dispersion models

By calculating the contribution to concentration of air pollutants in ambient air, and analysing co-variation with measured levels of pollutants at monitoring stations, it is possible to get an indirect indication of the quality of the results. A study has been done on the impact from shipping on air pollution in Gothenburg. Details can be found in Segersson et al (2012). Some of the results are here summarized as an example of dispersion modelling and calculations of shipping emissions done using Airviro. In Figure 11, results from dispersion modelling is compared to measured NO_2 concentration at the urban background station Femman in central Gothenburg. In Figure 12, the contribution from shipping is shown together with the contributions from other emission sources as well as the regional background concentration. It is clear from the figures that the contribution from shipping is to a large extent hidden among those of more dominant emission sources. With a monitoring site selected specifically chosen to distinguish pollution originating from shipping, it would be possible to perform a more detailed analysis. Nevertheless, it is also clear that the correlation with measurements is relatively good. This at least indicates that the emissions from shipping in the Gothenburg area are not significantly overestimated.

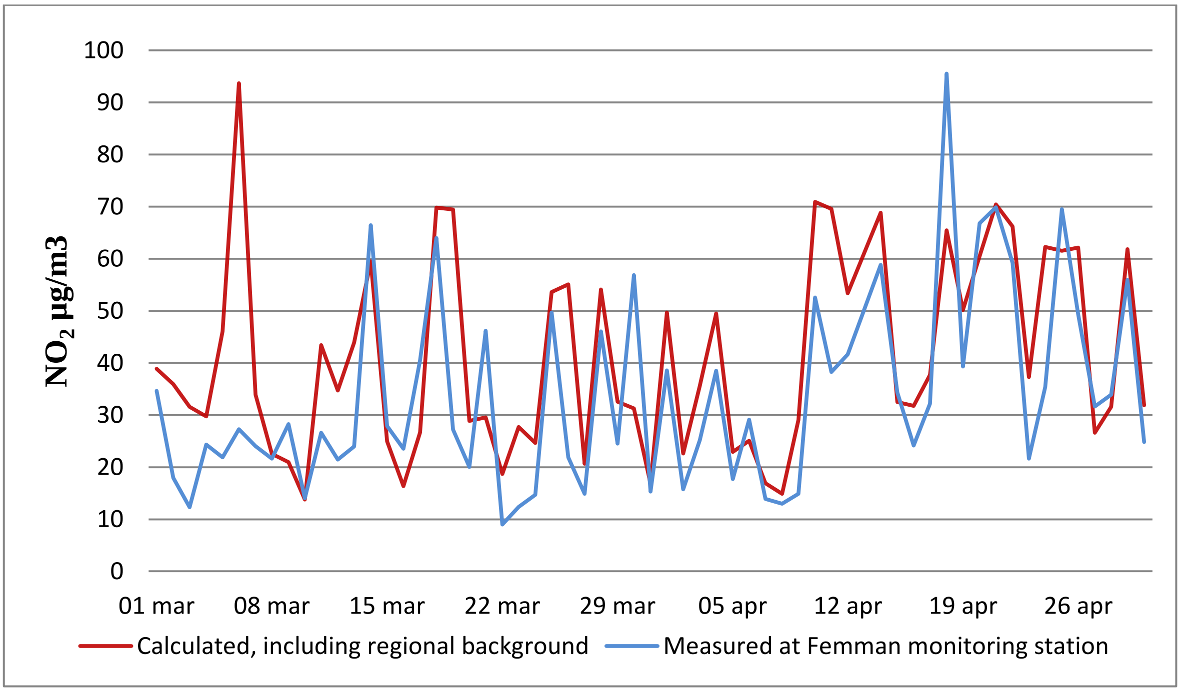

Figure 11. Comparison between measured and calculated daily average concentration of NO_2 [µg/m3] at the Femman urban background monitoring station in central Gothenburg during March-April year 2011. Post-processing has been performed to convert NO_x-concentrations into NO_2.

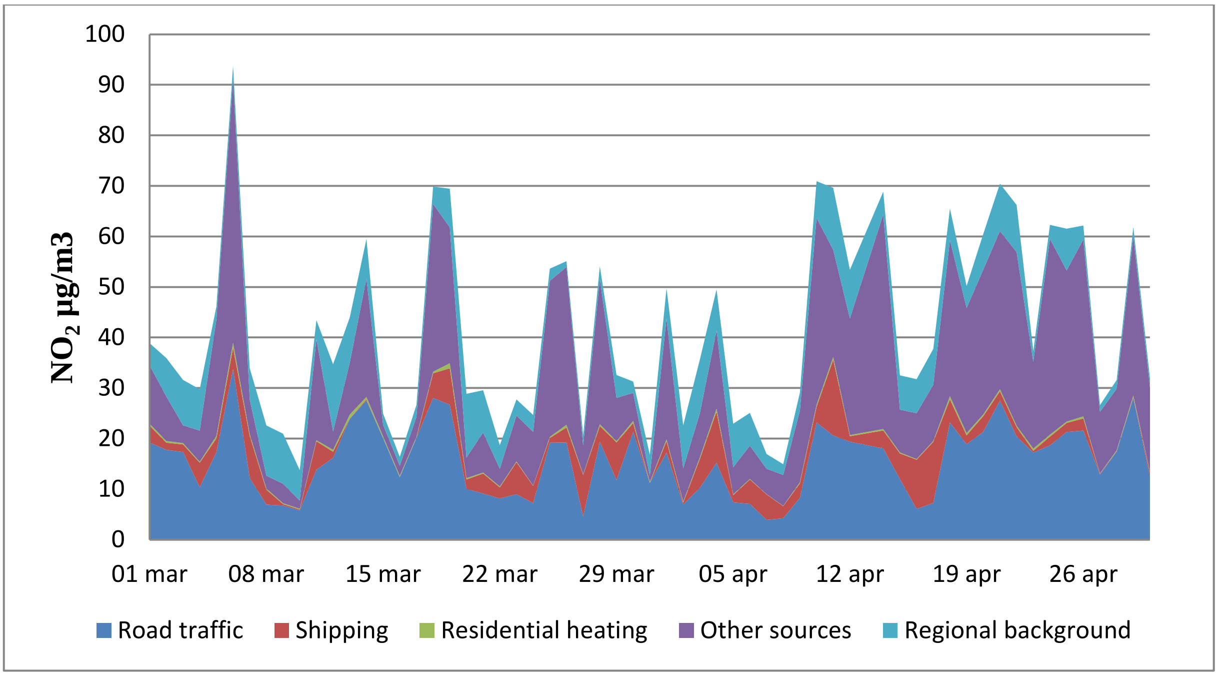

Figure 12. The contribution from the different emission sectors and background concentrations during a period of 2 months. All values are daily average concentrations.

4.2.4 Comparison with other ship emission inventories

Comparisons have been made with results from the STEAM2-model developed by FMI (Jalkanen et al., 2010 and Jalkanen et al., 2011). The STEAM2 model uses a very similar approach as the one described here. Probably the most significant difference affecting the results is that ship properties have been acquired from IHS Fairplay (formerly know as Lloyd's register), while the Shipair application of Airviro uses data from the Swedish Maritime Administration. The database of IHS Fairplay is more complete when it comes to ships that have never visited any Swedish port are likely to be described with more certainty in the inventory of FMI. There are also differences in how the estimations have been made, but these are considered of less importance. Comparisons with STEAM2 have only been made for NO_x, SO_x and CO_2. The numbers representing the STEAM2-model comes from "Baltic Sea Environment Fact Sheets 2012" published by HELCOM (Jalkanen et al, 2012). The emissions represent the total shipping during year 2011. The differences seen in the Figure 13 are considered relatively small, which is expected, since the calculation methods are similar.

A comparison has also been made with emissions from EMEP (European Monitoring and Evaluation Programme) representing international shipping (see Figure 14). The data from EMEP is widely used for dispersion modelling on regional scale. It should be noted however that according Vestreng (2003), emissions of NO_x and SO_x used by EMEP dates back to 1990. The emissions have been adjusted over the years, but are to the author's knowledge still based on the same original activity data.

It can be observed that the emissions from international shipping during year 2011, estimated by Shipair, are significantly lower than corresponding emissions in the EMEP inventory. The emissions estimated using the STEAM2 model of FMI represents total emissions instead of only international shipping. Therefore, no comparison with all three data sources is presented.

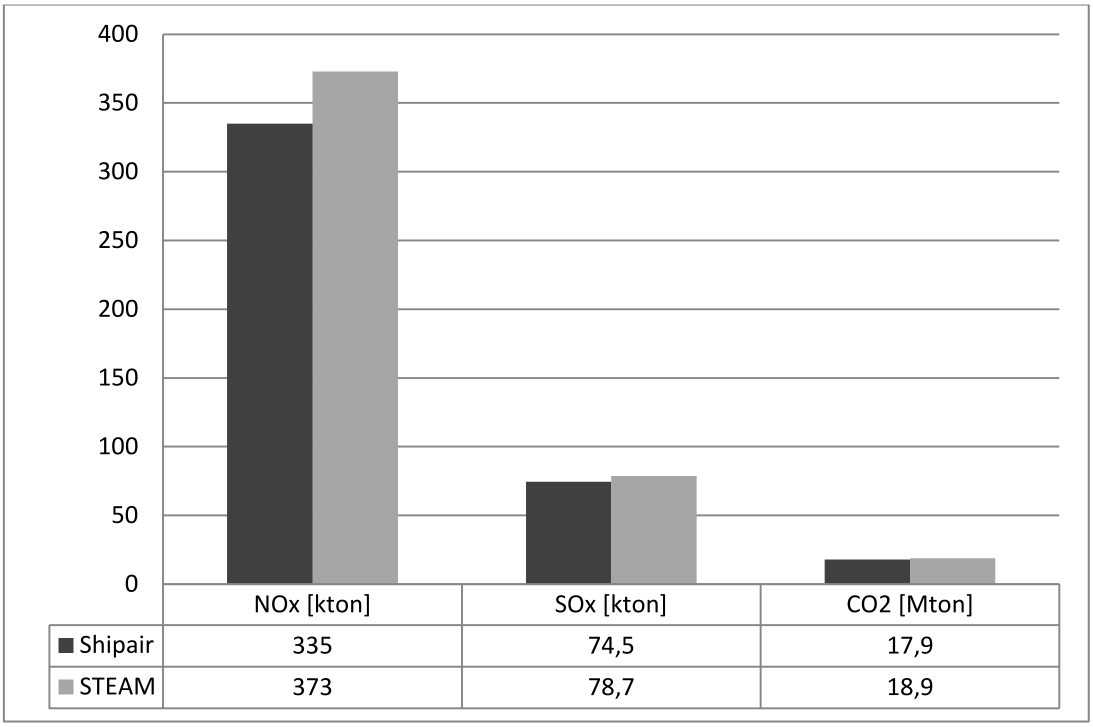

Figure 13. Comparisons of emissions calculated using Airviro/Shipair and emissions from the STEAM2 model.

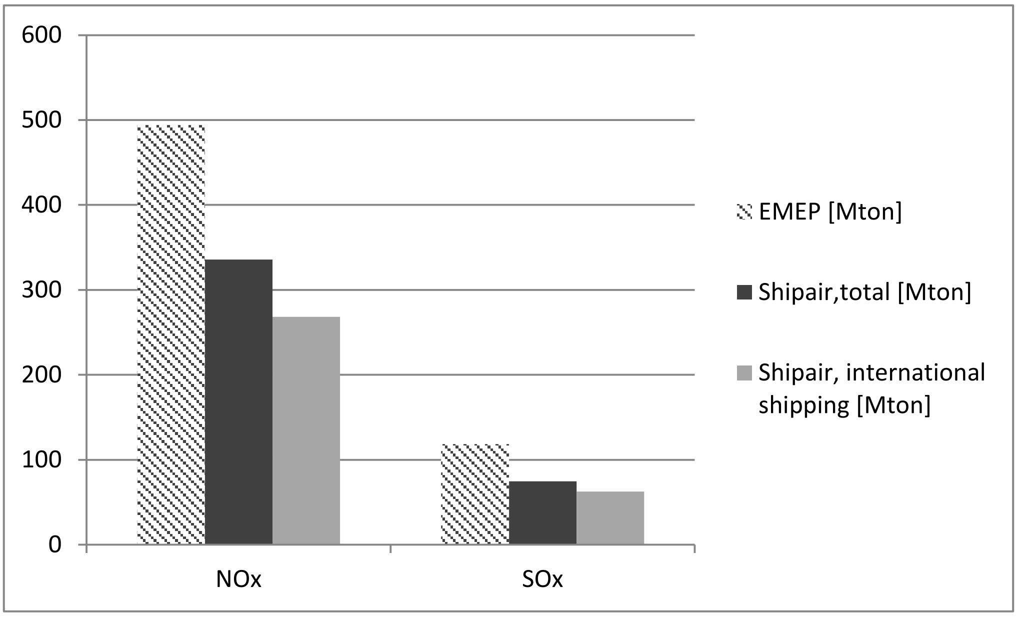

Figure 14. Emissions from international shipping estimated by EMEP compared to international shipping calculated using Airviro.

4.2.5 Comparison with national fuel statistics

Estimates for emissions from domestic shipping are made every year following the guidelines of IPCC (for climate gases) and of CLRTAP (for other air pollutants). According to the guidelines, domestic shipping emissions should be estimated from national fuel statistics. Domestic shipping is then defined as shipping between ports in the same country and using fuel bought within the country. In Airviro, emissions from domestic shipping are estimated based on the ship routes, and no restriction is made only to include emissions from ships using fuel bought within the country. It is considered likely however, that the vast majority of ships on route between Swedish ports are using Swedish fuel.

In Figure 15, comparisons between estimations made using Airviro and estimations based on fuel statistics are presented. The comparisons show relatively large differences, with Shipair in most cases giving significantly higher emissions than estimations based on fuel statistics. To some extent these differences probably come from the different methods to separate international from domestic shipping. Fuel statistics are sensitive to errors in the reporting from fuel vendors. It is considered likely that some of the fuel sold for international shipping is used for domestic shipping, thus causing an underestimation of the emissions attributed to domestic shipping. At the same time the method used by Airviro, where the emissions are classified by the origin and destination of each route, is likely to slightly overestimate the ship emissions, since ships using international bunker may also travel between Swedish ports. This comparison should not be seen as a validation of Shipair, but rather an as an indication of possible underestimations in the current Swedish international reporting of emissions from civil domestic navigation.

In Figure 16, the monthly variation in emissions during the years 2009-2012 is presented. It can be seen in the figure that the difference can be up to 50% between the month with minimum traffic and the months with more intense shipping.

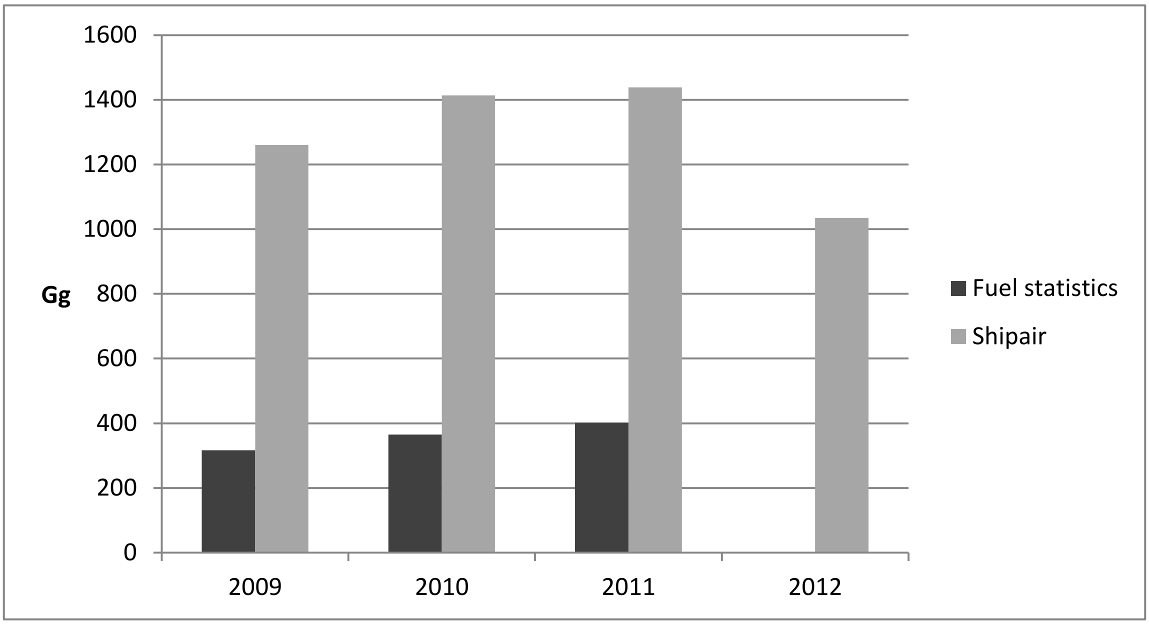

Figure 15.Comparison between emissions of CO_2 estimated from fuel statistics and ship emissions calculated using Shipair. Both estimates represent domestic civil navigation, excluding fishing and military navigation.

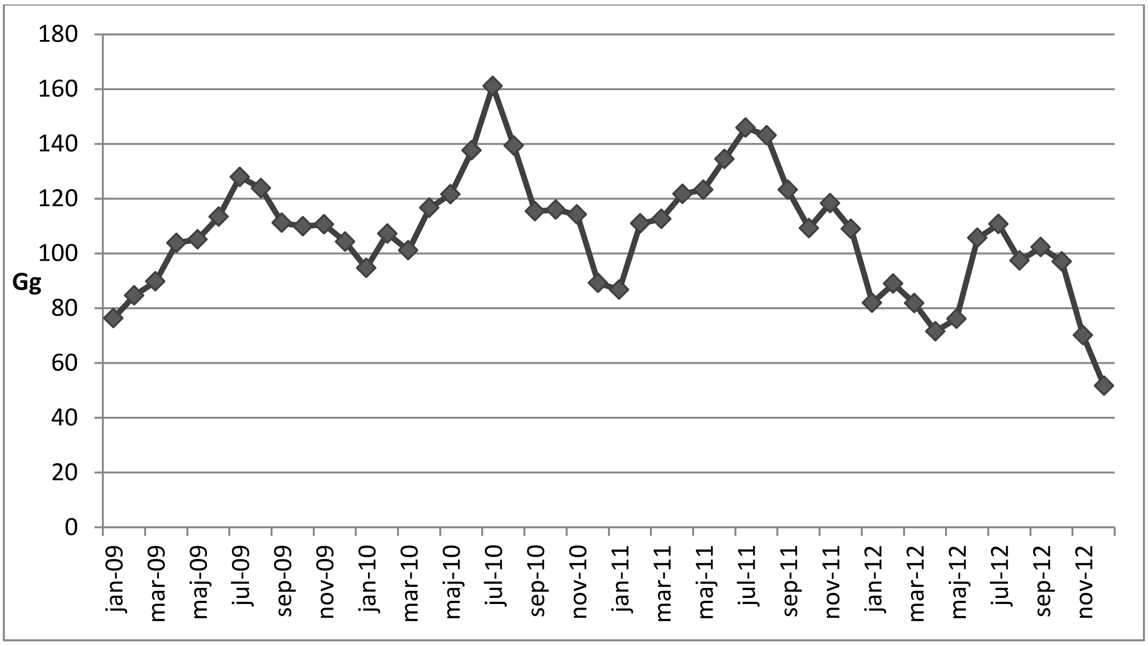

Figure 16. Monthly variations in CO_2 emissions from Swedish domestic shipping calculated using Shipair. A clear yearly variation can be seen with a peak during summer month and a minimum during winter months.

5 Conclusions

A method and a system to quantify emissions from shipping using positions from AIS has been developed. The system allows describing emissions with a high spatial and temporal resolution.

Processing routines have been developed to filter and complete AIS information, in order to describe ship trajectories. The routines filter out erroneous data, fill gaps and determine the operational mode of the ship. The processing also identifies all routes travelled by the ships by an origin and a destination, e.g. making it possible to separate domestic traffic from international traffic.

The developed methods have been integrated into the Airviro Air Quality Management System. The system has then been applied to describe emissions in the Baltic Sea. This application is named Shipair.

Verification shows that given knowledge of basic ship and engine properties, fuel consumption can be estimated with good precision.

Comparisons with calculations made by Finnish Meteorological Institute with a similar methodology gives comparable results, while comparisons made with emissions used by EMEP show larger differences.

It has been demonstrated that the system can be used as a dynamic emission database, providing detailed input data for dispersion models. A comparison has been made between measured concentration s in ambient air and concentrations calculated with a dispersion model. Since concentration is dominated by other emission sources than shipping, this comparison can only show that the estimated emissions are not significantly overestimated.

The system is operational and provides a basis for future evaluation of the environmental impact of shipping due to emissions of air pollutants. The design of the system allows for improvement and adaption of the emission model.

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Appendix 1. Ship categories used by SEI

Table 3. Ship categories used by the SEI-database.

Number	Category
0	Inactive but not unregistred ships
11	Tanker
12	OBO carrier
13	Oil tanker
14	Vegetable oil tanker
20	Gas carrier
21	LPG tanker
22	LNG tanker
30	Chemical tanker
31	Chemical tanker, BCH
32	Chemical tanker, IBC
40	Bulk carrier
41	Cement carrier
51	Barge carrier
52	Vehicle carrier
53	Container ship
54	Unit cargo vessel
55	Ro-ro cargo ship
60	General cargo ship
61	Refrigerated cargo ship
70	Road ferry
71	Passenger ship
72	Icebreaker
73	Fish factory ship
74	Research vessel
75	Heavy lift carrier
76	Offshore tug/supply ship
77	Passenger ship, international traffic
90	Ship for transportation of not more than 12 passengers
91	Tug/salvage ship
92	Fishing vessel
93	Pleasure craft
94	Barge
95	Service vessel
96	Naval vessel
99	Unspecified vessel

Appendix 2 –Emission Factor Functions

The expressions currently used to estimate emissions in Shipair are given below.

In the system a unit conversion is made since of the final result since Airviro expects emissions to be in g/s and SEI uses kg/hour.

All constants that are used in the expressions below are prescribed by the logic in SEI (Ship Emission Information) operated by the Swedish Maritime Administration.

It should be noted that these expressions are under continuous development.

List of variables used by emission activities in Shipair.

Variable	***Description***	***Unit***
P_{Cruise}^{ME}	Power output at cruise, main engine	kW
P_{Cruise}^{AE}	Power output at cruise, aux. engine	kW
P_{man}^{ME}	Power output while manoeuvring, main engine	kW
P_{hotel}^{AE}	Power output while hotelling, aux. engine	kW
F^{cruise}	Fuel consumption at cruise	kg/h
F^{man}	Fuel consumption while manoeuvring	kg/h
F^{hotel}	Fuel consumption while manoeuvring	kg/h
E_{subst}^{cruise}	Emission of substance *subst* while cruising	kg/h
E_{subst}^{man}	Emission of substance *subst* while manoeuvring	kg/h
E_{subst}^{hotel}	Emission of substance *subst* while hotelling	kg/h
V	Current speed over ground	knots
V_{max}	Max speed	knots
V_{design}	Design speed	knots
P_{inst}^{ME}	Total engine capacity, main engines	kW
P_{inst}^{AE}	Total engine capacity, aux. engines	kW
$usage_{cruise}^{AE}$	Usage factor, aux. engines, cruise	-
$usage_{man}^{ME}$	Usage factor, main engines, manoeuvre	-
SFC^{ME}	Specific Fuel Consumption, main engines	kg/kWh
SFC^{AE}	Specific Fuel Consumption, aux. engines	kg/kWh
EF_{subst}^{AE}	Emission factor, substance *subst*, aux. engine	kg/kWh, kg/kg
EF_{subst}^{ME}	Emission factor, substance *subst*, main engine	kg/kWh, kg/kg

Of practical reasons, the design speed, V_{design}, is estimated from max speed.

$$V_{design} = 0.94 * V_{max}$$

The empirical factor *k* is estimated under the assumption that 80% of main engines are used during cruise at design speed.

$$k = \frac{usage_{Vd}^{ME} * P_{inst}^{ME}}{V_{design}^{3}}, \qquad where\ usage_{Vd}^{ME} = 0.8$$

Power output from main engines at cruise is estimated using the previously calculated factor *k*. In case currents or other favourable conditions make the ship go faster than V_{max}, the estimated power output might exceed the installed power. To avoid this, the power output from main engines at cruise is limited to 95% of the installed power.

$$P_{Cruise}^{ME} = \min(0.95 * P_{inst}^{ME}, k * V^{3})$$

Power output from auxiliary engines during cruise is estimated using a prescribed engine load which is specific for each ship category.

$$P_{cruise}^{AE} = P_{inst}^{AE} * usage_{cruise}^{AE}$$

Power output from main engines during manoeuvring is estimated using a prescribed main engine load which is specific for each ship category.

$$P_{man}^{ME} = P_{inst}^{ME} * usage_{man}^{ME}$$

Power output from auxiliary engines during manoeuvring is estimated using a prescribed auxiliary engine load which is currently set to 0.5 for all ship categories.

$$P_{man}^{AE} = P_{inst}^{AE} * usage_{man}^{AE}, \qquad where\ usage_{man}^{AE} = 0.5$$

Power output from auxiliary engines during hotelling is estimated using a prescribed auxiliary engine load which is specific for each ship category.

$$P_{hotel}^{AE} = P_{inst}^{AE} * usage_{hotel}^{AE}$$

Fuel consumption during cruise is estimated by adding the consumption from main engines and auxiliary engines. Specific Fuel Consumption (SFC) is, as far as possible, specific for individual ships.

$$F^{cruise} = P^{ME}_{cruise} * SFC^{ME} + P^{AE}_{cruise} * SFC^{AE}$$

Emissions during cruise are estimated by adding contribution from main and auxiliary engines. For SO_x and CO_2 the emissions factors are expressed without unit (mass/mass) and multiplication with SFC is required. For other substances emission factors are given In kg/kWh.

$$E^{cruise}_{subst} = \begin{cases} P^{ME}_{cruise} * EF^{ME}_{subst} * SFC^{ME} + P^{AE}_{cruise} * EF^{AE}_{subst} * SFC^{AE}, & subst = SO_x, CO_2 \\ P^{ME}_{cruise} * EF^{ME}_{subst} + P^{AE}_{Cruise} * EF^{AE}_{subst}, & subst = NO_x, PM_{10}, PM_{2.5}, PAH, NMVOC \end{cases}$$

Emissions during manoeuvring are constant, since there is no dependency on ship speed. For simplicity these emissions are specified directly for each ship.

$$E^{man}_{subst} = E^{ME,man}_{subst} + E^{AE,man}_{subst}$$

$$F^{man} = (P^{ME}_{man} * SFC^{ME} + P^{AE}_{man} * SFC^{AE})$$

$$F^{hotel} = (P^{AE}_{hotel} * 0.5 * SFC^{AE})$$

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ISSN: 0283-7730

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