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FOREWORD

This study was carried out in the Finnish Environment Institute at the Research Programme for Global Change (GTO) during years 2005 and 2006. The focus was, firstly, to develop national integrated assessment modeling framework of air pollutants, and secondly, to enhance the general understanding of the magnitude of ship emissions and reduction potentials in the sea areas near Finland. The work was funded by the Ministry of the Environment and the KOPRA project in the technological programme ”FINE Particles - Technology, Environment and Health 2002-2005” of the National Technology Agency of Finland (Tekes). The authors gratefully acknowledge the financial support.

There are plenty of valuable existing information and data bases about ship movements, emissions and reduction technologies which this study utilized to a great extent. The most important data source for the baseline emission factors was the calculation system for the Finnish waterborne traffic, MEERI. The authors wish to acknowledge Kari Mäkelä from VTT Building and Transport for collaboration. The ship movements were estimated based on information from several sources. We thank Heli Haapasaari, Meri Hietala and Samuli Neuvonen from the Finnish Environment Institute, Kaj Forsius from HELCOM, Harry Federlay from the Finnish Maritime Administration, Eve Tuomola-Oinonen from the Port of Helsinki and Mirva Lehtonen from the Port of Hamina for their helpful attitude and delivery of information. Furthermore, we wish to acknowledge Nicola Robinson from European Commission Environment Directorate-General and Jan Hulskotte from TNO Built Environment and Geosciences for the discussions and information about emission reduction technologies and costs.

The study was also Johanna Wahlström’s master’s thesis work. The supervisor professor Carl-Johan Fogelholm from Helsinki University of Technology is acknowledged for his instructions and valuable comments.

We are also grateful to Carita Nybom from the Information Service of the Finnish Environment Institute for correcting the English and Swedish abstracts.

SYMBOLS AND ABBREVIATIONS

E	Energy consumption
EM	Amount of emissions
f	Emission factor
FC	Fuel consumption
M	Ship movements
m_{aver}	Average fuel consumption
m_S	Amount of sulphur in fuel
P	Engine power
s	Sailed distance
t	Time
v	Average sailing speed
x	Proportion of a engine type
y	Proportion of a fuel type

AIS	Automatic Identification System
CASS	Combustion air saturation system
DWI	Direct water injection
EGR	Exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
EU	European Union
FMA	Finnish Maritime Administration
FRES	Finnish Regional Emission Scenario model
HAM	Humid air motor
HFO	Heavy fuel oil
IMO	International Maritime Organisation
LNG	Liquefied natural gas
MARPOL	Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
MGO	Marine gas oil
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
STID	Steam injected diesel

CO	Carbon monoxide
$CO(NH_2)_2$	Urea
CO_2	Carbon dioxide
H_2O	Water
H_2SO_3	Sulphurous acid
H_2SO_4	Sulphuric acid
HC	Hydrocarbons
N_2	Nitrogen
NH_3	Ammonia
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_2	Oxygen
OH	Hydroxyl radical
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SO_4	Sulphate
SO_x	Sulphur oxides

CONTENTS

Foreword 3

Symbols and abbreviations 4

1 Introduction 7

2 Background 9

- 2.1 **Ship types** 9
- 2.2 **Ship engines** 9
  - 2.2.1 Engine sizes and rating 9
  - 2.2.2 Engines in cargo and passenger ships 10
- 2.3 **The main ports at the Gulf of Finland and the Gulf of Bothnia** 12
- 2.4 **Automatic Identification System (AIS)** 12

3 Methods and materials 13

- 3.1 **Ship movements** 14
- 3.2 **Engine sizes and fuel and energy consumption** 17
- 3.3 **Emission calculation** 18
  - 3.3.1 Sulphur dioxide emissions 18

4 Ship emissions in 2000 20

- 4.1 **Emissions on the sea routes** 21
  - 4.1.1 Gulf of Finland 21
  - 4.1.2 Gulf of Bothnia 23
- 4.2 **Emissions in ports, inland waters and from smaller vessels** 25
- 4.3 **Uncertainties and data gaps** 26

5 Techniques for reducing emissions from ships 27

- 5.1 **Formation of emissions in marine diesel engines** 27
  - 5.1.1 Sulphur dioxide emissions 28
  - 5.1.2 Nitrogen oxides emissions 28
  - 5.1.3 Particulate matter emissions and smoke 28
  - 5.1.4 Carbon monoxide and hydrocarbon emissions 29
- 5.2 **Reduction by internal engine adjustments** 29
  - 5.2.1 Combustion optimization 30
  - 5.2.2 Fuel injection optimization 31
  - 5.2.3 Common rail technology 32
  - 5.2.4 Turbo-charging and charge-air after-cooling 33
  - 5.2.5 Miller cycle 33
  - 5.2.6 Lubrication technology 34
  - 5.2.7 Combinations of internal engine measures 34
- 5.3 **Reduction by engine process modifications** 35
  - 5.3.1 Water injection 35
  - 5.3.2 Selective non-catalytic reduction 38
  - 5.3.3 Exhaust gas recirculation 39

5.4 **After-treatment technologies** 40
    5.4.1 Seawater scrubbing 40
    5.4.2 Selective catalytic reduction 40
    5.4.3 Particulate filters 42
    5.4.4 Oxidation reactor 42
5.5 **Alternative fuels and energy sources** 43
    5.5.1 Low-sulphur fuels 43
    5.5.2 Alternatives for diesel fuels 44
    5.5.3 Fuel cells 44
5.6 **New ship design and modification** 45
    5.6.1 Optimizing ships' design and operation 45
    5.6.2 New ship design 45
5.7 **Shore-side electricity** 47
5.8 **Costs of emission reduction** 48

6 Future shipping and ship emissions 50
6.1 **Background on ship emissions forecasts** 50
    6.1.1 Ship traffic development forecasts 50
    6.1.2 Emission regulations 51
    6.1.3 Current abatement technology in the ship engines 52
    6.1.4 Maturity and development of the abatement technologies 54
    6.1.5 Ship emission scenario studies 54
6.2 **Emission scenarios 2015** 55
    6.2.1 Assumed ship movements in 2015 55
    6.2.2 Technology assumptions in emission scenarios 55
    6.2.3 Ship emissions 2015 57

7 Discussion and conclusions 59

Bibliography 63

Appendix A 66

Documentation pages 68

1 Introduction

Maritime transport has clear environmental advantages: it expends relatively little energy and its infrastructure requirements are small compared to land-based transport modes (Kågeson, 1999). Due to low energy need, shipping is a highly carbon-efficient transport mode, i.e. carbon dioxide emissions are low compared to the weight of cargo transported. Shipping can be up to four times more efficient than road transport. Because of relatively small contribution to greenhouse gas emissions shipping is also good in the terms of mitigation of climate change. However, air pollution from ships has been unregulated until recently. As a result, fuel oils with high sulphur content are widely used and emission control technologies are not required. Ships currently produce about half as much sulphur dioxide (SO_2) as land-based sources and about a third as much nitrogen oxides (NO_x) (IUPPA, 2005). The International Institute for Applied Systems Analysis (IIASA) estimates that in Europe the amounts of SO_2 and NO_x emissions from shipping will surpass land-based sources in the 25 EU member states in 2020 (Amann et al., 2004).

Ships emit several hazardous air pollutants such as sulphur dioxide, nitrogen oxides and fine particles. Once emitted, airborne emissions can travel considerable distances so the shipping emissions affect land air quality. Also the emissions from ships during port stays can be substantial contributor to the local air quality (MES, 2005b). The increased air concentrations and deposition of air pollutants have several negative effects. Particulate matter emissions have contributed to increased mortality and morbidity in Europe. Shipping emissions are estimated to form 20-30 per cent of the concentration of secondary inorganic particles in most coastal areas in Europe. SO_2 and NO_x emissions increase acidification of sensitive forest ecosystems along the coastal areas in Europe among those the coasts of southern Finland. NO_x emissions also contribute to the formation of ground-level ozone and eutrophication. Groundlevel ozone causes damage to vegetation and human health and eutrophication affects biodiversity on land and coastal waters. Shipping is the largest single source contributing to acidifying and eutrophying deposition in many European countries. The emissions of SO_2 and NO_x and ground-level ozone also accelerate the deterioration of various materials. Especially acid environment is harmful to metals and buildings made of limestone or sandstone. (EEB et al., 2004)

So far the emissions from ships are evaluated in a few studies. Several inventories based on global energy statistics have been made. Corbett and Köhler (2003) have evaluated shipping emissions based on activity data and the results were much higher than in energy-based inventories. Eyring, Köhler, van Aardenne, and Lauer (2005) have presented an emissions inventory for international shipping for the last 50 years and developed shipping emission scenarios for future. Jonson et al. (2000) have evaluated the effects of international shipping to the emission levels in Europe. Entec has published a report on ship emissions associated with ship movements between the ports in the European Community (Stavrakaki et al., 2005). Also more specific evaluations have been made. Hulskotte et al. (2003) have made a shipping emission inventory for the ships at the Dutch inland and sea areas. Mäkelä et al. (2002) have performed a calculation system for waterborne traffic in Finland called Meeri. The system contains emissions of the ships calling at Finnish ports from the time they sail inside the Finland's economic area.

There are extensive ship traffic at the northern Baltic Sea. The number of ships sailing at those sea areas is predicted to grow fast in the future and hence the emissions from shipping are likely to become even larger environmental problem. Therefore, there is a pressure on finding technical solutions to limit the emissions. Techniques to reduce the emissions by as much as 80-90 per cent exists already. They can be very cost-effective compared to the measures for reducing emissions from land-based sources.

The aim of this study was to provide new information on the amount of current and future emissions from maritime transportation in Finland and in the sea areas near Finland. The goal was to investigate the contribution of different ship types to emissions and also get a view of the spatial distribution of shipping emissions. The study concentrates on emissions from cargo and passenger ship traffic on sea routes, which were calculated based on ship movements. The ship movements were evaluated based on different statistics. International cargo and passenger ship traffic constitutes a major part of the vessel movements at the selected sea areas and they are the main contributor to shipping emissions. Emissions from ships in ports and inland waters as well as emissions from smaller vessels in Finland were reviewed shortly based on literature to give an overall picture of the whole waterborne traffic and emissions in the studied areas. Technical possibilities to reduce emissions from ships and the reduction potential of the methods were studied based on literature. Finally future emissions in the Gulf of Finland and the Gulf of Bothnia were evaluated based on few scenarios. In the scenarios the effect of the implementation of different reduction technologies on emission levels were studied. The results of this study will be used to update and specify the ship emission calculation in the Finnish Regional Emission Scenario (FRES) model of Finnish Environment Institute (Karvosenoja and Johansson, 2003). FRES model is used as an integrated assessment tool of air pollution in order to promote policy making in Finland and nearby areas.

2 Background

2.1

Ship types

In general, ships can be divided into passenger and cargo ships. However, some passenger ships also carry cargo and some cargo ships take passengers as well. Regarding to this report, the main difference between the passenger and cargo ships is that the passenger ships have larger engines in relation to their tonnage than the cargo ships. The passenger ships are also faster than the cargo ships especially in the smallest size classes. Passenger ships include passenger vessels and ferries. Passenger vessels are ships that do not carry cargo where as passenger ferries has also one or more cargo decks and they transport more than 120 passengers. (personal communication, H. Federley, Finnish Maritime Administration, 4.5.2005)

Cargo ships can be further categorized according to their structure and type of cargo. Cargo ferries are similar to passenger ferries but they transport more cargo and less than 120 passengers. Bulk carriers transport unpacked cargo such as coal. Other dry cargo vessels are regular cargo vessels, which are loaded up with derricks through hatchway. Container ships are similar, but their cargo is in containers. Tankers transport oil, chemicals or gas. The RoRo (Roll on/Roll off) ships are ferries, which carry wheeled cargo: automobiles, trailers and railway carriages so they are further classified as cargo ferries. Reefers are ships, which carry cargo that is needed to keep cool such as fruits, vegetables, dairy products, fish and meat. Excluding the temperature control the reefers are similar to other dry cargo vessels or containers. (personal communication, H. Federley, FMA, 4.5.2005)

There are also smaller vessels such as fishing vessels and boats, work vessels and boats and recreational boats. Work vessels include icebreakers, tugs, connection vessels, route and oil combating vessels, surveying ships, customs' boats, Border Guards' vessels, vessels of sea salvage service and other work vessels and boats. (Mäkelä et al., 2002)

The sizes of the cargo and passenger ships are reported as gross tonnage. The gross tonnage is calculated based on mathematical formula. The number does not have any unit but the larger the gross tonnage is the larger is also the ship. (personal communication, H. Federley, FMA, 4.5.2005)

2.2

Ship engines

2.2.1

Engine sizes and rating

U.S. Environmental protection Agency (EPA) has divided marine engines applications into three categories according their sizes. Category 1 engines have rated power at or above 37 kW and specific displacement of less than 5 litres per cylinder. These engines are similar to land-based off-road engines. Category 2 engines are engines with a specific displacement of 5 to 30 litres per cylinder. Their land-based counterparts are locomotive engines. Category 1 and 2 engines are derived from or use the same technology as their land-based models. Therefore the emissions reduction technologies in the land-based off-road engines could be introduced for the marine category 1 and 2 engines. Category 3 engines are very large engines with a specific displacement at or above 30 litres. These engines are the size of land-based power plant generators and they are used for propulsion in the large ocean-going vessels.

The category 3 engines are currently designed for maximum fuel efficiency without considering the impacts on the NO_x emissions. Therefore the NO_x emission levels from these engines are very high. The engines already have advanced controls of charge air temperature and pressure, which are considered to be emission control strategies for smaller engines. (EPA, 1999).

Engine rating refers to the type of operating conditions the engine is designed to handle. For marine diesel engines the engine ratings correspond to how the engines are intended to be used. Thus marine engines are different in merchant and recreational use. In the recreational boats the engines typically have high performance rating. Merchant vessels' engines have other ratings depending on the vessel type. (EPA, 1999).

The light-duty commercial engines are used in seasonal fishing vessels and emergency rescue boats and they are similar to recreational vessels' engines but they have greater durability. Intermittent-duty commercial engines are used in commercial fishing boats, ferries and coastal freighters. These engines are designed for boats with either planning or displacement hulls that operate under variable speed and loads. Marine engines with medium continuous rating are designed to operate a large number of hours at fairly constant speeds and loads on vessels with displacement hulls. Engines with these ratings are typically Category 1 and 2 engines. (EPA, 1999).

Large vessels typically have marine engines with continuous rating. They are designed to operate at full load up to 24 hours per day and more than 5000 hours per year. This kind of engines has good durability and fuel efficiency and therefore they are feasible for large ocean-going vessels. (EPA, 1999)

Commercial vessels are usually displacement vessels meaning that the engines push the vessels through the water. The optimal operation of the commercial vessels is mostly depended on the hull characteristics, which are optimized for minimum drag. The commercial vessels are typically heavily used and the engines are designed for the usage of 4000 to 6000 hours per year at the higher engine loads. They are designed for a specific user and the purchaser can influence on many of the ship's characteristics including the engine choice. (EPA, 1999).

2.2.2
Engines in cargo and passenger ships

The power needed on ships is generated through main and auxiliary engines and boilers, and these are also the sources of emissions on board (Mäkelä et al., 2002). On average, a ship has 1.4 main engines and 3.5 auxiliary engines installed on board (Ritchie et al., 2005b).

The main engines consist almost without exception of one or several two- or four-stroke diesel engines and they produce the energy needed for propulsion system. In the larger cargo ships (gross tonnage more than 5,000) the low-speed two-stroke engines are common as the main engines. Low-speed diesels run at low engine revolutions enabling a direct drive applications to turn propellers. In the smaller cargo ships (gross tonnage less than 5,000) the main engines are usually medium speed four-stroke engines. They have a higher revolution speed and thus some form of intermediate transfer of power is required. The majority of the medium-speed diesel propulsion applications consist of reduction gears or electric propulsion motors. In the passenger ships several four-stroke engines constitutes the main engines. (Mäkelä et al., 2002; Diesel Technology Forum, 2005)

The auxiliary engines are used to produce the energy needed on board for electricity, pumps, cooling and heating devices, derricks, hydraulic devices and so on. The auxiliary engines are usually four-stroke engines. The sizes of them vary a lot depending on the energy demand on board, which is very different for different kinds of ships. On average, the size of the auxiliary engines is about 10 per cent of the size of the main engines. (Mäkelä et al., 2002; Klokk, 1995)

At the moment there are no alternatives to small and medium size diesel engines in marine applications. However, over last years gas turbine engines have became an alternative to large low-speed engines. They have been used in military vessels for many years, but only recently they are being installed into large ocean-going commercial vessels as well. Gas turbines use lighter distillate fuels and thus cause less SO_2 emissions compared to diesel engines. Furthermore, the combustion process can be better controlled in gas turbines and thus also NO_x emissions are lower compared to reciprocating engines. (Diesel Technology Forum, 2005)

The efficiency varies depending on the size, speed and general engine configuration. The reciprocating engines can achieve high efficiency over a broad load range. Furthermore, the high efficiency and power output remain constant over a wide range of intake temperatures. These are very important features for the ship engines since the load of the engines varies mostly between 30 and 85 per cent and the intake air temperature changes depending on the geographical location and the season. Other possible marine engine applications, gas turbines and gas engines, have thermal efficiencies well below low- and medium-speed diesel engines. In future fuel cells could be used in ships and their efficiencies is expected to be slightly higher than efficiencies of low-speed marine diesel engines. The efficiencies of different marine engines are listed in Table 2.1. (Wärtsilä, 2004; Kågeson, 1999).

The age of the marine engines is an important factor in the terms of fuel efficiency and environmental performance. Klokk (1995) have listed statistics of the merchant fleet but no information of the average age and lifetime of the engine installations were available. The average age and lifetime of the ships were 15 years and 26 years respectively in 1994. These give some idea of the average age and lifetime of the ships' engines but in a number of ships the engines are rebuilt or changed over the ships' lifetime. New ships are introduced about four per cent of the total fleet annually. In 1998 40 per cent of the ships at the Baltic Sea were older than 20 years. They contributed approximately 50 per cent of all the ship calls at the Baltic Sea region (Rytkönen, Siitonen, et al., 2002).

Table 2-1 Engine efficiencies of different marine engine applications (Kågeson 1999)

Engine type	Efficiency [%]
Low-speed diesel (60-250 rpm)	48-54
Medium-speed diesel (250-1000 rpm)	43-50
High speed diesel (1000 rpm)	40-43
Gas turbine 10 MW	32-39
Steam turbine	30-37
Gas diesel engine, medium speed	43-50
Gas Otto engine, medium speed	46-47
Gas Otto engine, high speed	37-40

2.3

The main ports at the Gulf of Finland and the Gulf of Bothnia

At the Gulf of Finland the biggest ports are Helsinki, Sköldvik, Kotka, Hamina, St. Petersburg and Tallinn. Sköldvik is the port of the oil company Neste oil and thus a large import port of mineral oils. It is the largest port in Finland in the terms of cargo turnover. The port of Helsinki is the largest general cargo and passenger ship port in Finland with more than 10000 port calls in year. The ports of Kotka and Hamina were used to known as transit ports for the forest products and now they are growing again after short decline period after the disintegration of the Soviet Union. The port of St. Petersburg is a large multipurpose port and it is divided into four areas, which are specialised to handle different products. The biggest product groups in the terms of cargo weight are oil products and metals. The port of Tallinn is the one of the largest companies in Estonia and it accounts for 78% of the total business volume in Estonia. There are about 60 vessel movements at the bay of Tallinn in a day. Most of the ships are small or medium size (GRT less than 10000). Other important vessel groups are the passenger vessels and ferries. (Rytkönen, Siitonen, et al., 2002)

At the Gulf of Bothnia the biggest ports are Turku, Naantali, Pori, Rauma, Rautaruukki and Kokkola at the Finnish side and Luleå at the Swedish side. The port of Luleå handles bulk, ore, coal and liquid cargo and it is the largest bulk port in Sweden. Naantali is an oil terminal of Neste oil, Pori and Rauma handle mostly export of the Finnish forest industry products, Kokkola handles ores, minerals and chemicals and the port of Rautaruukki in Raahe is a port of the Finnish steel company Rautaruukki. (Rytkönen, Siitonen, et al., 2002)

2.4

Automatic Identification System (AIS)

The countries surrounding the Baltic Sea have agreed to compile statistics on the ship movements at the Baltic Sea within HELCOM collaboration. The ship movement statistics are compiled with the Automatic Identification System (AIS) at the Baltic Sea from the beginning of July 2005. The HELCOM countries collect data through their AIS ground station network and send them to the AIS-statistic server in Denmark. All the ships with the size larger than 300 gross tonnage have to register to the AIS network and have the AIS equipment on board. (personal communication, K. Heikonen, FMA, 9.5.2005)

From the AIS statistics server the ship traffic information can be found from twelve passage lines at the Baltic Sea. These include the mouth of the Gulf of Finland and the mouth of the Gulf of Bothnia east from Aland and west from Aland. The statistics can be grouped in several ways for example by country, ship type and cargo type. The time period of the data vary from daily to yearly numbers.

A preliminary comparison of the AIS data available at the moment and the data used in this study indicate that at the moment the AIS data is not feasible data source considering this study because it does not register all the ships and the places where the statistics are compiled are not comparable with the sea areas used in this study. Therefore the AIS data was not utilized in this study when evaluating the future shipping emissions. However, it might become a useful tool in ship traffic and emissions assessments in the future.

3 Methods and materials

In this study the emissions were calculated for different types of ships at the fairways of the Gulf of Finland and Gulf of Bothnia for years 2000 and 2015. The pollutants considered were sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and hydrocarbons (HC). The cargo and passenger ships sailing at the sea routes were divided into smaller ship groups according to their type.

The types of cargo and passenger ships used in this study are:

- passenger vessels
- passenger ferries
- cargo ferries
- bulk carriers
- tankers
- containers
- other dry cargo vessels
- other vessels

The sea areas near Finland were divided into five parts to get a better spatial view of where shipping emissions were generated. The Gulf of Finland was divided into eastern and western side the border going between Helsinki and Tallinn in a way that the both ports were at the western side. The Gulf of Bothnia was divided into three parts: the Archipelago Sea, the Bothnian Sea and the Bothnian Bay. The area of the Archipelago Sea constitutes of the sea areas around Aland. The border of the western Gulf of Finland and the Archipelago Sea is situated at the western side of the port of Hanko. The northern border of the Archipelago Sea is at the southern side of the port of Rauma and norhern side of the port of Gefle. The border between the Bothnian Sea and the Bothnian Bay is situated at the northern side of the ports of Vaasa and Umeå. The five sea areas are presented in Figure 3.1.

In general the amount of emissions *EM* of a certain pollutant *(j)* from a certain kind of ships *(i)* in certain year *(t)* was calculated by estimating the ship movements *M*, ships' average engine power P and emission factors *f:*

$$EM(t)_{i,j} = M(t)_i \times P_i \times f(t)_{i,j.} \qquad (3.1)$$

Besides this, the ship emissions at the Finnish ports and emissions from work and recreational vessels and boats in Finnish coastal areas and inland waters were included in this study based on the results of the Meeri calculation system developed by VTT Building and Transport (Mäkelä et al., 2002).

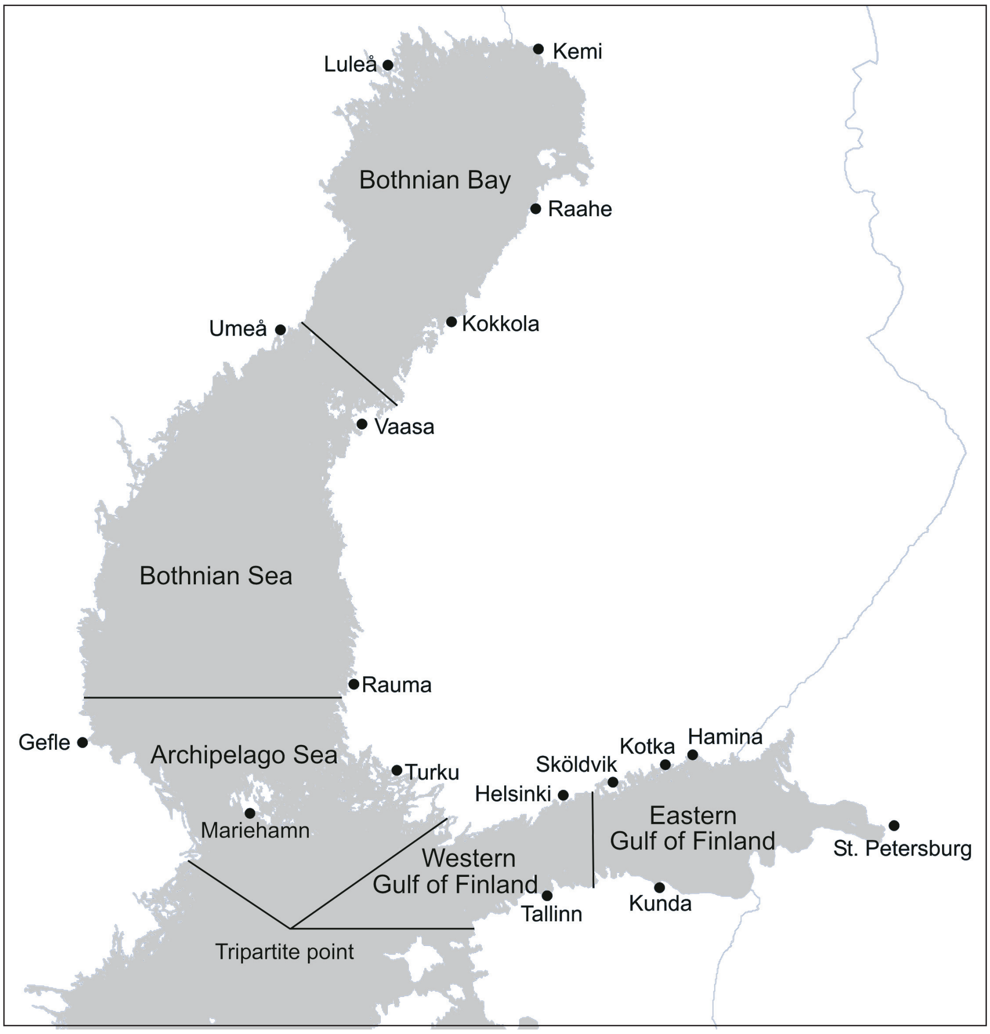

Figure 3.1 Sea areas included in this study.

3.1

Ship movements

The statistics of the ship movements at the Gulf of Finland, Gulf of Bothnia and inland waters of Finland in 2000 were gathered from various sources. A general picture of the cargo ship traffic volumes at the Baltic Sea in year 2000 was obtained from the report of Rytkönen, Siitonen, et al. (2002). This data was combined with more detailed statistics of port calls in Finland, Russia, Estonia and Sweden. The Finnish Maritime Administration (FMA) compiles statistics on the ships arriving to and departing from the Finnish ports each year (Table 3.1). These statistics include the number of the different types of cargo and passenger ships in international traffic and the combined gross tonnage of each of the ship types in each of the Finnish ports. FMA also compiles statistics on the port calls of the cargo ships in domestic traffic but the types of these ships are not known. However the domestic marine cargo traffic is mainly transport of oil and sand. (personal communication, H. Federley, FMA, 4.5.2005)

Information of the port calls at the Estonia and Russian harbours were found from the report of Swedish Maritime Administration where the port calls in Estonian and Russian harbours at the Baltic Sea at the second half of year 1998 are listed (Vieweg et al., 1999). The total numbers of the port calls in Estonian ports from year 2000 were found from the web pages of the port of Tallinn and the port of Kunda, which are the most important ports in Estonia at the Gulf of Finland (www.ts.ee, 2005; www.knc.ee, 2005). From the report of Rytkönen, Siitonen, et al. (2002) the number of ships sailed to and from St. Petersburg were found. All the ships sailing to Russia at the Gulf of Finland were assumed to sail to St. Petersburg. The proportions of the different kind of ships in Russian and Estonian ports in 1998 were calculated and then assumed that the distribution of the different ship types was the same in 2000. This way the numbers of the different types of ships calling at the ports of Tallinn, Kunda and St. Petersburg in 2000 were evaluated (Table 3.1). The average sizes of these ships were assumed to be the same than the sizes of the similar ships visiting the Finnish ports.

There was no information of the ship traffic in the Swedish harbours at the Gulf of Bothnia available. Therefore the number of ships visiting the Swedish ports was evaluated based on the figure in the report of Rytkönen, Siitonen, et al. (2002) where the traffic volumes at the largest ports at the Swedish side of the Gulf of Bothnia (Luleå, Umeå and Gefle) are presented. These numbers were combined with the number of the ship passages at the mouth of the Gulf of the Bothnia and the ship statistics from FMA for evaluating the total ship movements at the Gulf of Bothnia (Table 3.2). The distribution of the different types of ships sailing to Sweden was assumed to be the same with the ship type distribution of the ships sailing to Finnish ports at each of the three sea areas of the Gulf of Bothnia.

The passenger ships usually have regular routes. At the Gulf of Finland the main passenger ship routes are Helsinki - Stockholm and Helsinki - Tallinn. Besides these there were passenger vessels and cruise ferries visiting Helsinki, Kotka, Tallinn and St. Petersburg (Rytkönen, Siitonen, et al., 2002). At the Gulf of Bothnia the passenger ships sail at the routes Turku-Mariehamn-Stockholm and Vaasa-Umeå. There are also many passenger ferries visiting Aland.

The sailing directions of the cargo ships are not known from the statistics mentioned above. The directions are estimated based on information obtained from the ports of Helsinki and Hamina (personal communication, E. Tuomola-Oinonen, Port of Helsinki and M. Lehtonen, Port of Hamina, 23.5.2005), the information found from the web pages of some ports and the total traffic figures presented by Rytkönen, Siitonen, et al. (2002). The numbers of the ships sailing to different directions are only indicative and contain some uncertainty. However, in the case of cargo ships majority of the ships have origin or destination outside the selected sea areas and the shipping inside the Gulf of Finland and Gulf of Bothnia have only a minor role in total cargo ship traffic.

Table 3.1: Numbers of ships arriving to and departing from Finnish, Estonian and Russian ports at Gulf of Finland

	Finland	Estonia	Russia
Passenger ships	4030	3777	0
Passenger ferries	12038	8711	466
Cargo ferries	6941	488	586
Containers	1729	192	734
Bulk carriers	599	333	984
Other dry cargo vessels	5762	5483	9389
Tankers	2426	1705	1688
Other vessels	1036	109	1164
Domestic traffic	1660	0	0
Total	36221	20798	15011

Table 3.2: Numbers of ships arriving to and departing from ports of Archipelago Sea, Bothnian Sea and Bothnian Bay

	The Archipelago Sea	The Bothnian Sea	The Bothnian Bay
Passenger vessels	7	2	0
Passenger ferries	14497	910	0
Train ferries	597	0	0
Cargo ferries	4590	1913	1149
Containers	76	420	16
Bulk carriers	232	316	561
Other dry cargo vessels	2623	4179	3329
Tankers	1019	486	623
Other vessels	996	399	794
Domestic traffic	1453	534	441
Total	26091	9158	6472

The sailed distances are calculated separately for the vessels in international and domestic traffic. The cargo ships in international traffic arriving from west or departing to west at the Gulf of Finland and the ships arriving from south or departing to south at the Gulf of Bothnia are assumed to sail through the tripartite point, which is located south of Aland. The tripartite point is the crossing point of the economic areas of Finland, Sweden and Estonia.

At the Gulf of Finland the information obtained from the ports of Helsinki and Hamina gives an overall picture of the density of the seaborne traffic between Finland and Russia and Finland and Estonia. The numbers from the port of Hamina are assumed to apply also for the ports of Kotka and Loviisa since they have similar profile as export ports of forest products. From all other Finnish harbours at the Gulf of Finland the cargo vessels are assumed to sail to west. No statistics of the seaborne traffic between Russia and Estonia were found but the few pieces of information found from the web page of the port of Tallinn indicates this to be insignificant (www.ts.ee, 2005). Therefore it is assumed that ships from Estonia sail to west.

At the Gulf of Bothnia the majority of the cargo ships are assumed to have an origin or destination south from the Gulf of Bothnia and they visit only one port at the Gulf of Bothnia. Because there are more ship calls at the ports of the Gulf of Bothnia than the number of ship passages at the mouth of the Gulf of Bothnia rest of the ships are assumed to sail between Finland and Sweden.

At the Gulf of Bothnia the ships sailing to the different sea areas have different average sizes and thus different engine sizes. Therefore the sailed distances for the ships with origin or destination at the different sea areas are calculated separately at each of the three parts of the Gulf of Bothnia. To make the calculations simpler the specific distances to each of the harbours at the Gulf of Finland are used only for the largest ports and for the smaller ports average distances were used.

There was no information available of the cargo ship routes in domestic traffic. The major ports in domestic traffic are Naantali and Sköldvik oil terminals and the ports on islands (personal communication, H. Federley, FMA, 4.5.2005). Domestic vessel movements were evaluated based on the number of vessel journeys and estimated average sailed distance of 300 kilometres.

Besides the cargo and passenger ships there are also smaller vessels and boats sailing at the Finnish coastal areas and inland waters: work and fishing vessels and boats and recreational vessels and boats. In 2000 the number of work vessels and boats were approximately 1900, number of fishing vessels were about 3600 and number of recreational boats about 363000 (Mäkelä et al., 2002).

3.2

Engine sizes and fuel and energy consumption

The average engine sizes for the ships in different size classes at the selected sea areas were evaluated based on data in Meeri calculation system (Mäkelä et al., 2002). It was assumed that when sailing at the sea route a ship uses its main engines at 80 per cent load and its auxiliary engines at 20 per cent load. Also the ships' average speed was assumed to be the speed at 80 per cent engine load. The auxiliary engines were all assumed to be 4-stroke engines. The engine sizes, average speed at the 80 per cent engine load and the proportions of the 2-stroke and the 4-stroke engines for the different types of ships at the Gulf of Finland, the Archipelago Sea, the Bothnian Sea and the Bothnian Bay are listed in Appendix A.

The marine fuels are divided into two categories: heavy fuel oil (HFO) and light marine distillates. The light marine distillates are further divided into marine diesel oil (MDO) and marine gas oil (MGO), which often has the lowest sulphur content. Heavy fuel oil usually has high sulphur content. Large ships mostly have HFO as a standard fuel but they might use lighter fuel in their auxiliary engines. Small vessels use light marine distillates also in their main engines. (EEB et al., 2004)

A modern two-stroke diesel engine consumes fuel about 160 g/kWh where as the fuel consumption of a modern 4-stroke diesel engine is about 170 g/kWh. The older diesel engines consume fuel about 200-210 g/kWh (Mäkelä et al., 2002). In this study an average fuel consumption of 200 g/kWh was assumed for all the engines at all loads. The fuel consumption for the different kinds of ships, FC_i, was calculated by:

$$FC_i = (E_i^m + E_i^a) m_{aver} \tag{3.2}$$

where E^m and E^a are the energy consumptions of the main and auxiliary engines, respectively, and m_{aver} is the average fuel consumption, m_{aver} = 200 g/kWh.

The energy consumptions of the different ship types at the sea routes were calculated separately for the 2- and 4-stroke main engines and for the auxiliary engines. The energy consumption of the main engines E^m and of the auxiliary engines E^a (in kilowatt hours) at the sea routes were calculated by:

$$E_{i,k}^m = 0{,}8 \cdot \sum_{n=1}^{3} \frac{s_{i,n} x_{i,k,n}}{v_{i,n}} P_{i,n}^m \tag{3.3}$$

and

$$E_{i,k}^a = 0{,}2 \cdot \sum_{n=1}^{3} \frac{s_{i,n}}{v_{i,n}} P_{i,n}^a \tag{3.4}$$

where s is the distance that the ships sail at the different sea areas, v is the speed of the ships sailing to the different areas, x is the proportion of ships using 2-stroke and 4-stroke engines and P^m is the power of the main engines and P^a is the power of the auxiliary engines. The suffix *i* means the ship type, suffix *k* means the engine type (2-stroke or 4-stroke) suffixes *1 - 3* mean the sea area where the ships have their origin or destination. At the Gulf of Finland the average ship and engine sizes were assumed to be the same for a certain type of ships at the whole sea area and therefore only the first term was needed to calculate the energy consumption. At the Gulf of Bothnia the suffix *1* refers to the Archipelago Sea, suffix *2* refers to the Bothnian Sea area and suffix *3* refers to the Bothnian Bay.

3.3
Emission calculation

Shipping emissions at the sea routes were calculated in different ways for SO_2 emissions and emissions of the other air pollutants. The calculation of the amount of SO_2 was based on the fuel consumption of the ships and the average sulphur content in the fuels. The amounts of other pollutants were evaluated using emission factors that are depended on vessel and engine types.

3.3.1
Sulphur dioxide emissions

The amount of SO_2 emissions depends mainly on the amount of sulphur in the fuel.

Distribution of consumption of different liquid fuels and the amount of sulphur in the fuel for year 2000 used in this study are based on Meeri data (Mäkelä et al., 2002). The distribution of the consumption of fuels with different sulphur contents can be seen in Table 3.3. The average amounts of sulphur in fuel $m_{S,i}$ were then 16.9 g/kg fuel and 3.7 g/kg fuel for cargo and passenger ships respectively.

In the combustion process sulphur in fuel oxidizes mainly to sulphur dioxide. The molar mass of SO_2 (64 g/mol) is two times the molar mass of sulphur (32 g/mol) and therefore the theoretical amount of sulphur dioxide formed is two times the amount of sulphur in the fuel. According to IIASA the amount of sulphur that does not form sulphur oxides is approximately four per cent of the amount of sulphur in fuel. Thus, the amount of SO_2 formed $mso_{2,i}$ was calculated for cargo and passenger ships with equation:

$$m_{SO2,i} = 0{,}96 \cdot 2 \cdot m_{S,i} \tag{3.5}$$

Table 3.3: Distribution of consumption of fuels with different sulphur contents

Cargo vessels	Diesel oil/ gas oil	Heavy fuel oil (<1.5 % S)	Heavy fuel oil (1.5-2.7 % S)	Heavy fuel oil (>2.7 % S)
Proportion	0.094	0.286	0.502	0.118
Amount in fuel (g/kg)	0	7.5	21	36
Passenger vessels	**Gas oil (< 0.15 % S)**	**Marine diesel oil (<0.2 % S)**	**Heavy fuel oil (<0,5 % S)**	**Heavy fuel oil (<2 % S)**
Proportion	0.01	0.17	0.76	0.06
Amount in fuel (g/kg)	0.75	1	3.5	12.5

3.3.2
Other emissions

Emissions of NO_x, CO, HC and PM from the certain kind of ships at the sea routes were calculated by multiplying the energy consumption of the ships *E* with a certain emission factor *f*. The amount of the selected pollutant $EM_{i,j}$ emitted is then:

$$EM_{i,j} = E^{m}_{i,2-stroke} f^{m}_{j,2-stroke} + E^{m}_{i,4-stroke} f^{m}_{j,4-stroke} + E^{a}_{i} f^{a}_{j,4-stroke} \tag{3.6}$$

where the suffix *j* refers to the selected pollutant and suffixes *2-stroke* and *4-stroke* refer to the engine types. Emission factors of CO, HC, NO_x and PM emissions for the cargo and passenger ships used in this study for 2000 are based on data in Meeri system (Table 3.4) (Mäkelä et al., 2002). The results can be found in the Chapter 4.

Table 3.4: Emission factors for CO, HC, NO_x and PM (g/kWh) in 2000

	Load	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)
Cargo ships					
2-stroke	80 %	0.6	0.39	16.82	0.48
	20 %	0.8	0.49	16.25	0.57
4-stroke	80 %	1	0.39	13.3	0.29
	20 %	2	0.49	15.2	0.38
Passenger ships					
2-stroke	80 %	0.5	0.37	15.58	0.49
	20 %	0.66	0.46	15.05	0.59
4-stroke	80 %	0.83	0.37	12.32	0.29
	20 %	1.66	0.46	14.08	0.39

The total ship emissions in the fairways of Finnish inland waters and at ports as well as emissions from the work and recreational vessels were evaluated based on data in Meeri system. Emissions at the ports include the emissions that the ships produce at the berth and the emissions that the ships produce during twenty minutes of sailing to and from the harbour. The twenty minutes is evaluated to be the average time that the ships spend sailing at the harbour route and for the harbour manoeuvres on arrival and departure. (Mäkelä et al., 2002)

4 Ship emissions in 2000

The cargo and passenger ships sailing on sea routes were the largest sources of SO_2, NO_x and PM emissions of waterborne traffic in Finnish and nearby sea and lake areas in 2000 (Table 4.1). They contributed to more than 80 % of the total waterborne emissions for each of these pollutants. The areas where the largest amounts of pollutants were formed were also the areas where the numbers of ship movements were the largest. In the case of CO and HC emissions the major polluters were recreational vessels and boats, which contributed to more than 70 % of these emissions.

The amounts of SO_2 and NO_x from waterborne traffic were significant when compared to the emissions from Finnish land-based sources. They contributed to 49 % and 53 %, respectively, of the amounts from land-based sources in 2000 (Figure 4.1). The amounts of PM and CO emissions from waterborne traffic were less significant, about 5 %, compared to the amounts from land-based sources.

The results from emission calculations on the sea routes are discussed in detail in Sections 4.1.1 and 4.1.2. The emissions in Finnish ports and inland waterways and emissions from Finnish work and recreational vessels are reviewed in Section 4.2.

Table 4.1: Total emissions of waterborne traffic in Finland and northern Baltic Sea

	Energy consumption [PJ/a]	**SO_2 [Gg/a]**	**CO [Gg/a]**	**HC [Gg/a]**	**NO_x [Gg/a]**	**PM [Gg/a]**
Fairways	58.7	35.6	5.7	2.8	107.2	2.8
Eastern Gulf of Finland	6.8	5.1	0.7	0.3	12.8	0.3
Western Gulf of Finland	22.1	13.5	2.1	1.1	40.3	1.0
Archipelago Sea	21.5	10.4	2.1	1.0	37.6	1.0
Bothnian Sea	5.6	4.4	0.5	0.3	11.0	0.3
Bothnian Bay	2.6	2.1	0.2	0.1	5.2	0.1
Inland waters	0.1	0.07	0.01	0.004	0.2	0.006
Ports in Finland	4.6	2.4	0.6	0.2	7.3	0.1
Work and fishing vessels	3.6	0.3	0.7	0.2	5.7	0.1
Recreational boats	2.6	0.08	24.0	8.4	1.3	0.4
Total	69.4	38.3	31.0	11.7	121.5	3.4

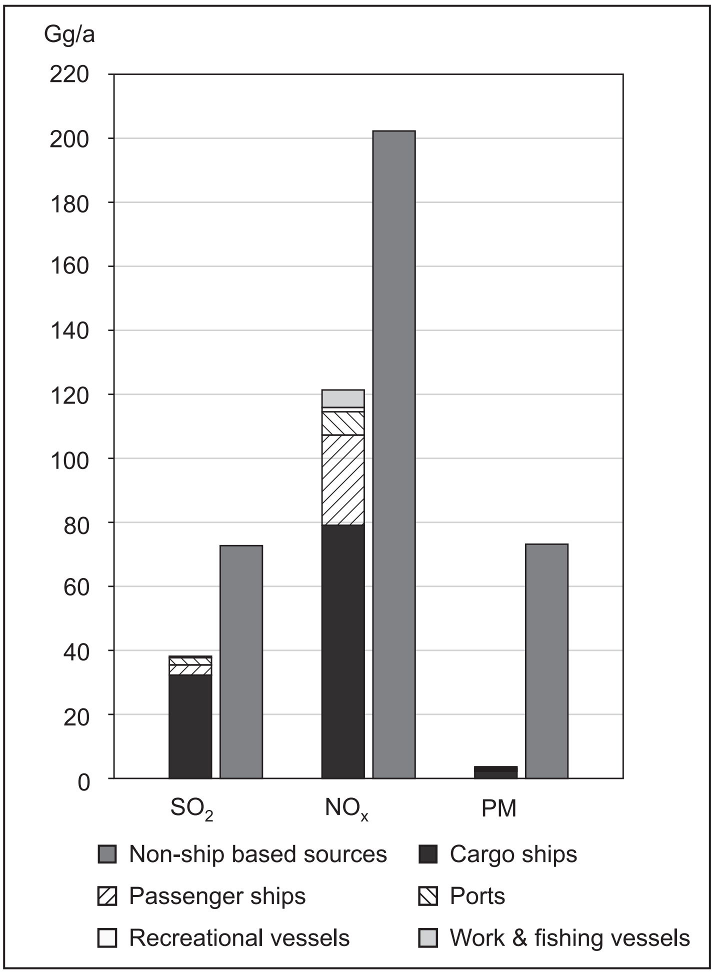

Figure 4.1: Emissions from waterborne traffic and non-ship based sources in Finland in 2000 (emissions from non-ship based sources reported in (Finnish Environment Institute, 2005)).

4.1

Emissions on the sea routes

4.1.1

Gulf of Finland

In the western side of the Gulf of Finland the shipping emissions were largest of the five sea areas included in this study. The largest contributors to SO_2 emissions were cargo ferries, other dry cargo vessels and tankers (Table 4.2). Despite the large number of passenger ferries their share of the SO_2 emissions was less significant. This is due the low-sulphur fuels that are frequently used in passenger ships. In the other emission categories the passenger ferries were a major pollution source together with cargo ferries and other dry cargo vessels. The passenger ferries were the largest contributors to CO and HC emissions. In case of NO_x and PM emissions the largest sources were cargo ferries and other dry cargo vessels with almost equal amount of emissions. Together they produced approximately half of these pollutants in the western Gulf of Finland.

This study was concentrated on quantifying shipping emissions on the sea routes in the sea areas near Finland. The amounts of emissions generated on the sea routes are significant also when the spatial distribution of air pollutant emissions in Finland and selected sea areas is considered. In general, ship-based emissions are largest on the sea routes in the western side of the Gulf of Finland and the Archipelago Sea.

Total NOx emissions generated on the sea routes and in Finland and their spatial distribution is presented in Figure 4.2. The spatial distribution of the ship-based NOx emissions corresponds well with the spatial distributions of the other ship-based pollutants considered in this study.

In the eastern side of the Gulf of Finland the emissions were significantly lower than at the western side. The SO_2 emissions were about 38 % and NO_x emissions about 32 % of the level of western side. The largest emission sources at the eastern Gulf of Finland were other dry cargo vessels and tankers (Table 4.3). Their share of the total emissions were 60-70 % depending on the pollutant.

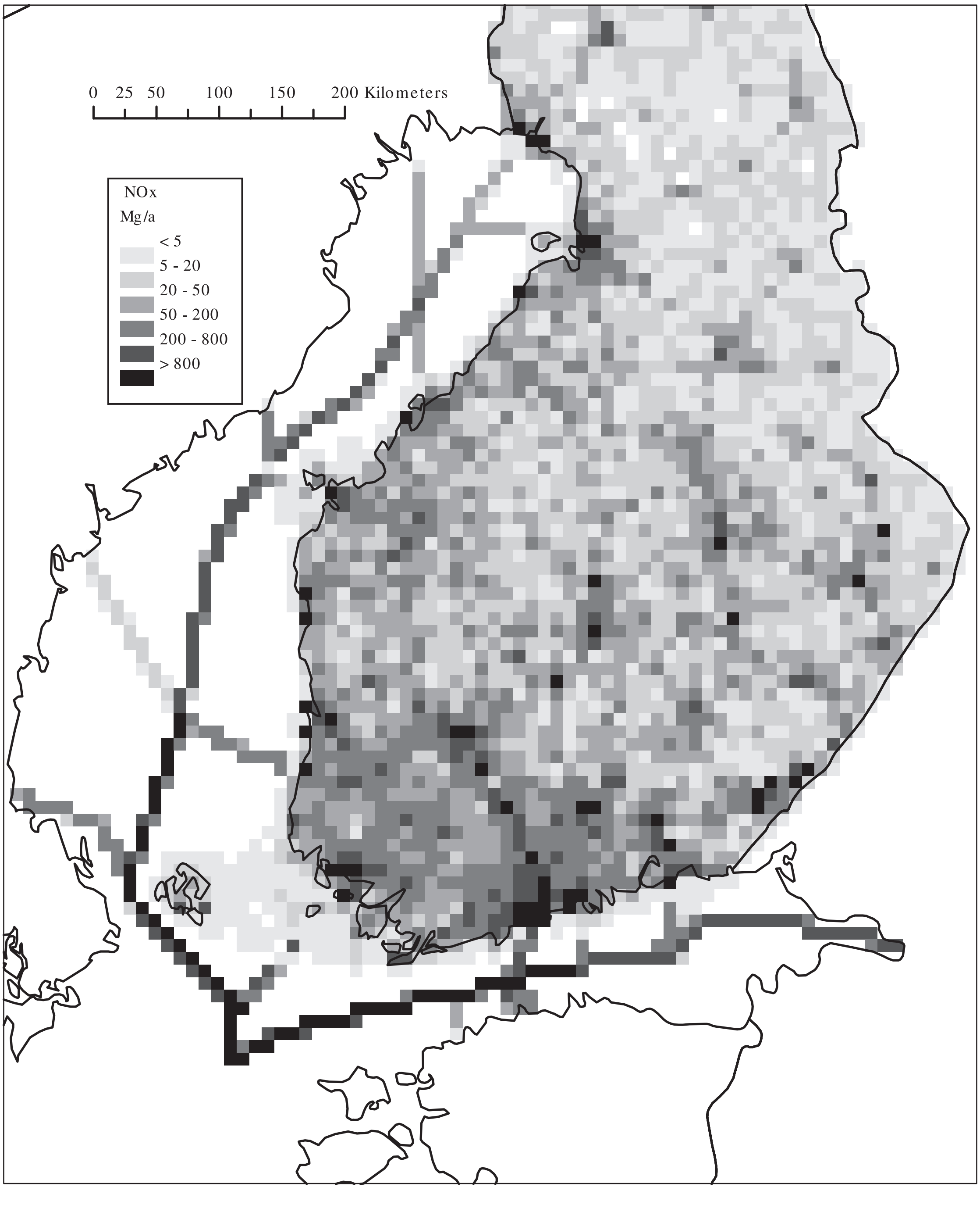

Figure 4.2. Total NO_x emissions in Finland (Karvosenoja et al. 2005) and on sea routes in 2000 pre-sented in 10×10 km^2 grid. On shoreline and in port areas emissions from land-based sources are shown.

Table 4.2: Ship emissions in western Gulf of Finland in 2000

	Energy consumption [TJ/a]	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Passenger vessels	953	162	99	43	1451	35
Passenger ferries	5759	979	605	263	8790	211
Cargo ferries	5039	4046	417	246	10262	285
Containers	727	584	67	36	1428	38
Bulk carriers	1101	884	93	54	2232	62
Other dry cargo vessels	4980	3998	471	247	10050	276
Tankers	3157	2535	359	153	5519	129
Other vessels	248	199	29	12	438	10
Domestic traffic	87	70	10	4	155	4
Total	22050	13456	2149	1058	40326	1049

Table 4.3: Ship emissions in eastern Gulf of Finland in 2000

	Energy consumption [TJ/a]	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Passenger vessels	75	13	8	3	114	3
Passenger ferries	458	78	48	21	698	17
Cargo ferries	614	493	51	30	1250	35
Containers	427	343	39	21	839	22
Bulk carriers	725	582	61	35	1469	41
Other dry cargo vessels	2468	1981	233	122	4981	137
Tankers	1696	1362	193	82	2965	69
Other vessels	177	142	18	8	294	7
Domestic traffic	126	101	15	6	223	5
Total	6765	5094	666	329	12832	336

4.1.2

Gulf of Bothnia

At the Archipelago Sea the largest polluters were passenger ferries and cargo ferries (Table 4.4). Also other dry cargo vessels produced a large share of emissions especially in the case of the SO_2 emissions. These three ship categories formed approximately three quarters of the SO_2 emissions and 80-85 % of other emissions. The passenger ferries had the largest share in all the emission categories except SO_2 emissions. The largest source of SO_2 were the cargo ferries.

At the Bothnian Sea the cargo ferries and the other dry cargo ferries were the largest sources of pollutions (Table 4.5). The third largest polluters were the other vessels but the amounts of pollutants emitted from these vessels were significantly smaller than the first two had. The total amounts of emissions in each of the emission categories were about 30 % or less of the amount of emissions in the Archipelago Sea. The difference in the number of ships was about 39 %. The different numbers are explained by the large number of passenger ships in the Archipelago Sea. On average they were larger and had larger engines than the cargo ships and thus polluted more. However, due to cleaner fuels used in them, the difference in SO_2 emissions were slightly smaller than in other emission categories. The amount of SO_2 emissions were 42 % of the amount in the Archipelago Sea.

Again at the Bothnian Bay the largest sources of pollutants were cargo ferries and other dry cargo vessels (Table 4.6). Also here the third biggest source of pollutions was the other vessels and, unlike elsewhere, here they polluted almost as much as the cargo ferries. The reason for this is the large size of the other vessels. They had larger engines than the cargo ferries that was the largest ship type at the other sea areas. In general, the amounts of each of the air pollutants were less than 20 % of the amounts in the Archipelago Sea and less than half of the amounts in the Bothnian Sea.

Table 4.4: Ship emissions in Archipelago Sea in 2000

	Energy consumption [TJ/a]	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Passenger vessels	14	2	1	1	22	1
Passenger ferries	10825	1841	1127	494	16503	395
Train ferries	358	287	37	19	785	22
Cargo ferries	4950	3974	413	241	10063	279
Containers	185	149	18	9	360	10
Bulk carriers	451	362	43	22	875	23
Tankers	897	721	80	44	1787	49
Other dry cargo vessels	2630	2112	276	129	4894	124
Other vessels	877	704	80	43	1731	47
Domestic traffic	355	285	42	17	622	15
Total	21543	10436	2116	1019	37642	962

Table 4.5: Ship emissions in Bothnian Sea in 2000

	Energy consumption [TJ/a]	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Passenger ferries	162	28	20	8	269	7
Cargo ferries	1538	1235	130	75	3119	86
Containers	106	85	10	5	206	5
Bulk carriers	278	223	29	14	520	13
Tankers	558	448	48	27	1123	31
Other dry cargo vessels	2124	1706	212	104	4039	104
Other vessels	824	661	70	40	1660	46
Domestic traffic	45	36	6	2	75	2
Total	5634	4421	524	275	11010	294

Table 4.6: Ship emissions in Bothnian Bay in 2000

	Energy consumption [TJ/a]	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Cargo ferries	536	431	45	26	1088	30
Containers	3	2	0,3	0,1	5	0,1
Bulk carriers	104	84	12	5	183	4
Tankers	291	234	25	14	590	16
Other dry cargo vessels	986	792	91	48	1937	52
Other vessels	504	405	42	25	1027	28
Domestic traffic	172	138	16	8	338	9
Total	2597	2085	231	127	5168	140

4.2

Emissions in ports, inland waters and from smaller vessels

The emission values in this section are based on the results of Meeri calculation system (Mäkelä et al., 2002). Ship-based emissions in the Finnish ports were largest in the ports of the western side of the Gulf of Finland and at the Archipelago Sea (Table 4.7). Also the individual ports where the emissions were largest are situated in these areas. Air pollutant emissions were largest in the port of Helsinki followed by the ports of Turku, Naantali and Mariehamn. In the eastern Gulf of Finland the emission levels were largest in the port of Hamina, in the Bothnian Sea in the port of Rauma and in the Bothnian in the port of Rautaruukki.

Emissions from cargo and passenger vessels in the inland waters (Table 4.8) were low compared to the emissions in the sea routes. The energy consumption of ships at inland waters were small due to small number of ship movements and small size of the vessels. Majority of the emissions in the inland waters are produced by dry cargo vessels.

Recreational vessels and boats generated majority of carbon monoxide and hydrocarbon emissions of the waterborne traffic in Finland. The reason for high CO and HC emissions is that most engines in recreational boats are two-stroke engines that burn gasoline inefficiently causing high emissions due to unburned fuel. Inefficient combustion process also causes high particulate matter emissions. Emissions from recreational boats, work and fishing vessels and icebreakers are presented in Table 4.9.

Table 4.7: Ship emissions at Finnish ports in 2000

	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Eastern Gulf of Finland	411	72	29	973	18
Western Gulf of Finland	704	197	71	2339	49
Archipelago Sea	701	221	78	2 573	56
Bothnian Sea	274	53	21	690	13
Bothnian Bay	262	46	18	618	11
Inland waters	27	6	2	75	1
Total	2 378	595	219	7 267	148

Table 4.8: Ship emissions at inland waters in Finland in 2000

	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Inland waterways	67	11	4	179	6

Table 4.9: Emissions of Finnish recreational boats, work and fishing vessels and icebreakers in 2000

	SO_2 [t/a]	CO [t/a]	HC [t/a]	NO_x [t/a]	PM [t/a]
Recreational boats	75	24047	8421	1301	351
Work and fishing vessels	149	646	208	4672	100
Icebreakers	128	39	25	1074	30

4.3

Uncertainties and data gaps

There are several uncertainties in the evaluation of the ship traffic at the Gulf of Finland and the Gulf of Bothnia. First of all, there is no data source where all the data needed could be found. The data is collected from various sources and it is from different years, although the main statistics used are from 2000. This causes some uncertainty because different statistics give different values and also the volume of ship traffic is growing each year. The statistics only include the number of ship calls in different harbours, but the origin and destination of the ships are usually unknown, which is another major cause of uncertainty.

The harbours have information of the origins and destinations, but they know only the final destination and other stopping places are still unknown. Because of this the journey of a few ships might be calculated partly twice. For most of the harbours at Gulf of Finland it is assumed that the ships sail to west and the traffic to Russia and Estonia has been evaluated to concentrate only on few ports. This might cause some underestimation to the ship traffic between Finland and Russia and Finland and Estonia. Also the ship traffic between Estonia and Russia are probably underestimated because of lack of coherent information.

The ship types are only known for the Finnish harbours. There is some information of the ship types in Estonian and Russian harbours also, but that is not similar with the FMA's way of categorizing ships. The different operators and data sources might also have their own way to categorize ships. For example passenger ferries take also cargo, so in some statistic they might be included into cargo ship category. At the Gulf of Bothnia all the ships from different harbours are calculated together and the distribution of different ship types is expected to be the same in each harbour. Thus the characteristics of each harbour are not taken into account and therefore the sailed distances for the different types of ships are not very accurate.

The assessment of ship movements might be improved when AIS (Automatic Identification System) monitoring system for the Baltic Sea is taken into use. It aims to provide coherent ship traffic information at the different parts of the Baltic Sea.

There are also uncertainties in the emission factors used. However, uncertainties in ship movements were estimated to clearly dominate the uncertainties in emission calculation.

5 Techniques for reducing emissions from ships

There are several technically and economically feasible techniques to reduce shipping emissions. These techniques are also very cost-effective compared to further emission reduction costs for land-based sources that are already relatively efficiently controlled. The methods to reduce sulphur dioxide emissions are the switch from fuels with a high sulphur content to low-sulphur ones and the introduction of the seawater scrubbing technology. For nitrogen oxides abatement the most promising methods are internal engine modifications, water injection techniques and exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) systems. Particulate matter emissions are reduced with the sulphur dioxide reduction measures and also oxidation catalysts and particulate filters can be used. Carbon monoxide and hydrocarbon emissions from ships are typically low and therefore there are no commercial techniques developed to reduce them separately from marine engines. However, some of the reduction techniques, such as the SCR and EGR systems, also lower amounts of CO and HC emissions. The emissions of the different pollutants can also be reduced by optimizing ships' design, using alternative power sources and using shore-side electricity at ports. In the following more detailed presentation of various emission reduction methods is given based on the literature study.

5.1

Formation of emissions in marine diesel engines

In diesel engines chemical energy of the fuel in converted into mechanical power. Diesel fuel is injected under high pressure into the cylinder where it evaporates and mixes with air and combustion process occurs. Exhaust gases are formed through complex combustion reactions and several parameters affect the formation of emissions (Borman and Ragland, 1998). Diesel exhaust constitutes of gases, vapours, aerosols and particles. They contain the following combustion products (Sarvi, 2004):

- carbon
- nitrogen
- water
- carbon dioxide
- carbon monoxide
- aldehydes
- nitrogen oxides
- sulphur oxides
- polycyclic aromatic hydrocarbons (PAH)

5.1.1
Sulphur dioxide emissions

SO_2 emissions are generated from the sulphur present in fuel. In the combustion process sulphur dioxide is formed through the reaction:

$$S + O_2 \rightarrow SO_2 \tag{5.1}$$

The amount of SO_2 emissions depends on the sulphur content of the fuel used. However, all the sulphur in fuel does not react with oxygen in the combustion process (Lyyränen et al., 1999; Lowenthal et al., 1994). Furthermore, a fraction of SO_2 oxidise to sulphur trioxide (SO_3). SO_3 can react with oxygen and convert back to SO_2. Another possible sink for SO_3 is the reaction with hydrogen to SO_2 and hydroxyl radical (OH) (Flagan and Seinfeld, 1998). Typically, the amount of SO_3 is five per cent of the amount of sulphur oxides (SO_2 and SO_3) (Wärtsilä, 2004). Sulphur trioxide causes corrosion and is thus a serious concern to engine operators. SO_3 is also a precursor of sulphuric acid, which in turn can form sulphate particulate matter emissions. Sulphuric acid can be formed in the reaction with water when exhaust gases containing SO_3 are cooled (Flagan and Seinfeld, 1998):

$$SO_2 + H_2O \rightarrow H_2SO_4 \tag{5.2}$$

5.1.2
Nitrogen oxides emissions

Nitrogen oxides (NO_x) emissions consist of nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrogen and oxygen are converted to nitrogen oxides through a complex process comprising hundreds of different chemical reactions and many intermediate products. The main source of nitrogen is the engine's intake air. Also some fuels contain nitrogen which may also react with oxygen forming NO_x. These reactions require high temperatures that exists in the burning fuel sprays in the combustion chamber. NO is formed first and a part of it converts to NO_2 later in the process: during expansion and in the exhaust process. The typical ratio of NO to NO_x is 0.95 in diesel engine exhaust gases. When the exhaust gases are released to the atmosphere, NO oxidizes to NO_2 within few hours. (Wärtsilä, 2004; Young, 2006)

The amount of NO_x formed depends on the combustion temperature, premixing of fuel and air and duration of the fuel in the cylinder. The NO_x formation rate is highest with a high combustion temperature, poor premixing and long fuel duration (Wärtsilä, 2004). High peak temperatures are typical for unregulated diesel engines because the fuel is injected early to achieve more complete combustion and thus higher fuel efficiency (EPA, 1999). A change of 100 ºC in temperature may change the amount of NO_x by a factor of three. Thus temperature control is an essential means of NO_x reduction. (Young, 2006)

5.1.3
Particulate matter emissions and smoke

Particulate matter (PM) emissions consist of three fractions: soot (dry carbon particles), soluble organic fraction (hydrocarbons absorbed and condensed on carbon particles) and hydrated sulphuric acid (SO_4). In conventional diesel engines the formation of particulate matter is depended on the efficiency and completeness of the combustion process, the amount of hydrocarbons, sulphur and ash in the fuel and the amount of lubricating oil used. Some of the fuel particles do not burn completely and they are emitted as droplets of heavy liquid or carbonaceous material. The incomplete burning is a result of locally low quantities of excess air. The conversion of fuel to unburned particle is most likely to happen when the last bit of fuel is injected or the engine operates at high load. At higher engine loads more fuel is injected and time for combustion is shorter. A mistimed or otherwise poorly operating fuel injection and poor mixing of fuel within the cylinder also result incomplete combustion and increased the particulate matter emissions. Some of the lubricating oil may be partly burned causing particulate matter emissions. When using heavy fuel oil more than 50 per cent of particulate matter emissions are formed from ash and sulphur components in the fuel while using light fuel oil most of the particles consist of carbon and hydrocarbons. (Wärtsilä, 2004; Sarvi, 2004).

There are two different pathways of soot formation in diesel combustion. At low temperatures only aromatics and highly unsaturated hydrocarbons of high molecular weight contribute to formation of soot. Condensation reactions of aromatic compounds produce PAH (polycyclic aromatic hydrocarbons) and soot directly. At high temperatures all hydrocarbon fuels produce soot if burned at sufficiently rich stoichiometry. First hydrocarbons are fragmented into simpler compounds of one or two carbon atoms in pyrolysis. Then soot is formed through slow oxidation reactions. (Karila et al., 2004)

A diesel engine can produce three different types of smoke. These are blue smoke, black smoke and white smoke. White and blue smoke consists of lubricating oil and fuel particles, which are unburned, partially burned or decomposed. Blue smoke indicates a poorly overhauled or tuned engine. White smoke can be seen when a cold engine is started and it also consists water droplets. Black smoke is composed of soot, oil and unburned fuel particles from the incomplete combustion and it is caused by mechanical problem in the engine. (Sarvi, 2004)

5.1.4

Carbon monoxide and hydrocarbon emissions

The formation of carbon monoxide (CO) is a result of incomplete combustion, which is caused due to lack of combustion air or low temperature in some points in the combustion chamber. The same reasons lead also to the formation of hydrocarbons (HC). Hydrocarbons can also be formed from evaporating of the lubrication oil towards the end of the firing period. (Wärtsilä, 2004)

In the diesel engines the CO and HC emissions are usually low compared to other emission sources because of the effective combustion and large amount of excess air. When burning heavy fuel oil the hydrocarbon emissions are lower than from the light fuel oil combustion due to lower evaporating level. (Wärtsilä, 2004)

5.2

Reduction by internal engine adjustments

Many parameters influence the combustion efficiency and emission formation in the combustion process. These include fuel injection timing, combustion chamber geometry, compression ratio, valve timing, turbulence, injection pressure, fuel spray geometry and rate, peak cylinder temperature and pressure and charge air temperature and pressure. A wide range of methods for decreasing the emissions by modifying the engines i.e. altering the parameters mentioned above has been introduced. Many of these methods aim to reduction of NO_x emissions by lowering peak temperature and pressure in the cylinder. This generally decreases the engine's thermal efficiency and increases the amount of PM emissions (and also CO and HC emissions). However some internal engine adjustments can be done to compensate the negative effects. Therefore the control of several in-cylinder parameters is important in diesel engines to ensure low emission levels and good fuel economy. The parameters that affect the combustion process and the formation of emissions can be divided into three categories. The three factors that determine the combustion event and results are charge air characteristics, fuel injection characteristics and combustion conditions in the combustion chamber. The techniques to improve those three segments are described in the sections below. The combustion optimization includes fuel injection timing retard, optimizing of combustion chamber geometry and usage of swirl. The charge air characteristics are improved with turbo-charging and aftercooling of the charged air. Developing the fuel injection system means developing of fuel injection pressure, nozzle geometry, control of injection timing and rate, common rail fuel injection, electronic-hydraulic control of fuel injection and exhaust valve actuation. (EPA, 2003; de Jonge et al., 2005)

Usually engine manufacturers use a combination of several engine modification techniques to limit the emissions from diesel engines (de Jonge et al., 2005). The different combinations tested and used and their effects on emission rates are also discussed later in this chapter.

5.2.1

Combustion optimization

Retarding the fuel injection timing is a simple method for reducing NO_x emissions. The retarded injection shortens the premixed burning phase, when high temperatures occur and lowers the cylinder temperature and pressure leading to lower NO_x emission rates. However, due to shortened combustion time less energy is extracted from fuel and the lower temperature and pressure in the cylinder makes the oxidation of PM less effective. Thus fuel consumption and HC and PM emissions are increased. Combining retarded injection with other fuel injection improvements can delay the start of the injection without altering the end of combustion process. (EPA, 2003)

The reduction of NO_x emissions is dependent on the retardation and the fuel injection duration. Reduction rate up to 30 % has been achieved, but because of the increase in fuel consumption with the retardation the NO_x emission reduction of 10 to 15 per cent has been recommended as best potential reduction. (Trozzi and Vaccaro, 1998)

The retarded injection timing can be achieved mechanically or electronically. Mechanical timing control devices are currently in use in most engines on which the injection timing is set to enable optimal performance at the vessel's most frequent cruising speed when combustion temperature and pressure are highest (EPA, 2003). Electronic systems such as Electronic Unit Injector (EUI) controlled by microprocessor have been used in light fuel diesel engines. With EUI the engine performance is improved and the emission level lowered. However, wider use of the EUI system is limited since the performance of the solenoid valves used in electronic control devices is deteriorated in high temperatures that exist in low-speed diesel engines. Also, the high viscosity of the fuel causes difficulties in the fuel supply through the passage of the control valve. Therefore the electronic system cannot be used in heavy fuel oil fired low-speed diesel engines. (Trozzi and Vaccaro, 1998)

Optimization of the shape of the combustion space has an important role in cutting down PM emissions since incomplete combustion is a major source of PM emissions (Karila et al., 2004). Emission reductions have already been achieved by modification of the combustion chamber. Besides that, additional changes can be made to achieve further improvements in emission control. The combustion chamber parameters that are currently under investigation are the shape of the chamber and location of the injection, reduced crevice volumes and compression ratio. (EPA, 2003)

The tests made by Heider and Eilts (2001) on a MAN B&W diesel engine show that the deposition of fuel that causes increase in soot emissions is avoidable with a flat, unfissured shape of combustion chamber. Combustion chambers with small dead volumes enable better utilization of air during operation under low excess air ratios. The tests also showed that wide piston bowl with raised central hump is an optimal structure when optimizing NO_x and soot emissions and fuel consumption. Some manufacturers have reported smaller inner diameter bowls generate jet/piston interaction that delays the combustion process. At the end of combustion they can generate faster burning rate due to higher turbulence level during jet/piston interaction and as a result the soot oxidizes more efficiently (EPA, 2003).

Higher compression ratio can reduce cold start PM emissions and improve fuel economy. The increased compression ratio can be achieved by redesign of piston crown, longer connecting rod or longer piston. However, increased compression ratio increases combustion pressure and may reduce the engine safety. These issues set limits for raising the compression ratio (EPA, 1999). Wärtsilä uses increased compression ratio as a part of their up-grading package for low-NO_x combustion. They have developed new connection rods to increase compression ratio and new cylinder liners and antipolishing rings to match the increased compression ratio. The higher compression ratio has been combined with optimal injection timing and rate and a reduction of 35 % in NO_x emissions have been achieved (Wärtsilä, 2001).

Swirl can be used to decrease the local fuel-to-air ratio, which leads to lower particulate emissions. Extra fresh air is fed into the fuel spray in vertical direction, which increases mixing of air and fuel and thus combustion process is improved (Karila et al., 2004). The effects of swirl depend on the engine but some common effects can anyway be listed. Reduction in soot emissions is gained but at the same time formation of NO_x is increased. At low loads the better mixing of fuel and air reduces HC, PM and smoke emissions. At high loads swirl causes a slight reduction in PM emissions and fuel consumption. Some of the negative effects, such as the increased formation NO_x can be reduced by a high-pressure fuel system. It also enhances the positive effects such as reduction in PM emissions. When considering only soot emissions usage of swirl is especially beneficial when large orifice diameter is used in fuel spray. (EPA, 1999)

5.2.2

Fuel injection optimization

The fuel injection can be further optimized in the terms of emission reduction and fuel consumption. Thus, the control of many variables involved in fuel injection is essential to reduce diesel engine emissions. The variables that are under research are injection pressure, nozzle geometry, timing of the injection and rate of the injection. (EPA, 1999)

The most common method in adjusting the fuel injection is exchange of conventional fuel valves to low-NO_x slide valves. They are designed to optimize the spray distribution in the combustion chamber while the temperatures in the engines and thus engine reliability are kept the same. With the slide valves the NO_x emissions are reduced by 20 %. The slide valves are available only for low-speed 2-stroke engines and nowadays all the new 2-stroke engines are equipped with slide valves to meet the IMO emissions standards. Also retrofitting the slide valves is an easy operation and requires only few hours work by the ship's crew per cylinder. (de Jonge et al., 2005)

To overcome the loss in thermal efficiency with the retarded injection timing the fuel injection pressure can be raised up to 144-160 MPa. This improves atomization of fuel and mixture of fuel with air and therefore enables the combustion to be complete faster (Trozzi and Vaccaro, 1998). Increased fuel injection pressure also has a positive effect on particulate matter and hydrocarbon emissions and fuel consumption. These effects remain if higher injection pressure is applied without retarded injection but then NO_x emissions tend to increase (EPA, 2003). Tests made by Heider and Eilts (2001) show that by reducing injection nozzle area visible smoke is avoided from a 25 % load without any further measures. Smaller injection areas improve the mixture of fuel and air and thus increases NO_x emissions. The increase can be compensated with retarded fuel injection and an increase in fuel consumption is avoided by increased compression ratio. The authors believe that this combination is the best compromise in optimising soot emissions at low load, NO_x emissions at high load and fuel consumption.

The recent development in the fuel injection technology is the systems that use rate shaping or multiple injections to vary the delivery of fuel over a single injection. Injection of only a small quantity of fuel in the beginning decreases the rapid increase in pressure and temperature that is characteristics for diesel engines. Then most of the fuel is injected into the flame that is already established allowing a steady burn that decreases the formation of NO_x emissions without increasing watter particulate emissions. The rate shaping can be done mechanically and electronically. It has been shown to reduce NO_x emissions by up to 20 %. High pressure multiple injections can reduce NO_x emissions substantially without increasing (PM) emissions. The most important parameters of multiple injections for achieving maximum emission reduction with optimal fuel efficiency are the delay before the final fuel pulse and the duration of the final pulse. This strategy is the most efficient when used with retard injection timing enabling efficient NO_x emissions reduction without increase in PM emissions. The multiple injection systems can be used in electronically controlled engines. (EPA, 1999)

The Hydraulically actuated Electronically controlled Unit Injector (HEUI) system is developed by Caterpillar and Navistar and it provides electronic control over the fuel injection timing and duration allowing also rate shaping. The system operation is not depended on engine speed so the engine can be optimized over larger operation range. For large engines (over 1.5 litres/cylinder) similar system is Mechanically actuated Electronically controlled Unit Injection (MEUI) system. It controls injection pressure, timing and rate shaping independent of the engine speed. Caterpillar has achieved injection pressure of 200 MPa with MEUI system. (EPA, 1999)

5.2.3

Common rail technology

Common rail system is an advanced fuel injection technology, which aims to greater control of fuel injection to improve emissions and overall engine performance. In the common rail system injection pressure and rate are controlled independently from the engine speed and load. Therefore common rail system can keep the fuel injection pressure high and constant at all engine loads enabling the engine to operate without visible smoke. (Sarvi, 2004)

At the conventional fuel injection system the pressure drops at low engine loads resulting in large fuel droplets some of which survive until they hit the combustion space surfaces generating smoke emissions. In common rail system this is prevented with the high pressure injection, which keeps fuel droplet size small. The small droplets are burned before hitting the combustion space surfaces. (Wärtsilä, 2002)

The free selection of the injection pressure and injection start enables the diesel engine to meet the differing requirements at the same time. For example the low NO_x

emissions at medium load and invisible smoke at low load and idling. Primarily the common rail system improves the engine's environmental performance at low loads. At the full load the improvements are only small because the engine performance has been optimized for high loads throughout the years. (Eyring, Köhler, Lauer, and Lemper, 2005)

Besides smokeless operation the common rail technology helps to achieve lower and more constant running speed, reduces fuel consumption especially at part loads and improves combustion process thus the e-ciency due to optimized fuel injection (Kytölä and Heim, 2004). With common rail system the risk of pressure waves is avoided by splitting up the fuel volumes in several accumulators. Common rail technology also improves the engine safety because high-pressure fuel exists only in the hot box of the engine. (Sarvi, 2004)

The common rail system consists of fuel pumps, accumulators, injectors and control unit. The fuel pumps feed high-pressure fuel into the accumulators, which in turn distribute the fuel to the injectors. Each accumulator is electronically connected to the control unit and to fuel injectors of two cylinders. The accumulators are also connected to each other with piping called common rail. The pumps get the power from the camshaft of the engine. It is possible to include two pumping cycles into one camshaft revolution because the fuel pumping and injection timing are not connected with each other. Also less fuel pumps are needed compared to conventional systems because in the common rail system each pump feeds two cylinders. (Kytölä and Heim, 2004)

5.2.4
Turbo-charging and charge-air after-cooling

Modern diesel engines are mostly turbo-charged to increase power output and reduce fuel consumption of the engine. A turbocharger utilizes waste energy in the exhaust gases to drive turbine linked with a centrifugal compressor. The compressor boosts the intake air pressure and thus more air is forced into a cylinder (EPA, 1999).

Increased air-to-fuel ratio reduces PM emissions because it enables particles to oxidize more efficiently. Due to higher air inlet temperature caused by turbocharger the combustion temperature raises. To prevent this an efficient charge-air cooling is used. Cooling of the charged air with turbo-charging leads to the best result in emission reduction. (Karila et al., 2004)

In the charge air after-cooling the compressed air is cooled to reduce temperatures in the combustion chamber and thus the formation of NO_x. The after-cooling is initially developed to improve the specific power output of an engine by increasing the density of charge air. For the marine engines two types of after-cooling technologies are used: jacket-water after-cooling and raw-water after-cooling. The marine engines have an easy access to large cooling medium, oceans and lakes, and therefore EPA believes that after-cooling could have a significant role in reducing NO_x emissions from marine diesel engines. (EPA, 1999)

After cooling also condensates water out of the charge air. This amount may be substantial depending on humidity of air and amount of after-cooling. There are ways to divert the water from engine disposal so it is available to use in other emission control strategies for example for water injection. (EPA, 2003)

5.2.5
Miller cycle

Miller cycle is adapted from the Otto cycle and patented by Ralph Miller in the 1940s. The changed features from the conventional engine are lower compression ratio, highpressure turbo-charging, variable air inlet valve timing and charge-air cooling.

The Miller cycle can be adapted to both two- and four-stroke diesel engines. In the Miller cycle the compression ratio is lowered and the expansion ratio is kept the same than in conventional engines. As a result the temperature in the combustion chamber is lowered but the power output remains unchanged. (Karila et al., 2004)

The lower compression ratio is achieved by early or late inlet valve closing or by opening the exhaust valve during the compression stroke. The early closing of the inlet valve is the most feasible option. It causes the air in cylinder to expand as the piston move downwards after closing the valve. This lowers the charge-air temperature and pressure in the cylinder. As a result the combustion temperature is lower and less nitrogen oxides are formed. There are no pumping losses related to air flow from cylinder to intake port. This increases the efficiency of Miller cycle. Negative effects of Miller cycle are an increase in fuel consumption and an increase in the particulate matter emissions because less soot is oxidized at the lower temperatures. (Karila et al., 2004)

Wärtsilä has adapted early inlet valve closing on their diesel engines. They have achieved to cut down NO_x emissions 35 % (reduction from beginning of 1990) and at the same time the fuel consumption has been kept unaffected or slightly decreased. (Wärtsilä, 2003)

5.2.6
Lubrication technology

The cylinder lubrication oil feed rate has an influence to particulate watter emissions. When the cylinder oil feed rate is reduced PM emissions are also reduced. The cylinder lube oil consumption forms a large share of the engine's operating costs and therefore reducing the lube oil consumption is important also from the economic point of view. (MAN B&W, 2004)

MAN B&W has developed a high-pressure electronically controlled lubrication system. With this system the lube oil is injected into the cylinder at the optimal position and time and thus very low feed rates have been achieved. As a result particulate matter emissions are reduced and less cylinder oil is wasted in the engine. (MAN B&W, 2004)

5.2.7
Combinations of internal engine measures

The engine manufacturers use different combination of these methods to meet the current IMO emission limits. The most common combination used is increased compression ratio, adapted fuel injection, valve timing and different nozzles (EPA, 2003). The different internal engine modifications used by a few engine manufacturers are listed in Table 5.1. The reduction rate of 30-40 % in NO_x emissions can be achieved with all of these different combinations (de Jonge et al., 2005).

Table 5.1: Internal engine modifications used by marine engine manufacturers (EPA, 2003; MAN B&W, 2004; Heider and Eilts, 2001)

Manufacturer	Internal engine modifications
Wärtsilä	Retarded injection Miller cycle valve timing Higher compression ratio Increased turbo efficiency Higher maximum cylinder pressure Common rail injection
MAN B&W	Variable fuel injection timing Increased fuel injection intensity Increased compression ratio Miller cycle valve timing Common rail technology Electronically controlled lubrication system
Caterpillar	Higher compression ratio Higher cylinder pressure Higher charge pressure Flexible injection system
FMC	Two stage injection Miller cycle valve timing Greater stroke/bore ratio Adjustable compression Two stage turbocharger Low intake temperature
Yanmar	Retard injection Shorter combustion time Higher compression ratio Higher boost pressure Reduced nozzle hole size Increased number of holes

5.3

Reduction by engine process modifications

To achieve greater reductions in NO_x emissions than those 20-30 % achieved with internal engine modification engine process modification tools are needed. Engine process modifications mean changing the engine process by introducing new substances to the combustion process. These substances include water, urea or recycled exhaust gases.

5.3.1

Water injection

Addition of water to the combustion process is a promising approach for NO_x reduction. There are many techniques based on water injection to cut down the NO_x emissions. They all take advantage of water's ability to lower the peak temperatures in the combustion chamber and hence reduce the NO_x formation (Wärtsilä, 2003). Besides this water have several other effects on the diesel combustion process (Karila et al., 2004):

- lower flame temperature
- reduced cooling losses
- increased cylinder pressure
- reduced enthalpy loss in the exhaust gas
- longer ignition delay and premixed combustion phase
- faster pressure rise and increased heat release after the start of ignition
- suppressed thermal fuel decomposition

The techniques using the water injection are direct water injection (DWI), use of emulsified fuel and humid air motor (HAM). At all of these the water must have good quality to prevent clogging and in most methods the fuel consumption tend to increase. At high NO_x reduction rates the emissions of unburned CO, HC and PM tend to increase. (Wärtsilä, 2003)

Direct water injection

In the DWI method water is injected into the engine cylinders right after fuel injection when the temperature in the cylinders is optimal for the NO_x reduction process. In direct high pressure water injection the water is injected into the combustion chamber during the fuel injection. This enables cooler combustion space and hence lower NO_x emission level. The atomized water droplets vaporize immediately in the combustion chamber and the peak temperature is lowered as a combined effect of vaporization of liquid water absorbing heat and increased specific heat of the gas around the flame. If too much water is added the volume of the injected liquid increases leading to too long injection duration, which increases soot formation. (Sarvi, 2004)

The water is injected separately from the fuel enabling the water to be injected at the right time and place to obtain the highest possible reduction rate of NO_x. The water injection happens through combined injection valve and nozzle. The nozzle contains two needles enabling water and fuel can be injected independently and water injection does not affect the engine operation whether it is on or not. This also offers a possibility to inject large amount of water without having to de-rate the engine. In the direct high-pressure water injection a high-pressure pump is needed to get the water to the required pressure of 21-40 Mpa (Schmid and Weisser, 2005; Sarvi, 2004).

The typical water-to-fuel-ratios used are in the range of 0.4-0.7 and then the reduction rate of 50-60 % is achieved (de Jonge et al., 2005). When this amount of water is added the quantity of water is substantial and the logistics for providing the fresh water on board must be given some thoughts. Fresh water generators can be heated with the engine’s cooling water or using steam from exhaust gas economizer. The sufficient tank capacity with the necessary fresh water handling system requires some space on board also (Schmid and Weisser, 2005). The cruise ships have the source of fresh water already since the drainage water for example from showers could be filtered and used in the DWI system. On the other ships the water storage would probably be displacing the fuel storage or cargo space. The former option would limit the sailing distance of the ship and latter would decrease its revenue (EPA, 2003).

The DWI has advantages over the other water injection techniques. The liquid water is close to the flame and away from the wall and the fuel-water percentage can be changed for various operating systems (Sarvi, 2004). The possibility to use high water-to-fuel ratio enables a high NO_x reduction potential with DWI. However, a few disadvantages are also related to DWI technology. Major design changes are necessary for fitting the system on an engine. The system increases the fuel consumption and smoke emissions and it cannot be used at low loads at least at the full efficiency in order to avoid formation of white smoke and increase in black smoke (Eilts and Borchsenius, 2001). The costs are higher than with the other water injection techniques because high amounts of fresh water and additional equipment for engine are needed (Eyring, Köhler, Lauer, and Lemper, 2005). Also the lifetime of the water injection nozzles is short (Eilts and Borchsenius, 2001). The DWI technology is not recommended to use with fuel with high sulphur content (more than 3% S). Further research is required to find the best fuel/water percentage for different load conditions (Sarvi, 2004).

Emulsified fuel

In the emulsified fuel -method water is mixed with fuel oil by means of homogenizer before injecting the fuel into combustion chamber. The injection of emulsified fuel enables effective atomization and good distribution of the fuel in the combustion chamber. This results in more complete combustion with lower fuel consumption, a cleaner engine and a reduction in the amount of NO_x, CO, HC and PM pollutants. To obtain the optimal spray in the combustion chamber the recommended size of the water droplets is maximum 5µm. This is easily obtained by using ultrasonic homogenisers. The system also needs a water distiller since the water used for emulsification must be clean and without salts. (Sørgård et al., 2001; MAN B&W, 2004)

In theory, NO_x reduction of 50 % is possible to achieve with the usage of emulsified fuel. However, the reduction rate is proportional to the amount of water added to the fuel and this amount is limited by the maximum delivery capacity of the fuel injection pumps. Therefore the engine has to be derated or the reduction is limited to about 10-20 %. To obtain better reduction rates also at the full load it is necessary to redesign the fuel injection system, camshaft and its drives etc. Also the injection nozzles have to be adapted to the increased amount of fuel. With the new nozzle design the fuel consumption and temperatures might deteriorate if the engine is used without water. The proportion of water is also limited by the viscosity of the emulsion and the amount of heat required to reduce the viscosity for injection. This property of the water fuel emulsion cannot be affected by engine or system design. (Schmid and Weisser, 2005)

MAN B&W (2004) reports test results where 10 % NO_x reduction for each 10 % of water added was achieved for the two-stroke engine. According to the company it is possible to cut the NO_x emissions 20-50 per cent with the emulsified fuel. MAN B&W have also combined the usage of emulsified fuel with variable injection timing believing that it is an optimal package to reduce emissions when considering the compromise of environmental benefits and costs of the system. This system uses fuel-water emulsion with 15-20 % water and retarded injection timing is used at the loads below 80%. The NO_x emissions are cut down to 8 g/kWh and it also has a positive effect on smoke emissions. (Eilts and Borchsenius, 2001)

Trozzi and Vaccaro (1998) refer also a study on emulsified fuel, in which the usage of emulsified fuel at four different engine loads (25, 50, 75 and 100 %) and with two different fuel injection nozzle hole diameters were tested. As a result the emission decreased with an increase in water ratio for marine diesel oil and marine fuel oil. They achieved 60 per cent reduction of NO_x emissions at 60 % water ratio. CO, HC and PM emissions increased at lower engine loads (less than 30 %) but at higher engine loads amount of CO decreased and HC and PM emissions were unaffected. The fuel consumption increased with an increase in water ratio: 10 % increase in water ratio caused 1 % increase in fuel consumption.

Karila et al. (2004) reports studies of water-fuel emulsion with Caterpillar marine engines using heavy fuel. They were comparing the method to the direct water injection and found out that emulsified fuel system was better method in simultaneous NO_x and soot reduction. The group tested emulsions containing 10 %, 20 % and 30 % water and the latter gave the best result for both NO_x and soot emission reduction. Wärtsilä has made some research on emulsified fuel, but used Orimulsion to run the engines. The rate of NO_x reduction has been up 30 % compared to normal heavy fuel oils. (Wärtsilä, 2003)

Humid air motor

Humid air motor (HAM) is a technology where water vapour is added to the combustion air and the formation of NO_x emissions reduces. First the combustion air is turbo-charged and heated and then guided through a specially designed cell where the air is humidified and cooled by taking up moisture from warm cooling water until the air is saturated. Seawater can be used as cooling water and it is heated by thermal losses from the cooling of the engine's jacket and turbo-charging. The saline water from the process is guided back to the sea. (Kågeson, 1999)

HAM technology can reduce NO_x emissions up to 80 % down to level of 4 g/kWh. To achieve that about three times as much water vapour as fuel must be introduced into the combustion chamber. (Eyring, Köhler, Lauer, and Lemper, 2005)

Other advantages of HAM are that it makes the combustion smoother, helps to keep the combustion temperature constant and prevents so-called hot spots in the engine. Usage of HAM reduces fuel and lubricating oil consumption so it has an advantage of reducing also the operating costs of the engine. The bunker oil quality or the engine's workload does not affect the performance of this method (Kågeson, 1999). HAM system involves a distillation process that enables the use of the readily available seawater in the system. This is an advantage compared to other water injection systems, which require clean fresh water. The drawback of the system is the large surface and volume of the humidifier and required heat exchanger, which have high investment costs. (Eyring, Köhler, Lauer, and Lemper, 2005)

Wärtsilä has been developing similar methods to HAM system called Combustion Air Saturation System (CASS) and Steam Injected Diesel (STID). In the CASS technology high pressure water is injected into the inlet air after turbocharger. There are no commercial CASS applications yet but it will be introduced as an option for all Wärtsilä's four-stroke diesel engines. In STID system low-pressure steam is mixed with combustion air before the turbocharger or injected into combustion air after the turbocharging or directly into the air receiver. Beside this high-pressure steam is injected straight to combustion space. Mixing combustion products and steam in high turbulence improves oxidation and hence the soot emissions should reduce significantly. Steam injection also improves efficiency of the process i.e. lower the fuel consumption. However, it is still under development and not available for commercial applications yet. In CASS the potential NO_x reduction is 50-60 % but in STID the reduction is only 25 %. (Hellén, 2005)

5.3.2

Selective non-catalytic reduction

Selective non-catalytic reduction (SNCR) works similarly to SCR method (discussed in Section 5.4.2) but without the use of catalyst. In SNCR a reducing agent (ammonia NH_3 or urea $CO(NH_2)_2$) is injected into the engine's combustion chamber and it reacts with nitrogen oxides formed in combustion converting them to nitrogen and water. The reaction needs a high temperature within the range of 900 - 1000 ºC and sufficient reaction time to be efficient. If the process is run above the sufficient temperature range the production of NO_x increases and below it the ammonia emissions increase. Because of the required high temperature the reducing agent must be injected into the combustion chamber or cylinder right after the combustion or into the exhaust gas immediately thereafter. With the SNCR system NO_x emissions can be reduced by more than 95 %. (Sørgård et al., 2001; Marintek, 1999)

The SNCR method is not as feasible as SCR since it consumes more ammonia. To achieve NO_x reduction of 50 % four times the stoichiometric amount of NH_3 is required. So only 10-12 % of the ammonia react with NO_x and the rest is just burned off. The cost of ammonia is about the same as the cost of heavy fuel oil (Trozzi and Vaccaro, 1998). Other problems are also related in introducing the SNCR technology on engines. The SNCR system needs extensive modifications to be made on the engine, which lowers the overall engine performance and degrade the fuel economy (Marintek, 1999). Also in the SNCR some unwanted side reactions may occur and these should be overcame in order to make SNCR a feasible NO_x reduction option for ships (Klokk, 1995). Alternative reducing agent such as $(HNCO)_3$, HNCO and $(NH_4)_4SO_4$ have been suggested but the price of them makes them undesirable option (Marintek, 1999).

5.3.3

Exhaust gas recirculation

In the exhaust gas recirculation (EGR) system a portion of exhaust gases is guided through a filter, cooled and circulated back to the engine charge air. This will change the physical properties of the charge air and it will have higher thermal capacity. This in turn decreases the peak temperatures and hence the formation of NO_x during the combustion process. In the recirculation process the oxygen concentration of the charge air is lower and thus less O_2 is available to react with nitrogen. EGR system also lowers the combustion speed. (Sørgård et al., 2001)

Because of the reduced amount of oxygen and longer burning time the PM emissions tend to increase especially at the high loads. This problem can be minimized by reducing the recirculated gas flow during the operation at high loads. This would also prevent a loss in total engine power output. The increase of particulate emissions can also be lowered by cooling the recirculated exhaust gas or using high intake boost pressures. By cooling the recirculated gas much higher amount of exhaust gas can be added to the charge air. At low loads this may increase the NO_x emissions because it increases ignition delay but at high loads the reduction rate can even improve. Turbo-charging the recirculated gas has similar effect than cooling. When the gas is turbo-charged more exhaust gas can be added to the charge air without decreasing the amount of fresh air. (EPA, 1999)

Entec reports the reduction of 35 % in NO_x emissions with exhaust gas recirculation (de Jonge et al., 2005). MAN B&W has made some tests at 75 % engine load and NO_x emissions were decreased by 50 % at the 20 % recirculation rate. Also PM emissions were decreased by 20 % and HC emissions by 10 %. However, fuel consumption increased slightly and CO emissions doubled. At lower recirculation ratios the results were similar but with slighter changes compared to values without EGR. (Kjemtrup, 2002)

The major obstacle in usage of EGR is that removing all the particulate matter before the exhaust gas enters the combustion chamber again is very di-cult. The particles stick on cylinder walls and contaminate the lubrication oil by increasing its viscosity. Also the extensive use of residual fuel oil in ships sets some restrictions to the usage of EGR system by causing some complications to the EGR system. These complications are caused mainly by particles, which influence the turbocharger operation and cause increase in smoke emissions. Soot can also deposit in EGR system piping, coolers and valves causing reduction in efficiency of the system in time. Sulphur species in exhaust gases present corrosion problems when forming sulphuric acid. The usage of EGR may also accelerate the deterioration and wear of the combustion chamber. (de Jonge et al., 2005; Klokk, 1995)

To overcome the issues with particulate matter and sulphuric species some attempts to use electrostatic precipitator and catalyst to remove particulate matter and wet scrubber techniques to remove sulphuric species have been made. MAN B&W has obtained promising results in short-term EGR tests (Kjemtrup, 2002). Despite this, the probability to use EGR widely in commercial applications using heavy fuel oil in next five years is minimal (de Jonge et al., 2005).

At the moment there are no EGR systems in use and no full-scale marine test is made. Even with the future development and advances with EGR on marine engine durability, it is likely that EGR will still be best suited for engines using high-grade low-sulphur marine distillates. (de Jonge et al., 2005)

5.4

After-treatment technologies

The after-treatment technologies are systems that are installed to remove pollutants from the exhaust gases that come out of the engine. The after-treatment systems have no effect on engine process and formation of emissions.

5.4.1

Seawater scrubbing

Seawater scrubbing can be used to reduce SO_2 concentration in exhaust gases. The method is based on the presence of alkaline HCO_3 and SO_4 compounds in the seawater. The alkaline compounds neutralize sulphur oxides in the scrubber and they are transferred to the water in the form of sulphates (Trozzi and Vaccaro, 1998). Then the water is filtered to remove particles and filtered water is re-circulated back into the sea (EEB et al., 2004). In theory the scrubber can reduce the SO_2 emissions to virtually zero and simultaneously reduce PM and NO_x emissions significantly (MES, 2005a). Studies made on seawater scrubbing show that SO_2 emissions can be reduced up to 95 % and PM emissions can be reduced about 80 % (EEB et al., 2004). There is still uncertainty in how releasing sulphur-containing wastewater affects sea (EEB et al., 2004). Some experience has been gathered from the first prototype of the scrubbing system, which was installed on the ferry M/S Kronprins Harald in 1991. This experience showed that the amount of sulphur discharged with the water to the sea is negligible compared to the amount of sulphate that seawater naturally contains. (Trozzi and Vaccaro, 1998)

The Annex VI of the MARPOL requires the cleaning system such as seawater scrubber to be approved and the waste streams cannot be discharged into enclosed ports, harbours and estuaries unless it is documented that the discharging does not cause any negative effects to the ecosystem of the area (EEB et al., 2004). IMO Marine Environment Protection Committee has accepted the Guidelines for On-Board Exhaust Gas SO_x Cleaning System, which consists of technical guidelines for the on-board wet scrubbing systems. This means that seawater scrubbers are now on track to achieve a class approval. The scrubber manufacturer MES believes to have the first type approved scrubbing system installed in early 2006. This system is supposed to work in the area where the EPA regulations of the wastewater apply and the system is in line with them. (MES, 2005a)

5.4.2

Selective catalytic reduction

Selective catalytic reduction (SCR) is a technique to remove nitrogen oxides from exhaust gas exhaust. It is done by spraying aqueous urea ($CO(NH_2)_2$) or ammonia (NH_3) as reducing agent into the exhaust gases at a temperature of 290 - 350 °C and the exhaust gases are guided through a catalytic converter. There ammonia reacts with the nitrogen oxides forming nitrogen and water. (Wärtsilä, 2004) The reactions are:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{5.3}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \tag{5.4}$$

The catalytic reactor is a steal box which contains several layers of replaceable catalyst elements made of some precious metal, a dosing and storage system for the reducing agent and a control system. The injection of urea or ammonia is controlled by nozzles with a feedback loop, which reacts to the amount of NO_x in the flue gases. The lifetime of the catalyst elements is from three to five years for liquid fuels and longer for engines operating on gas. When the SCR is installed the housing usually replaces silencer in the exhaust uptakes. This reduces noise and also makes the system suitable for both new and retrofit installations. The SCR is an add on system meaning that it does not interfere with the basic engine design and is not dependent on the engine manufacturer. (Wärtsilä, 2003; de Jonge et al., 2005)

The reduction of NO_x emissions in the SCR system is more than 90 per cent (EEB et al., 2004). According to Eyring, Köhler, Lauer, and Lemper (2005) the SCR system is able to reduce NO_x emissions by 90-99 %, HC emissions by 80-90 %, CO emissions 80-90 % and soot emissions 30-40 %. ABB Fläkt had the longest running SCR system in a merchant ship in 2001 with about 50,000 hours in operation. During the whole time the reduction of NO_x emissions have remained in the range 97-98 per cent. Also the HC emissions have been decreased 88% and CO emissions 53 % (Sørgård et al., 2001). Kjemtrup (2002) reports a reduction rate of more than 93 % in MAN B&W engine deliveries equipped with SCR. When the reduction rate of NO_x is high the engine operation can be optimized especially for low PM emissions and fuel consumption (Karila et al., 2004).

The down sides of the SCR method is that it is a rather expensive investment, the volume of the system is equal with the size of the engines and it consumes lots of urea which is needed to store on board and handle by the ship crew (Klokk, 1995). To achieve high reduction rates the size of the SCR system must be increased and more complicated premixing and injection systems are needed. Also a high NH3/NO_x ratio is needed to achieve the high reduction rate. All these reasons increase the investment and operating costs of the system (Wärtsilä, 2003). The high NH_3/NO_x ratio may lead to increased ammonia emissions too. This so-called ammonia slip happens when all the urea injected into the reactor do not react with the NO_x and are thus emitted to the atmosphere with exhaust gases. Besides being a pollutant ammonia also causes corrosion in the exhaust channel (de Jonge et al., 2005). The SCR system may also require use of low-sulphur fuel or the low-sulphur fuel at least benefits the application of the system. In the SCR some of the SO_2 in the exhaust gases is oxidized to SO_3, which can form sulphurous acid (H_2SO_3) or sulphuric acid (H_2SO_4). This is an inevitable process in the SCR system because at high reduction rates there are lots of extra urea present in the process. Sulphurous acid combined with ammonia forms ammonia salt, which is a solid with high melting point and thus leads to increased particulate emissions. Sulphuric acid in turn causes rapid corrosion in the SCR and in the other exhaust system facilities. However, a SRC system combined with usage of a fuel with a sulphur content of 2.6 % has proved to work without problems. (Trozzi and Vaccaro, 1998; Sørgård et al., 2001)

At the moment the SCR system is installed to more than fifty ships (EEB et al., 2004). There are lots of research and development going on in this field concerning new catalyst and alternative reducing agent (e.g. hydrocarbon) and also decomposition of nitrogen oxides without reducing agents. However, significant improvements compared to the traditional SCR system have not been introduced yet. (Klokk, 1995)

5.4.3

Particulate filters

The particles can be removed from the exhaust gases with cyclones, electrostatic filters and filter bags. The cyclones remove particles using centrifugal force, electrostatic filters use electromagnetism and in the filter-bag system the particles are trapped in the bags. These methods are tested and in use in the onshore industry. However none of these methods have been tested on the ships so there is no information available of the efficiency of such method onboard ships. Also the investment costs are unknown. (Kågeson, 1999)

Diesel particulate filters (traps) have been developed for high-speed diesel engines. The most common filter type is a wall-flow monolith filter. The filters first capture and then oxidize particles. The oxidation process is also called filter regeneration. It is the most challenging part in the particle filtering process and various methods for it has been developed, which also work well in difficult engine operating conditions such as low loads and speeds. The downside of the filter system is increased fuel consumption due to increased exhaust gas back pressure and additional energy needed for the regeneration. Yet there are no filters large enough for medium-speed engines on the market. The largest filter available is suitable for about 500 kW engine power. It would be possible to install several filter units in parallel but the system would become too expensive in the medium- and low-speed engines. (Karila et al., 2004)

The research on particulate traps focuses on developing new filter materials and regeneration methods. The regeneration strategies studied are use of an additive to act as a catalyst to enable spontaneous oxidation for regeneration and improvement of active regeneration with microwave or other burner technology. (EPA, 1999)

Lin has made a study on particulate traps in a four-stroke marine diesel engine. In the experiment a catalyzed particulate filter was installed in the tail pipe of the engine. As a result the CO concentration in the exhaust gases was lowered significantly and the reduction was greatest at the highest engine speed. Also the concentration of nitrogen oxides was lowered at the high engine speeds but increased a little at the lower engine speeds. The smoke opacity was reduced and at various engines speed the smoke opacity readings were near zero. The presence of the filter in the marine diesel engine resulted in a slight increase in fuel consumption rate and carbon dioxide concentration, while fuel conversion efficiency, air-to-fuel ratio and oxygen concentration were decreased. (Lin, 2002)

5.4.4

Oxidation reactor

In the oxidation method the CO and HC pollutants in the exhaust gas are oxidized into CO_2 and H_2O in an oxidation reactor. This rector can be installed in combination with a SCR unit. The reduction potential of the oxidation reactor is 70 % for the HC emissions and 90-95 % for the CO emissions (Sørgård et al., 2001).

Also PM emissions can be reduced with oxidation catalyst. However the result is pretty moderate since the catalyst oxidizes gaseous hydrocarbons and the soluble organic fraction, which is a portion of particulate matter. The catalyst does not affect the carbon portion of PM. The soluble organic fraction forms 30-60 % of the total mass of PM emissions and the catalyst can remove 50-90 % of it depending on temperature. The reduction of 50 % is achieved at 150 °C and the reduction of 90 % is achieved at 350 °C. The problem of the catalyst is that it oxidizes sulphur dioxide forming sulphates especially at the high temperatures and thus PM emissions are increased. (EPA, 1999)

5.5
Alternative fuels and energy sources

5.5.1
Low-sulphur fuels

The SO_2 emissions from the ships are proportional the sulphur content of the fuel they use. That is why the easiest and cheapest method for reducing sulphur dioxide emission is to use fuel with lower sulphur content. Low-sulphur HFO has higher quality and because of that it causes less wear on the machinery and needs less lubricating oil and maintenance. That makes the engine run smoother and reduces the risk of operating problems. In addition, the use of low-sulphur fuels have a decreasing effect on particulate matter emissions. (EEB et al., 2004) A switch to the low-sulphur fuel does not require any engine modifications (EEB et al., 2004). However, some attention must be given to the cylinder lubricating oil grade and feed rate as well as to the jacket cooling water temperatures. Also some modifications are needed to the fuel storage and handling system on board if several grades of heavy fuel oil are used since the different grades can be incompatible. The different fuel oil grades may also require use of different lubricating oil grades and the storage and handling of lubricating oils must be reorganized also. (Schmid and Weisser, 2005)

At the moment the average sulphur content in marine HFO is 2.7 per cent. According to a new study from NGO Secretariat on Acid Rain a lowering of the sulphur content to 0.5 % would reduce sulphur dioxide emissions from international shipping around Europe by more than three-quarters by 2010 (Ågren, 2005b). A switch from fuels of sulphur content of 2.7 % to fuel with sulphur content of 1.5 % will decrease PM emissions by 18 per cent and a switch to fuel with sulphur content of 0.5 % will decrease PM emissions by more than 20 per cent. (Ritchie et al., 2005a)

The study of Swedish NGO Secretariat on Acid Rain showed that the benefits of using low-sulphur fuel would be significantly greater than the costs. Benefits were calculated to exceed the costs by at least 2.2 times and up to 7.5 times depending on a fuel cost assumption. The benefits were also calculated separately for the different sea areas. For the Baltic Sea the benefit-to-cost ratios were the lowest. When calculated with the lowest fuel cost estimate the ratio was 2.8 and when assuming the highest fuel cost the ratio was 0.8. The Baltic Sea was the only sea area in the study in which the costs exceed the benefits. This is explained by the fact that the benefit figures do not take all the benefits into account. Particularly in the case of the Baltic Sea, the significant potential of reducing acidification damage to ecosystems in northern Europe was left out of the study. (Ågren, 2005b)

There are three different ways to meet the increasing demand of low-sulphur HFO. The cheapest option is re-blending, which could make available in the EU about five million tonnes of HFO with the sulphur content of 1.5 % or less. The price of this option is 10-16 euro per tonne. However it is not probable that significant amounts of HFO with less than 0.5 % sulphur could be delivered with this method. The second option is the processing of low-sulphur crude oils. The estimated cost of this method would be 40-45 euro per tonne. The most expensive option is desulphurization of the HFO. This method requires new investments in refinery desulphurization and the estimated price would be 50-90 euro per tonne. (EEB et al., 2004)

5.5.2

Alternatives for diesel fuels

Diesel fuel is the most common fuel in the compression ignition engines and it will maintain its place at least in the near future. The EU has set a goal of replacing 20 % of the fuels used in transport with alternative fuels by 2020. The fuels that could replace diesel are primarily biofuels, natural gas and hydrogen. Because the world's crude oil reserves are still large and changing the infrastructure is expensive the replacement of diesel fuel will probably be slow. (Karila et al., 2004)

Bio-oils such as palm oil, coconut oil, rapeseed oil and soy oil are suggested to be used in small diesel engines. For the marine applications they are too expensive yet. This situation could change when wastes from food industry would be used. The bio-oils have been tested in medium-speed land-based diesel engines with the power of several megawatts for few years and the first commercial applications are already in use (Eyring, Köhler, Lauer, and Lemper, 2005).

Biodiesel is mono alkyl ester of long-chain fatty acids produced from renewable sources (Eyring, Köhler, Lauer, and Lemper, 2005). Biodiesel and its blends have lower the particulate watter and hydrocarbon emissions at full load compared with conventional diesel. Reductions of 10 to 70 % in PM emissions have been reported with different blends, engines and test cycles. The reduction potential of HC emissions is 20-25 % and CO emissions 40-45 %. The NO_x emissions may increase up to 10 %. (Karila et al., 2004).

The natural gas consists mostly of methane. The methane content is usually 80-98 %. Methane has a wide flammability range allowing a lean mixture in the engines. It burns slowly with a low flame temperature. The natural gas combustion in the diesel engines produces very low levels of CO and particulate emissions. It does not have an effect on the level of HC emissions. (Karila et al., 2004)

The first liquefied natural gas (LNG) driven ferry in the world has been ordered by More og Romsdal Fylkesbåtar. The vessel is estimated to produce 90 % less nitrogen oxides emissions comparing to a conventional vessel with diesel engine propulsion. (Sørgård et al., 2001)

Wärtsilä has a dual-fuel four-stroke engine, which is able to run on natural gas and light fuel oil. The engine can be switched between the two fuels during operation. Also usage of heavy fuel oil is possible with small modifications. Efficiency of Wärtsilä dual-fuel engines is 47 %, which is higher than can be reached with any other gas engines. The amount of SO_2 and NO_x emissions produced in a dual-fuel engine is only a few per cent of the amount produced in a conventional two-stroke engine. Also the carbon dioxide emissions are significantly lower and the operational costs are little bit smaller. As a downside the total energy consumption increases a bit. These results are based on calculations, model tests and simulations made by Wärtsilä. (Wärtsilä, 2004)

Marine gas turbines could be used as an alternative propulsion technology. The marine gas turbines burn high-quality marine gas oil (MGO) and have low SO_2 and NO_x emissions. Also the noise and vibration levels are decreased. The drawbacks are the high price of the fuel and low efficiency of the system compared to diesel engines with the same output, which increases the fuel consumption and CO_2 emissions. (Eyring, Köhler, Lauer, and Lemper, 2005)

5.5.3

Fuel cells

Application of fuel cells on board would remove totally the problem of NO_x emissions. A hydrogen-fueled ship could use a fuel cell coupled to an electric drive. Since the high temperatures and long start-up time would not be problematic in ships the fuel cell technology used could be solid oxide or molten carbonate. (Keith et al., 2000)

There are already few commercial installations of fuel cells onboard small ships (15 kW). For the larger vessels, which power demand can be in the range of 60 MW, the application of the fuel cells is still a long way in the future. Also infrastructure for the ideal fuel of fuel cells, hydrogen is missing. Therefore ships would need a much larger tankage volume to cover the same energy need than with diesel fuels (Eyring, Köhler, Lauer, and Lemper, 2005). However, the fuel storage would not reduce the actual payload on the large vessels since that type of vessels typically have significant unused internal volume (Keith et al., 2000). The other problem in the fuel cell application is that they are not economically competitive with the internal combustion engines. The efficiency of these two systems is estimated to be roughly the same but the fuel cells are more expensive than the diesel engines. (Keith et al., 2000)

Many technical problems in the fuel cell technology are needed to resolve in the future and also solutions to decrease the capital costs to more competitive level with diesel engines are needed (Eyring, Köhler, Lauer, and Lemper, 2005). A significant research effort has been put into marine fuel cells at the moment but it focuses on high reliability onboard power instead of propulsion (Keith et al., 2000).

5.6

New ship design and modification

5.6.1

Optimizing ships' design and operation

In the terms of emission reduction much can be gained by optimizing the ships' design and operation or even the whole transport system. Large ships consume less fuel per a unit of cargo and thus produce less air pollutions. They are also faster to operate than smaller ships so with the same fuel requirement they can transport more cargo. Therefore for the ship operators it is economical and more beneficial from an environment standpoint to operate with large and fast ships. (Schmid and Weisser, 2005)

Cleaning and painting ships has an effect on the pollution levels. If the ship is cleaned and painted when it is dry-docked a slight reduction in emission levels is achieved because of the lower resistance of the ship. (Trozzi and Vaccaro, 1998) Optimizing of ship systems other than engine such as propeller, rudder and hull can improve the energy effciency and thus environment performance of the ship significantly. Marintek has evaluated that the energy and emission reduction potential with an optimized hull shape and a better propeller for a new ship can be up to 30 per cent. (Eyring, Köhler, Lauer, and Lemper, 2005)

To improve the ship's energy efficiency energy recovery can be used. Instead of wasting the heat energy in the exhaust gases it can be utilised to produce steam, which is then used in the areas of the ship that would normally require the use of oil-fired boilers. However, in the recent years the number of soot ores in the exhaust gas boilers has been increased. The risk of soot ores can be lowered by optimizing the temperature difference between the exhaust gas and the water/steam circle, exhaust gas velocity and water inlet velocity. Also soot blowing up to every two hours reduces the risk of soot fires. (Sørgård et al., 2001)

5.6.2

New ship design

Several Swedish companies have together developed a new type of ship called Ecoship. Ecoship is a container ship developed for traffic on the Swedish inland waterways. The group designed a totally new hull construction and substituted the conventional marine engines to ten diesel engines normally used in trucks. (Elvingson, 2003)

The truck diesels fuel with very low-sulphur content can be used leading to cleaner exhaust gases. The cleanest diesel fuel for trucks contains only 10 ppm sulphur where as in a conventional marine bunker oil the average sulphur content is 27,000 ppm. The engines are equipped with SCR units and particulate filters. These remove 95% of NO_x emissions and 90 % of PM emissions. However, the filters are intended to use mainly when the ship is in port. The separate engines also make it possible to run all the engines at optimal speed in the terms of efficiency through an advanced power management system. This keeps idling to a minimum and thus improves the energy efficiency of the ship. The propellers of the ship are electrically driven enabling to use fuel cell as a power source in the future. Besides the environmental aspects the engines have other advantages as well. The engine room of the Ecoship is a modularised power plant consisting of a number of power units (diesel engine and generator), which makes the maintenance of the engines easier and leaves about 15 % more space for cargo. (Elvingson, 2003)

The Ecoship's hull is rounded and this feature should reduce the water resistance by 10-15 % compared with a ship with the conventional hull shape. The hull is mainly constructed of single bend plates with soft lines and most of the weldings in a longitudinal direction. It follows the flux of the water causing lower wake and allowing the ship to operate efficiently on various speeds. The reduced resistance will reduce the fuel consumption and CO_2 and SO_2 emissions. The Ecoship has a 30 centimetre larger draught but the same length and width compared to a conventional container hull design of the same size. The Ecoship also has larger dead weight due to a lighter engine room and thus lighter construction of the ship. (Hermansson, 2001)

The first oil tanker using truck-engine has been built in 2004. Several of the technical solutions of this vessel have been adapted from the Ecoship concept although this ship is smaller and not quite that streamlined. The new vessel has a diesel-electric drive system. Five 16-litre truck engines are used to generate the electricity for electric motors that power the propulsion system of the vessel. The truck diesels can be run on diesel oil containing very little sulphur and therefore the sulphur dioxide emissions of the new ship are significantly smaller compared to a conventional oil tanker using common bunker oil. Another improvement in the new vessel is that the oil load is housed in a thermos structure. When in a conventional oil tanker the energy used to heat the oil is equal to power needed for propulsion, in the new vessel the effective insulation makes it possible to heat the oil now and again. Thus the energy use end emissions are reduced. (Swedish NGO Secretariat on Acid Rain, 2005b)

Wärtsilä has taken part in developing new ship design. The most important projects have been developing the new liquefied natural gas (LNG) carrier using dual-fuel engine and environmentally advanced Enviropax RoPax ship. The main focus in both of these projects was improving of the vessels' propulsion efficiency through the use of speed-adapted propellers, high efficiency HR nozzles and a new hub for controllable pitch propellers. (Wärtsilä, 2004)

In the new LNG carrier the dual-fuel engine replaces the steam turbine used in a conventional carriers of that type. The steam turbine has been used because of the opportunity to use the boil-off gas that evaporates from the LNG carrier's cargo as a fuel in a steam boiler. The dual-fuel engine operates with better efficiency than the steam turbine and hence fuel consumption is lower and smaller fuel tanks can be used. Also using several duel-fuel engines instead of one steam turbine enables the use of the optimal engine load for achieving the best efficiency. Also the duel-fuel engines require less space than a steam turbine and therefore a smaller engine room is needed and more space is available for payload onboard. These advantages enable the totally new ship design where the total resistance is lower, length of the vessel is greater and it has faster engines. This leads to significant improvement in the vessel's cargo capacity and operating speed. The total economics of the LNG carrier is thus improved because the costs and emissions per shipped tonne are decreased. (Wärtsilä, 2004)

The Wärtsilä's dual-fuel engine has recently been installed into a LNG ship of Gaz de France. The ship will be used to carry gas from Algeria to France. The estimated waste from cargo is 0.18 per cent per day of the total load of 74,000 cubic metres of liquefied gas and this amount is sufficient to run the ship's engines on gas. Using gas lowers the nitrogen oxides emissions to one-tenth of the conventional diesel engines and the emissions of SO_2 will virtually be eliminated because the gas is almost sulphur-free. (Swedish NGO Secretariat on Acid Rain, 2005a)

The Enviropax project was a joint development project of Wärtsilä, ABB and Aker Finnyards and is similar to the Swedish Ecoship concept. The goal of the project was designing a new RoPax vessel that has better overall economy and environmental performance. These should be gained through optimizing the vessel's hull, machinery and propulsion systems. As a result a new diesel-electric and diesel-mechanical machinery concept was developed. This combines the best sides of the both systems and it provides lower power demand, optimum engine load and greater flexibility in use of installed capacity. The engine is equipped with a common rail system and a compact SCR unit to minimize the fuel consumption and NO_x and smoke emissions. Also, a new propulsion system with better efficiency was developed. With the new vessel a reduction of 6-10 % in fuel consumption has been achieved. Although the investment costs of the new vessel are a little bit higher compared to a conventional vessel savings in operating costs are expected. (Wärtsilä, 2004)

5.7

Shore-side electricity

When ships are docked at the ports they normally use their auxiliary engines to provide the electricity needed on board. These engines use high-sulphur marine heavy fuel oil or lower-sulphur marine gas oil resulting air pollutant emissions. The alternative for running the auxiliary engines on port is use of shore-side electricity. However, it requires investments and some modifications to be made in the ports and on board. There are a few ports where hooking up to shore-side electricity is already possible for certain kind of vessels and the experience from them has shown that the modern shore-side electricity systems are simple to use and it is fast to switch to use the shore-side electricity when the ship arrives to the port. (Ågren, 2004) Swedish MariTerm has made a study on the costs of shore-side electricity. They found usage of shore-side electricity to be two to four times more expensive than generating the electricity on board by engines running on heavy fuel oil when they only took the direct costs into account. However, when the external costs were also evaluated the usage of shore-side electricity turned out to be the cheaper option. The external costs, which are caused by the damage that the emissions to air cause to health and environment, are much lower for vessels connected to shore-side electricity supply. Depending on the fuel the external costs of generating the electricity on board were found to be 15 to 75 times higher than using shore-side electricity generated by a modern coal-fired power plant. (Ågren, 2004) Another recent study on shore-side electricity was carried out by American ENVIRON for the port of Long Beach in California. The study included twelve ships representing various ship types, ship ages, service routes and port call frequencies. It was found out that for five of the twelve ships introduction of shore-side electricity would be cost-effective and using shore-side electricity on those ships would remove 90 % of the emissions generated on the twelve study ships. All those five ships have high power demand for accommodation services, frequent port calls and significant time at port per call and thus they have significant energy consumption at port. As a conclusion the analysis show that for vessels of high power consumption at berths it would be cost-effective to use shore-side electricity and it would also cut down their emissions significantly. (Ågren, 2004)

There are already plenty of good experiences of the usage of the shore side electricity, for example the ports of Gothenburg, Seebrucke, Seattle and Los Angeles. At the moment the use of shore-side electricity is now potentially cheaper than using low sulphur fuel because of the high price of oil. If the ships obtained exemption of electricity taxes the shore-side electricity would be even more attractive economically. The European Commission will publish a recommendation addressed to governments and ports to promote the shore-side electricity. (Robinson, 2005)

5.8

Costs of emission reduction

There are some uncertainty related in evaluations of costs of the different abatement techniques since many of the techniques are still under development or the number of installations is still small. Those reasons also limit the availability of the cost information. The newest cost evaluation is made by the consultant group Entec that has calculated costs for several of the most common nitrogen oxides and sulphur dioxide abatement technologies. The eciencies and costs of the different emissions reduction methods given below are based on estimates of de Jonge et al. (2005), except for low-sulphur fuels. The efficienciey and costs are summarized in Table 5.2.

The cheapest reduction method for NO_x is the installation of slide valves. The costs for emission reduction by introducing slide valves to new or young engine are approximately 12 and 9 euros per tonne NO_x reduced for small and medium/large vessels, respectively. For the older engines the costs are 60, 24 and 15 euros/tonne NO_x reduced for small, medium-size and large vessels, respectively.

The costs of applying a combination of internal engine measures, such as retard injection, higher compression ratio, increased turbo efficiency, common rail injection, higher cylinder pressure and low intake temperature, the costs of tonne NO_x reduced are 98, 33 and 19 euros for small, medium-size and large vessels, respectively. These costs are calculated for new engines. These measures still require more research and this is also taken into account by including the future research and development costs required by manufacturers in the cost estimations.

The costs of the water injection are estimated for DWI and HAM technologies. For DWI the costs for new engines per tonne of reduced NO_x are 411, 360 and 345 euros for small, medium-size and large vessels, respectively. With HAM technology the costs vary from 198 euros to 268 euros per tonne NO_x reduced for new engines depending on vessel's size. For retrofitting the system the costs would be between 263 and 306 euros per tonne NO_x reduced. Viking Line's ferry Mariella is so far the only ship where the technology is installed and thus estimating the costs for other ships is difficult. HAM has significantly higher initial costs than other NO_x abatement measures. One reason for this is the high pre-installation costs, for example the costs related to research and development.

With the SCR system the NO_x abatement costs depend on the fuel used. The SCR installation is most expensive for ships using fuel with high sulphur content when the costs vary between 526 and 809 euros per tonne NO_x reduced depending on the vessels size and whether the system is installed on a new engine or retrofitted to an old one. For the ships sailing in areas where the sulphur content in fuel is limited the system is slightly cheaper due to the usage of low-sulphur fuel. In that case NO_x abatement costs are 398-613 euros per tonne NO_x reduced. For the ships using very low-sulphur marine diesel oil the costs are in the range of 313-483 euros per tonne NO_x reduced. For switching the fuel to a low-sulphur one a wide range of estimated values for the price premia of the low-sulphur fuels has been presented (Ritchie et al., 2005a). Between the years 1990 and 2001 the price differential between low-sulphur marine HFO (less than 1 % sulphur) and high-sulphur marine HFO (3.5 % S) was 19 dollars per tonne on average. This means the cost of reducing SO_2 emissions were 400 euros per tonne SO_2 reduced (EEB et al., 2004). Concawe have estimated that if the fuel is switched from a fuel with sulphur content of 2.7 % to a fuel with 1.5 % sulphur the price for SO_2 abatement is 1230 euros per tonne SO_2. If the fuel with 2.7 % sulphur were switched to a fuel with a sulphur content of 0.5 % the costs would be 1690 euros per tonne of SO_2 reduced. Ritchie et al. (2005a) have estimated the costs based on the average fuel price differential information of BeicipFranlab. According to this estimation the costs of tonne SO_2 abated are approximately 2050 euros when the fuel switching is done between the fuels with sulphur contents of 2.7 % and 1.5% and approximately 1440 euros when the switching is done between the fuels with sulphur contents of 2.7 % and 0.5 %.

According to calculations of Ritchie et al. (2005a) seawater scrubbing is a very promising option for SO_2 abatement in the terms of the costs per tonne SO_2 reduced. The costs range from 320 euros to 390 euros when the system is installed on a new engine and from 500 euros to 580 euros when the system is retrofitted. However, sea water scrubbing is still under development and no commercial installations are introduced yet.

Table 5.2: Costs of different emissions reduction methods

Technology	Reduction potential	Costs
Slide valves	20 % NO_x	10 – 60 euros/tonne NO_x
Internal engine measures	30 % NO_x	20 – 100 euros/tonne NO_x
Direct water injection	50 – 60 % NO_x	350 – 410 euros/tonne NO_x
Humid air motor	70 – 80 % NO_x	200 – 310 euros/tonne NO_x
Selective catalytic reduction	90 – 99 % NO_x, 80 – 90 % CO and HC, some PM	310 – 810 euros/tonne NO_x
Switch to low-sulphur fuel (2.7 -> 1.5 % S)	40 % SO_2, 18 % PM	1230 – 2050 euros/tonne SO_2
Switch to low-sulphur fuel (2.7 -> 0.5 % S)	80 % SO_2, 20 % PM	1440 – 1690 euros/tonne SO_2
Seawater scrubbing	95 % SO_2, 80 % PM	320 – 580 euros/tonne SO_2

6 Future shipping and ship emissions

The future development of shipping emissions at the northern Baltic Sea up to year 2015 were evaluated in this study. In this section only the emissions generated from cargo and passenger ships at the sea routes of the selected sea areas were included in the emission study. Ship traffic volumes were estimated based on predicted growth rates of shipping at the Gulf of Finland and the Gulf of Bothnia. Future emissions at the sea routes were calculated with four different technology scenarios.

6.1
Background on ship emissions forecasts

6.1.1
Ship traffic development forecasts

COWI (1998) has estimated the maritime traffic to double in average at the Baltic Sea by year 2017. The growth of the general cargo and bulk traffic is assumed to triple. For the oil transportation the growth is assumed to be only 40 % but this is probably an underestimation since the oil transport from Russia is expected to grow even more. The average annual growth rate is predicted to be 4.7 % for general cargo, container, reefer and RoRo traffic, 2.2 % for the bulk carrier traffic and 1.4 % for oil and gas tankers.

Rytkönen, Hänninen, and Sonninen (2002) have estimated maritime transportation to double at the Gulf of Finland by 2010-2015. They also estimate tanker traffic to become threefold in 10 years. The growth is mainly due to new harbour projects at Russia. The port of St. Petersburg has developed fast in the recent years and Russia is building several new ports at the Gulf of Finland: Primorsk, Lomonosov, Batareynaja and Ust-Luga. Also the Baltic ports have many ongoing harbour development projects. Especially the Muuga oil terminal in Tallinn has grown rapidly. However, the growth in the transportation figures will not directly increase the ship call figures or uses of fairways at the same rate because the average size of the cargo vessels will increase also.

The new harbour capacity at the Gulf of Finland is estimated to decrease the growth of the transit traffic in the Baltic harbours. However, the positive development of the economy in the Baltic countries and Russia will influence the maritime traffic at the Baltic Sea. Russia will take care of the shipping of its raw materials but new materials will be imported to Russia so the transit trac in the Baltic States will stay in balance or even grow. (Rytkönen, Hänninen, and Sonninen, 2002)

The estimated growth in the number of port calls by 2015 vary in the three countries at the Gulf of Finland. At the Finnish ports the number of ships is assumed to increase by approximately 60 per cent, at the Estonian ports the estimated increase is approximately 90 per cent and at the Russian ports the number of port calls is estimated to increase by about 180 per cent. Then the number of port calls would be 35000-39000 per year at the Gulf of Finland. The number of the ship passages at the mouth of the Gulf of Finland is estimated to be 70100 in 2015. (Rytkönen, Siitonen, et al., 2002)

At the Gulf of Bothnia the annual growth rate for both seaborne export and import is assumed to be 2.5 % in tonnage up to year 2010. In seaborne export the largest increases will be in the export of paper and metals. In import the products with largest growth rate will be ores, concentrates, coal and coke. Also the import of minerals and chemicals needed in chemical and paper industries will increase. The estimated number of the cargo ship passages at the mouth of the Gulf of Bothnia in 2015 is 31600. In year 2000 the number was 23338 so the increase will be 35 %. The increase is assumed to be the same at all the major ports at the Gulf of Bothnia. (Rytkönen, Siitonen, et al., 2002)

However, there are several factors decreasing the growth in the seaborne tra-c at the Gulf of Bothnia. The road network from Finland to the North-West Russia is poor and major investments are needed to make the link to North-Western Russia through Bay of Bothnia attractive. The economical situation at the northern Russia is poor which will also decrease the economy. The Bay of Bothnia is ice-bound half of year, which increases the transportation costs. Also the cargo constitutes mostly of the raw materials with low added value of industrial products. Finally the population centres in the Northern areas are small and scarce. Because of these reasons even assuming the annual growth rate of 2 % would be an optimistic estimation. However, the situation can change fast if the oil and gas reservoirs at the Northern Russia are taken into use. Then the proposed Barents and Archangel corridors would increase the port throughput at the Bothnian Bay significantly. The fast development would require foreign investments, but at the moment the uncertainties in the Russian legislation repel the foreign investors. There are proposals for the new railway connections between northern Finland and Russia. Implementation of these would have a positive impact to the annual growth rate of the seaborne traffic. (Rytkönen, Siitonen, et al., 2002)

Forecasting the development of the passenger ship traffic is more difficult than forecasting the development of the cargo traffic, since there are more factors influencing the development (Rytkönen, Siitonen, et al., 2002). There are about 300 passenger ferries visiting St. Petersburg each summer and about 200 passenger ferries visit Helsinki and Tallinn. The amount of these vessels is expected to stay at current level in the coming years (Hänninen et al., 2002). In 2000 there were 10 million passengers on the passenger ferries sailing from the ports of Turku and Helsinki to the ports of Stockholm and Kapellskär. Another important route for passengers was the Helsinki-Tallinn route with six million passengers in 2000. The passenger traffic on these routes is not expected to grow anymore. Some forecasts even suggest a decrease of 15-25 % in the shipping capacity due to decreased income from the alcohol sales on board. The new taxation policy of the EU will lead the shipping companies to establish new routes from the EU countries to the Baltic countries and Russia. This increase will keep the passenger traffic volume in Finland at the current level. (Rytkönen, Siitonen, et al., 2002)

6.1.2

Emission regulations

Globally the shipping activities are regulated by the United Nations' International Maritime Organisation (IMO). IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI contains measures for limiting air pollution from ships and it came into force in May 2005. Annex VI introduces a global sulphur cap of 4.5 % for marine heavy fuel oil and three sulphur emission control areas (SECAs): the Baltic Sea, the North Sea and the English Channel. In the SECAs the sulphur content of the fuel used in ships must be below 1.5 % or the ships must limit their SO_2 emissions to the level of 6 g/kWh. This limit will start to apply in May 2006. Annex VI contains also limits for NO_x emissions from diesel engines with a power output of more than 130 kW. Emission limits of Annex VI are summarized in Table 6.1. (IMO, 2006)

Also European Union has recently agreed on new directive concerning ship emissions. The main limits in the directive are a 1.5 % sulphur limit for fuels used at the Baltic Sea, the North Sea (from May 2006) and the English Channel (from autumn 2006) and for fuels used in passenger ferries, which operate on regular service between EU ports (from May 2006) and a 0.1 % sulphur limit for fuels used in inland waterway vessels and ships at berths in EU ports (from January 2010). The agreement on the new directive contains also a commitment that applying the 1.5 per cent sulphur limit to all the EU sea areas and establishing a second phase with sulphur limit of 0.5 % will be examined in a review foreseen for 2008. (Ågren, 2005a)

In the U.S. Tier 1 emission standards, which came into force in 2004, are equivalent to the MARPOL Annex VI emission limits (Karila et al., 2004). The more stringent emission limits of Tier 2 have already been adopted in the U.S. and the U.S. government has requested IMO to consider more stringent emission limits. The emission standards of Tier 1 apply for new engines built in 2004 or after and the stricter rules apply for small engines build after 2005 or 2007 depending on the size class (Table 6.1) (Hyvättinen and Hildén, 2004).

The EU has proposed to harmonize the emission limits with the U.S. standards for engines used in inland waterway vessels. These limits are included in the Stage III standard for non-road diesel engines (Table 6.1). Emission standards for the recreational vessels are under decision-making process in the EU. Further harmonization of the emission standards between the EU, Japan and the U.S. is under work. (Karila et al., 2004)

Several countries have already now adapted stricter emission limits at their own territories. Sweden has introduced a system of environmentally di_erentiated fairway dues and Norway has environmentally differentiation in the tonnage tax. Also complementary reductions in port dues are offered in many Swedish ports, in the port of Mariehamn and in the port of Hamburg. Vessels with Green Award certificate are awarded with a 50 % rebate on port dues in 50 ports around the world. (Wärtsilä, 2003)

6.1.3

Current abatement technology in the ship engines

When the diesel engines are delivered they have been prepared to meet the IMO's NO_x emission limits. These standards are not especially strict all the new engines have complied with them since the late 1990s. Required NO_x level is achieved with optimised fuel injection valves and nozzles and if necessary with retarded fuel injection. If there will not be stricter limits than the current IMO standards no further measures to cut down the emissions will be needed. (MAN B&W, 2004)

However, local policy instruments and environmental agreements of the shipping companies have encouraged several installations of new technologies to reduce emissions below IMO level (Hyvättinen and Hildén, 2004). More efficient internal engine modifications, direct water injection, emulsified fuel and SCR technologies are in commercial use in many cargo ship engines. Engine manufacturers also offer these techniques on new engines. (Hellén, 2005; MAN B&W, 2004)

The Swedish fairway and port discounts for ships with low NOx emissions have encouraged the passenger shipping companies Silja and Viking Line to invest in different NO_x reduction technologies (Hyvättinen and Hildén, 2004). Silja has adapted SCR technology on the main engines of its cruise ships at the Turku-Stockholm route. The ships on the Helsinki-Stockholm route have DWI technology on their main engines and SCR systems on their auxiliary engines. Viking Line has installed HAM system on one of its ships on the Helsinki-Stockholm route and uses SCR technology on one ship on the route Mariehamn-Stockholm. All of the passenger ships of those companies use low-sulphur fuel with sulphur content of 0.5 % or less. The third important passenger ship operator at the Gulf of Finland, Tallink, has not introduced any emission abatement technology yet. (Silja Oy Ab, 2004; Viking Line, 2006; AS Tallink Grupp, 2005)

Table 6.1: Regulations for air pollution from ships

Category	**Displacement (D) dm^3 per cylinder**	**CO (g/kWh)**	**NO_x (g/kWh)**	**PM (g/kWh)**	**Date**
MARPOL Annex VI emission limits $D > 30$ dm^3	$n < 130$ r/min	-	17	-	2005 -
	130 r/min $\leq n$ $n < 2000$ r/min	-	$45n^{(-0.2)}$	-	2005 -
	$n \geq 2000$ r/min	-	9.8	-	2005 -
Stage III / Tier 2 standards for inland waterway vessels	$P \geq 37$ kW, $D < 0.9$	5	7.5	0.4	2005- (*) / 31.12.2006
	$0.9 \leq D < 1.2$	5	7.2	0.3	2004- (*) / 31.12.2006
	$1.2 \leq D < 2.5$	5	7.2	0.2	2004- (*) / 31.12.2006
	$2.5 \leq D < 5.0$	5	7.2	0.2	2007- (*) / 31.12.2008
	$5.0 \leq D < 15$	5	7.8	0.27	2007- / 31.12.2008
	$15 \leq D < 20$ $P < 3300$ kW	5	8.7	0.5	
	$15 \leq D < 20$ $P \geq 3300$ kW	5	9.8	0.5	
	$20 \leq D < 25$	5	9.8	0.5	
	$25 \leq D < 30$	5	11	0.5	
Stage IV (proposal) standards for inland waterway vessels	$P \geq 37$ kW, $D < 0.9$	5	1.5	0.02	31.12.2010
	$0.9 \leq D < 1.2$	5	1.5	0.02	
	$1.2 \leq D < 2.5$	5	1.5	0.02	
	$2.5 \leq D < 5.0$	5	1.5	0.02	21.12.2011
	$5.0 \leq D < 15$	5	1.5	0.02	
	$15 \leq D < 20$ $P < 3300$ kW	5	1.7	0.02	
	$15 \leq D < 20$ $P \geq 3300$ kW	5	2	0.02	
	$20 \leq D < 25$	5	2	0.02	
	$25 \leq D < 30$	5	2.2	0.02	

6.1.4

Maturity and development of the abatement technologies

Ritchie et al. (2005b) have evaluated the maturity and possible development in the usage of the most common and promising emissions abatement techniques. The most mature techniques are SCR and usage of slide valves, shore side electricity and low sulphur fuels, which all are already proven for application. The technologies that are promising but require more development are some of the internal engine measures, DWI, HAM, EGR and seawater scrubbing. Complete development of the various internal engine measures report will take at least about five years. The DWI and HAM are so far used only in a certain type of vessels and more development is required to fit them other types of ships too. Seawater scrubbing and EGR technologies are lacking of commercial installations. Also, EGR technology requires significant development to be compliant with engines using fuels with high sulphur content too.

According the engine manufacturer MAN B&W the next generation of emission control technologies are HAM and EGR systems which are under development (MAN B&W, 2004). Wärtsilä is now concentrating on CASS technology that is supposed to reduce NO_x emission significantly especially when used with water-fuel emulsion (Hyvättinen and Hildén, 2004). Both companies are also developing common rail fuel injection, which is expected to become important technology in all engines in future (Hellén, 2005; Vogel et al., 2004).

Eyring, Köhler, Lauer, and Lemper (2005) forecasts that within next five to ten years NO_x emissions can be reduced by 20-30 % from the current IMO standards with internal engine measures. Further reduction of 20-30 per cent could be achieved by introduction of emulsified fuel. The adaptation of the SCR and HAM technologies could help to achieve higher reduction but they have the problems of the high investment and operating costs and space requirement in the machine room. The SCR could be more attractive if it were developed to operate safely with poor-quality fuels with more than 1.5 % sulphur.

Alternative energy sources are not expected to replace diesel engines as the main propulsion system in ships in the near future because of the lack of testing. Furthermore, the availability of lighter oil fractions than HFO is restricted at ports at the moment and time is needed to establish a proper infrastructure for alternative fuels. Therefore it is not expected that a significant shift from the current diesel-only fleet to a fleet using alternative energy sources or fuels would happen until year 2020. (Eyring, Köhler, Lauer, and Lemper, 2005)

6.1.5

Ship emission scenario studies

Eyring, Köhler, Lauer, and Lemper (2005) have described four different future technology scenarios considering the development of diesel engines. These scenarios are clean, medium design, IMO compliant and business-as-usual. The clean scenario is very optimistic assuming very low-sulphur content in the fuels and aggressive NO_x reduction in the future. It assumes that most of the new ships are equipped with a technology that reduces NO_x and other emissions efficiently (DWI, HAM, SCR). The medium design scenario assumes a relative low-sulphur content in the fuels (1.2-1.8 %) and moderate NO_x reductions, which could be achieved through the same technologies as in the clean scenario but they would not be that widely used. The IMO compliant scenario assumes that the IMO regulations are fulfilled. In all of these three scenarios it is also assumed that some part of the diesel fuel consumption is replaced with alternative fuels and energy sources by year 2050. The business-as-usual scenario assumes that the IMO regulations will be met but no alternative fuels or energy sources are used.

Trozzi and Vaccaro (1998) have presented a methodology for estimating future emissions from ships in Europe. They have developed three emission reduction scenarios for SO_x and NO_x: low, medium and high reduction scenarios. In these scenarios it is assumed all the marine diesel oil and marine gas oil sold in the EU have a maximum sulphur content of 0.2 %. The sulphur content of the HFO is assumed to be 2 % in the low reduction scenario, 1.5 % in the medium reduction scenario and 1 % in the high reduction scenario. For NO_x the reduction of 10 % is assumed in the low reduction scenario, 30 % in the medium reduction scenario and 80 % in the high reduction scenario. The reduction of 10 % would be achieved by using injection timing retard and intake air treatment. The medium reduction scenario would require the use of water injection, emulsified fuel or exhaust gas recirculation. The high reduction would be obtained by using catalytic or non-catalytic reduction.

6.2

Emission scenarios 2015

6.2.1

Assumed ship movements in 2015

When evaluating the future emissions the number of ship movements was estimated based on VTT's estimates summarized in section 6.1.1. According to Rytkönen, Siitonen, et al. (2002) cargo ship traffic at the mouth of the Gulf of Finland and at the western side of the Gulf of Finland will double. At the eastern side of the Gulf of Finland the Russian ports have a major role in traffic volumes. Cargo ship traffic to Russian harbours will increase to 2.8-fold compared to the ship traffic volume in 2000. At the Gulf of Bothnia the increase will be about 35 % according to the prognosis of Rytkönen, Hänninen, and Sonninen (2002).

The energy consumption was assumed to increase at the same rate with the growth in traffic volumes. Thus it was assumed that the fuel and energy consumption of the ships will double at the western Gulf of Finland and become 2.8 times larger at the eastern Gulf of Finland. At the Gulf of Bothnia the energy consumption was assumed to increase by 35 % at all the three sea areas. The proportions of the 2-stroke and 4-stroke engines in the cargo ships are assumed to stay approximately same as they are now although the sizes of the ships will increase.

The passenger ship traffic has increased by approximately 30 per cent at the Finnish harbours at Gulf of Finland and Gulf of Bothnia since 2000 (personal communication, H. Federley, Finnish Maritime Administration, 4.5.2005). It was assumed that the passenger ship traffic will not increase significantly any further.

6.2.2

Technology assumptions in emission scenarios

For evaluating the future ship emissions at the sea areas around Finland, four different scenarios were used for cargo ships and two different scenarios for passenger ships (Table 6.2). For the cargo ships the scenarios are Baseline, Moderate_NewEngines (M_New), Moderate_AllEngines (M_All) and Ambitious (A). In the Baseline scenario only the mandatory emission standards were assumed to be met but no further emission reduction methods are introduced. In the three other scenarios some further technically mature emission control methods were assumed to be used. For the passenger ships only two different scenarios, Baseline and Ambitious, were studied because of the better current environmental performance of passenger ships. Some passenger ship operators have already reduced their ship emissions voluntarily. Therefore, Baseline scenario for passenger ships was equivalent with the Moderate_AllEngines scenario assumptions for cargo ships.

In the Baseline scenario the cargo ships were assumed lower their emissions in a way that they will meet the mandatory emission limits. As the Baltic Sea is one of the SECAs the sulphur-content of the fuels used in the ship engines is obliged to be 1.5 % or less starting from May 2006. Due to lower sulphur content in fuels particulate matter emissions will also decrease. The switch to fuel with sulphur content of 1.5 % will decrease the particulate matter emissions by approximately 18 % (Ritchie et al., 2005a). For calculating NO_x emissions the emission limits at the average rotational speeds of 155 rpm and 625 rpm for two-stroke and four-stroke engines, respectively, were used. IMO's NO_x limits are then 16.4 g/kWh and 12.4 g/kWh respectively. These limits can be achieved by introducing internal engine adjustment measures.

The passenger ships use mostly fuels with sulphur content of 0.5 % or less. In ten years all the passenger ships at the Gulf of Finland and the Gulf of Bothnia were assumed to use fuels with the sulphur content of 0.5 % except those 18 % of the ships, which already use marine diesel oils and gas oils. When switching a fuel with the sulphur content of the average 2.7 % to a fuel with the sulphur content of 0.5 %, the reduction in PM emissions is at least 20 % (Ritchie et al., 2005a), which is the reduction rate assumed here. The passenger shipping companies have installed some additional NO_x reduction technology on some of their ships already. These measures have been done in order to maintain good company image and because of the local regulations in Sweden. Those regulations are expected to tighten in the future. Therefore it can be expected that the passenger ship operators will continue the emission reduction and all the passenger ships will have some additional emission reduction technology installed. Also in next ten years the shipping companies will probably purchase new ships and those will have the NO_x abatement technology installed already. Thus it was assumed already in the Baseline scenario that the passenger ships will reduce the NO_x emissions by 60 % from the level of 2000.

To reduce the emissions well below the IMO's NO_x standard level some engine process modification or after treatment technology has to be introduced. According to de Jonge et al. (2005) the costs of NO_x abatement with some these systems are close to each other and the factors that have the largest effect on the abatement costs are the size of the vessel and whether the system is installed on a new engine or retrofitted. Thus it can be assumed that if emissions are controlled more than required it will be done first on new engines. When the shipping companies buy new ships they want to be prepared for stricter emission standards that might come into force during the engine's lifetime. Since in 2000 50 % of the ship calls at the Baltic Sea area were made by the ships at the age of 20 years or older, half of all the ships were assumed to be replaced before year 2015. Thus it was assumed that in 2015 50 % of the ships are built after year 2000 and they have some additional emission reduction technology in use. In scenario M_New the alternative technology was assumed to be some engine process modification method with the reduction of 60 % from the NO_x emission level of 2000. The sulphur content of the fuel was assumed to stay the same as in the Baseline scenario, i.e. 1.5 %.

In scenario M_All process modifications were assumed to be retrofitted on the existing engines in cargo ships too. Then all the ships would have some additional emission reduction technology installed and NO_x emission reduction rate of 60 % will apply to all the ships. This will only affect NO_x emission rates and other emissions will stay at the same level as in the Baseline and M_New scenarios.

In the Ambitious scenario emission rates were evaluated in a situation where all the cargo and passenger ships were assumed to use a more advanced NO_x reduction technology: SCR. The PM, HC and CO emissions are reduced simultaneously. The reduction effciencies of SCR assumed here were 90 % for NO_x, 80 % for CO and HC and 30 % for PM emissions. Also fuel with the sulphur content of maximum 0.5 % were assumed to be used.

Table 6.2: Technology assumptions and emission reduction rates in scenario study.

Scenario	Reduction method	Reduction potential (below current level)	Applied to
Cargo ships			
Baseline	Internal engine measures, sulphur in fuel max. 1.5%	IMO NO_x standard level, 18% PM, 32% SO_2	All engines
Moderate_NewEngines	Engine process modification, sulphur in fuel max.1.5%	60% NO_x, 18% PM, 32% SO_2	New engines (low-sulphur fuels to all engines)
Moderate_AllEngines	Engine process modification, sulphur in fuel max. 1.5%	60% NO_x, 18% PM, 32% SO_2	All engines
Ambitious	SCR, sulphur in fuel max. 0.5%	90% NO_x, 80% HC, 80% CO, 30% PM, 70% SO_2	All engines
Passenger ships			
Baseline	Engine process modification, sulphur in fuel max. 0.5%	60% NO_x, 20% PM, 10% SO_2	All engines
Ambitious	SCR, max. 0.5% sulphur in fuel	90% NO_x, 80% HC, 80% CO, 30% PM, 10% SO_2	All engines

6.2.3

Ship emissions 2015

In the Baseline scenario, i.e. in the situation that would comply with the legislative requirements, emissions from cargo ships increase substantially at the Gulf of Finland by 2015 (Table 6.3). NO_x emissions will increase by about 110 per cent. The increase is smallest in the amount SO_2 emissions due to the strictest regulation. However, the increase is still about 50 per cent. The regulation of the sulphur content of fuel also reduces the growth in PM emissions, which is 80 per cent. For passenger ships the emissions do not increase substantially in the Baseline scenario because the increase in ship traffic is more moderate (Table 6.3). The increase in SO_2 emissions is 20 per cent and the increase in PM emissions is four per cent from year 2000. NO_x emissions decrease by about 50 per cent because of increasing use of control technologies. CO and HC emissions from the passenger ships increase at the same rate with the increase in ship traffic, by 30 per cent. In scenarios M_New and M_All only the amount of NO_x emissions decrease from the level of the Baseline scenario due to the technology assumptions that only affect NO_x emissions (Table 6.3). In scenario M_New the NO_x emissions are about 70 per cent of the amount in the Baseline scenario. Still they are 50 per cent larger than in 2000. In scenario M_All NO_x emissions are about 40 per cent of the amount in Baseline and they are also 10 per cent lower than in 2000.

In the Ambitious scenario SO_2 emissions are reduced by 60 per cent from the IMO standard level and 40 per cent from the level of year 2000. Also the amounts of NO_x, CO and HC are significantly lower than in 2000. The NO_x emissions are reduced by approximately 80 per cent and CO and HC emissions are reduced by 60 per cent from the level of year 2000. However, the amount of PM emissions produced is still 50 per cent larger than in 2000.

Emissions from passenger ships decrease from the level of 2000 in the Ambitious scenario (Table 6.3). NO_x emissions decrease to a quarter of the amount in the Baseline scenario and to a tenth of the amount in 2000. CO and HC emissions are decreased by three quarters and PM emissions are decreased by 10 per cent from the level of 2000.

At the Gulf of Bothnia NO_x emissions from cargo ships increase by approximately 20 per cent from year 2000 in the Baseline scenario (Table 6.4). In scenario M_New the NO_x emissions are reduced by 10 per cent and in scenario M_All by about 50 per cent from the level of year 2000. SO_2 emissions from cargo ships decrease by 10 per cent from the level of 2000 in the Baseline scenario and in scenarios M_New and M_All. PM emissions increase by 5 per cent and CO and HC emissions increase by 30 per cent in all three scenarios. In the Ambitious scenario SO_2 emissions are reduced by 60 per cent of the level of year 2000. The reduction in NO_x emissions is approximately 87 per cent and in PM emissions about 10 per cent. CO and HC emissions are reduced by three quarters from the level of year 2000. The development of passenger ship emissions at the Gulf of Bothnia is similar with the development at the Gulf of Finland in both scenarios (Table 6.4).

Table 6.3: Shipping emissions at Gulf of Finland in 2015.

	Energy consumption [PJ/a]	**SO_2 [Gg/a]**	**NO_x [Gg/a]**	**PM [Gg/a]**	**CO [Gg/a]**	**HC [Gg/a]**
Cargo ships						
In 2000	21.6	17.1	41.8	1.1	2.0	1.1
Baseline	46.7	25.3	87.6	2.0	4.4	2.3
Moderate_NewEngines	46.7	25.3	62.0	2.0	4.4	2.3
Moderate_AllEngines	46.7	25.3	36.5	2.0	4.4	2.3
Ambitious	46.7	11.1	9.1	1.7	0.8	0.5
Passenger ships						
In 2000	7.2	1.2	11.1	0.3	0.8	0.3
Baseline	9.4	1.5	5.7	0.3	1.0	0.4
Ambitious	9.4	1.5	1.4	0.2	0.2	0.09

Table 6.4: Shipping emissions at Gulf of Bothnia in 2015.

	Energy consumption [PJ/a]	**SO_2 [Gg/a]**	**NO_x [Gg/a]**	**PM [Gg/a]**	**CO [Gg/a]**	**HC [Gg/a]**
Cargo ships						
In 2000	18.4	15.1	37.0	1.0	1.7	0.9
Baseline	24.9	13.5	47.1	1.1	2.3	1.2
Moderate_NewEngines	24.9	13.5	33.3	1.1	2.3	1.2
Moderate_AllEngines	24.9	13.5	19.6	1.1	2.3	1.2
Ambitious	24.9	5.9	4.9	0.9	0.5	0.2
Passenger ships						
In 2000	11.0	1.9	16.8	0.4	1.1	0.5
Baseline	14.3	2.3	8.7	0.4	1.5	0.7
Ambitious	14.3	2.3	2.2	0.4	0.3	0.1

7 Discussion and conclusions

In this work the emissions from maritime transport and emission reduction potential in the Gulf of Finland and the Gulf of Bothnia were studied. The emissions were calculated by estimating ship movements on the selected marine areas in 2000 and 2015 on four different technology scenarios. The emissions reduction potential was evaluated based on a literature study on emission reduction technologies for ship engines. At the moment there are extensive cargo and passenger ship traffic at the Gulf of Finland and the Gulf of Bothnia. The busiest routes are at the western side of the Gulf of Finland and the Archipelago Sea. Reason for this is that the main directions of the cargo ship traffic are west from the Gulf of Finland and south from the Gulf of Bothnia. The number of cargo ship passages were approximately 34000 at the mouth of the Gulf of Finland and 23000 at the mouth of the Gulf of Bothnia. Beside this, there are several passenger ships sailing daily at these sea areas. At the Bothnian Sea, the Bothnian Bay and the eastern side of the Gulf of Finland the majority of the ships movements are made by cargo vessels.

Air pollutions from shipping are of special concern at the moment. Because of the lack of regulations the emissions from ships have continued to grow while emissions from land-based sources have been reduced. The largest environmental problems related to shipping are caused by SO_2 and NO_x emissions. The amount of these produced by the ships sailing on the studied sea routes contributed 49 % and 53 % respectively of the amount from Finnish land based sources in 2000. The total amount of shipping based SO_2 emissions were approximately 36000 tonnes and amount of NO_x emissions were 107000 tonnes on the sea routes in 2000.

Geographically the shipping emissions are largest in the areas where the tra-c volumes are largest. Approximately 70 per cent of all the ship-based emissions on the sea routes are generated at the western Gulf of Finland and the Archipelago Sea. Shipping emissions generated in the eastern Gulf of Finland and the Bothnian Sea contribute both about 10 per cent of the total emissions on the sea routes. Emissions from other waterborne traffic than ships on sea routes, i.e. in port areas and inland waters and from work and recreational vessels, contributed only 10 per cent of the total SO_2 and NO_x emissions and 20 per cent of the total PM emissions. The majority of HC and CO emissions, however, are caused by recreational vessels powered with 2-stroke gasoline engines that were not at the scope of this study.

When comparing the different ship types the largest sources of NO_x and PM emissions are passenger ferries, cargo ferries and other dry cargo vessels. The cargo ferries are in general quite large and thus their energy consumption is high. Furthermore, large ships mostly use two-stroke engines that have higher pollution levels than four-stroke engines. Passenger ferries have large engines and the number of passenger ship movements is high, which leads to high NO_x emissions. SO_2 emissions from passenger ships, however, are not as extensive as from cargo ships because the fuels used in passenger ships have significantly lower sulphur content.

There are several techniques to reduce the shipping emissions. Currently the engine manufacturers and regulators are concentrated on reduction of SO_2 and NO_x emissions. The level of SO_2 emissions is mainly depended on the sulphur content of fuels used. At the moment the average sulphur content of the marine fuels used is 2.7 %. Heavy fuel oils with the sulphur content of 0.5 % and marine diesel oils with the sulphur content of 0.2 % are available on the market but their demand suffer from their high price compared to fuels with higher sulphur content. Other possibility to cut down SO_2 emissions is an introduction of sea water scrubber to clean the SO_2 from exhaust gases.

NO_x emissions are reduced by engine design and after-treatment technologies. Most commonly used techniques are internal engine adjustments, which include several methods for optimizing the combustion conditions and fuel injection and charge air characteristics in terms of nitrogen oxides and particulate matter emissions. With these modifications a reduction of 30 % in NO_x emissions can be achieved. For further reduction of nitrogen oxides the most potential techniques are water injection to the engine process by direct injection, water-fuel-emulsion or humid air, exhaust gas recirculation and selective catalytic reduction. With exhaust gas recirculation the NO_x reduction potential is 35-50 %, with DWI and fuel-water-emulsion 50-60 %, with HAM 70-80 % and with SCR 90-99 %. Fuel quality and many of the NO_x reduction technologies also affect the emissions of PM, CO and HC.

IMO has set emission standards for SO_2 and NO_x emissions from marine vessels that came into force in May 2005. The limit for SO_2 emissions is 6 g/kWh in the Baltic Sea area which can be achieved by limiting the sulphur content of fuels used to maximum 1.5 %. IMO's NO_x limits range from 9.8 to 17 g/kWh depending on the engine speed, with higher limits for slower engines. These limits are quite weak in terms of effective NO_x reduction. Engine manufacturers have prepared their engines to meet the NO_x standards for several years now by the introduction of internal engine modifications.

Air pollutant emissions from shipping will increase sharply in the future in the marine areas near Finland. The current emission regulations for ships have only small decreasing effect on emission rates, mainly on sulphur dioxide emissions. The reductions achieved with the regulations will be overtaken by the growth in ship traffic if no other emission reduction technology is installed on ships. The emissions of SO_2 and NO_x will be 42000 and 149000 tonnes, respectively, in 2015 in the situation when current emission regulations will be fulfilled. These would contribute approximately 60 % and 110 % of the amount of non-ship based emissions in Finland, respectively (Figure 7.1). Thus, there is a need for tighter regulation.

Introduction of more efficient emission abatement technologies can help to reduce shipping emissions significantly below the current level despite the growth in traffic volumes. The potential is substantial especially on cargo ships. The results from the scenario study show that already the implementation of a water injection technology on new engines could lead to reduction in the NO_x emission level in the Gulf of Bothnia and decrease the growth rate of NO_x emissions in the Gulf of Finland. If same technology would be installed on all cargo ship engines NO_x emissions would decrease in the Gulf of Finland too. Installation of an effective after-treatment system such as SCR combined with fuel with sulphur content of maximum 0.5 % would reduce emissions from cargo ships significantly, between 60 and 90 per cent in the amount of SO_2, NO_x, CO and HC emissions, with more moderate reduction in PM emissions.

The emission situation of passenger ships differ from cargo ships. Already now many of the passenger ships use cleaner fuels than cargo vessels and some passenger ships have some additional NO_x reduction technology installed onboard. This development is predicted to continue since the good environmental performance will help passenger shipping companies to built a good company image and also gives an economic advance when environmentally differentiated fees are applied. This will lead to further reductions of NO_x, PM, CO and HC emissions. SO_2 emissions are relatively low already because of the low-sulphur fuels used in passenger vessels. For further emission reduction below the levels estimated in the scenario study, a great potential is especially in particulate matter emissions. The reduction of particulate matter emissions could be achieved by the introduction of EGR and seawater scrubbing technologies. Seawater scrubbing reduces also SO_2 emissions. The price of low-sulphur fuels will presumably increase in the future along the growing demand. This would make the seawater scrubbing more desirable option for some of the ships. Seawater scrubbing technology lacks, however, wide experience on actual ship operation, and therefore its potential till 2015 was estimated to be limited. Also growing use of common rail technology will reduce particulate matter emissions at partial loads and thus it has a positive effect on ship emissions near the ports.

In future the emission standards are predicted to be tightened by IMO and EU. A further reduction of 30 per cent to the IMO's NO_x standards would mean future emissions to be on the level of results from Moderate scenarios. However, changing the regulations is a long process and they are not predicted to be changed in next few years. If new stricter standards are implemented they will probably apply only to new engines and will only gradually reduce the emissions over a longer time period. Thus the possible new regulations would not have large effects on emissions in 2015. On the other hand the economic incentives and voluntarily emission reduction programs may also lead to the emission levels of the Moderate scenarios. In both cases the SO_2 emissions would decrease to a level between the Moderate and Ambitious scenarios since it is likely that new regulations or economic instruments would also limit the sulphur content in fuels below the current standards.

The results from the four technology scenarios show that there are a great reduction potential in NO_x and SO_2 emissions from ships. However, reduction in emission levels is not likely without stricter emission regulations or powerful economic instruments that would encourage all the ships invest on NO_x abatement techniques and switch to low-sulphur fuels. The results of this study will be incorporated into the Finnish Regional Emission Scenario (FRES) model of Finnish Environment Institute. FRES model is used as an integrated assessment tool of air pollution. It enables effects-oriented assessment studies on e.g. acidification, eutrophication, and human health impacts, in order to promote policy making in Finland and nearby areas.

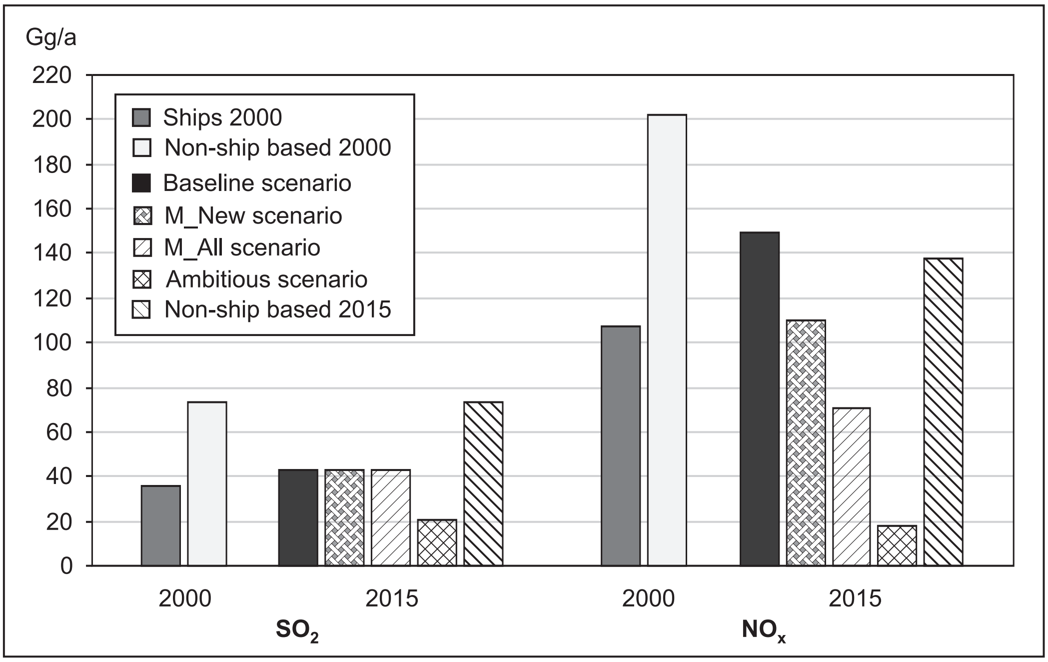

Figure 7.1: Ship based and non-ship based emissions in 2000 and 2015 (emission from nos-ship based sources are evaluated in (Karvosenoja et al., 2003))

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Appendix A

Ship engines' sizes and types.

Table A.1 Gulf of Finland

	Power of the main engines [kW]	Power of the auxiliary engines [kW]	Proportion of 4-stroke engines	Proportion of 2-stroke engines
Passenger vessels	17060	786	1	0
Passenger ferries	14333	1447	1	0
Cargo ferries	12534	1447	0.08	0.92
Containers	5019	786	0.25	0.75
Bulk carriers	8571	1122	0.1	0.9
Other dry cargo vessels	2763	520	0.76	0.24
Tankers	8571	1122	0.1	0.9
Other vessels	1236	346	0.72	0.28
Domestic traffic	1236	346	0.72	0.28

Table A.2 Archipelago Sea

	Power of the main engines [kW]	Power of the auxiliary engines [kW]	Proportion of 4-stroke engines	Proportion of 2-stroke engines
Passenger vessels	26924	1770	1	0
Passenger ferries	26924	1770	1	0
Train ferries	12534	1447	0.08	0.92
Cargo ferries	12534	1447	0.08	0.92
Containers	2763	520	0.76	0.24
Bulk carriers	8571	1122	0.1	0.9
Other dry cargo vessels	1236	346	0.72	0.28
Tankers	5019	786	0.25	0.75
Other vessels	1236	346	0.72	0.28
Domestic traffic	1236	346	0.72	0.28

Table A.3 Bothnian Sea

	Power of the main engines [kW]	Power of the auxiliary engines [kW]	Proportion of 4-stroke engines	Proportion of 2-stroke engines
Passenger vessels	14333	1447	1	0
Cargo ferries	8571	1122	0.1	0.9
Containers	5019	786	0.25	0.75
Other dry cargo vessels	2763	520	0.76	0.24
Tankers	5019	786	0.25	0.75
Bulk carriers	8571	1122	0.1	0.9
Other vessels	2763	520	0.76	0.24
Domestic traffic	672	230	0.97	0.03

Table A.4 Bothnian Bay

	Power of the main engines [kW]	Power of the auxiliary engines [kW]	Proportion of 4-stroke engines	Proportion of 2-stroke engines
Passenger vessels	25293	1770	1	0
Cargo ferries	8571	1122	0.1	0.9
Containers	2763	520	0.76	0.24
Other dry cargo vessels	5019	786	0.25	0.75
Tankers	8571	1122	0.1	0.9
Bulk carriers	2763	520	0.76	0.24
Other vessels	12534	1447	0.08	0.92
Domestic traffic	2763	520	0.76	0.24

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Abstract

Ships are a significant source of air pollutant emissions, especially NOx and SO2. Pollution levels will increase in the future due to growth in ship traffic and lack of effective regulations. So far, related research has been concentrated on emissions from land-based sources, and very few shipping emission inventories exist to date.

The aim of this study was to evaluate emissions and the technical reduction potential of SO2, NOx, CO, HC and PM from waterborne traffic in Finland and in marine areas near Finland in 2000 and 2015. The energy consumption of ships in 2000 was estimated based on statistics mapping ship movements in the ports of Finland, Russia, Estonia and Sweden. Combined with emission factors, this data was used as a basis for evaluating the total amount of emissions. Emissions in 2015 were calculated based on predicted growth rates in ship traffic and four different reduction technology scenarios.

In 2000 the ship-based SO2 and NOx emissions on sea routes totalled 36000 and 107000 tonnes, respectively. Current international regulations have little impact on emission rates in the studied marine areas. The required reduction technologies are internal engine modifications and fuel with a maximum sulphur content of 1.5 %.

The results of the scenario study show that ship-based SO2 and NOx emissions will increase by 20 % and 40 % respectively by 2015 if no further emission reduction methods are introduced. These emissions could be reduced significantly through introduction of more effective reduction technologies, such as lowering the sulphur content in fuel, adding water to the engine process, exhaust gas recirculation and selective catalytic reduction technology. The potential is substantial, especially for NOx emissions from cargo ships, which could be reduced by approximately 90 % from the 2015 baseline level.

Keywords	air pollution, ship traffic, emissions, environment technology			
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Tiivistelmä

Laivat ovat merkittävä ilmansaasteiden, erityisesti SO_2:n ja NO_x:n, lähde. Laivojen päästöt kasvavat tulevaisuudessa lisääntyvän laivaliikenteen sekä vähäisten päästörajoitusten myötä. Ilmapäästöjen tutkimus on keskittynyt maalähteisiin ja siksi laivojen päästöistä on toistaiseksi olemassa vain vähän tietoa.

Tämän työn tavoitteena oli selvittää laivaliikenteen SO_2-, NO_x-, CO-, HC- ja hiukkaspäästöjen määrää sekä niiden vähennyspotentiaalia Suomessa ja Suomen läheisillä merialueilla vuosina 2000 ja 2015. Vuoden 2000 laivapäästöt on arvioitu pohjautuen tilastoihin laivaliikenteestä Suomen, Ruotsin, Viron ja Venäjän satamissa ja näiden perusteella arvioituun laivojen energiankulutukseen väylillä sekä päästökertoimiin. Vuoden 2015 päästöjä on arvioitu liikennemäärän kasvuennusteiden sekä neljän skenaarion avulla, joilla tutkittiin erilaisten vähennystekniikoiden käyttöönoton vaikutusta päästöihin.

Vuonna 2000 meriväylillä syntyneet SO_2-päästöt olivat noin 36000 tonnia ja NO_x-päästöt noin 107000 tonnia. Nykyisillä kansainvälisillä päästörajoilla ei ole merkittävää vaikutusta laivapäästöjen määrään tutkituilla merialueilla. Rajojen noudattaminen edellyttää moottorin palamisprosessin säätöä sekä polttoaineen rikkipitoisuuden rajoittamista 1,5 prosenttiin.

Skenaariotarkastelun tulokset osoittivat, että SO_2- ja NOx-päästöt kasvavat 20 % ja 40 % vastaavasti Suomen läheisillä merialueilla vuoteen 2015 mennessä, mikäli tehokkaampia vähennystekniikoita ei oteta käyttöön. Tehokkaammilla vähennystekniikoilla, kuten polttoaineen rikkipitoisuuden pienentämisellä, veden lisäyksellä polttoprosessiin, pakokaasujen takaisinkierrätyksellä ja selektiivisellä katalyyttisella vähennystekniikalla, voidaan päästöjä vähentää merkittävästi. Erityisesti rahtilaivojen NO_x-päästöjen vähennyspotentiaali on merkittävä, noin 90 %, verrattuna vuoden 2015 perustasoon.

Asiasanat	ilman saastuminen, laivaliikenne, päästöt, ympäristöteknologia			
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Painopaikka ja -aika	Edita Prima Oy, Helsinki 2006			

PRESENTATIONSBLAD

<table>
<tr><td>Utgivare</td><td colspan="3">Finlands miljöcentral (SYKE)</td><td>Datum
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<tr><td>Författare</td><td colspan="4">Johanna Wahlström, Niko Karvosenoja och Petri Porvari</td></tr>
<tr><td>Publikationens titel</td><td colspan="4">Ship emissions and technical emission reduction potential in the northern Baltic Sea
Fartygutsläpp och teknisk minskningspotential i norra Östersjön</td></tr>
<tr><td>Publikationsserie och nummer</td><td colspan="4">Reports of Finnish Environment Institute 8/2006</td></tr>
<tr><td>Publikationens tema</td><td colspan="4"></td></tr>
<tr><td>Publikationens delar/ andra publikationer inom samma projekt</td><td colspan="4">Publikationen finns tillgänglig på Internet:
www.environment.fi/publications</td></tr>
<tr><td>Sammandrag</td><td colspan="4">Fartyg är betydelsefulla källor till luftföroreningar, speciellt SO_2 och NO_x. Utsläppen kommer öka i framtiden på grund av ökande fartygstrafik och avsaknad av effektiv reglering. Forskning om luftutsläpp har fokuserats till landbaserade källor och därför finns det endast lite information om utsläpp av fartyg.

Syftet med detta arbete är att beskriva fartygstrafikens utsläpp och de reduktionsmöjligheter som finns när det gäller SO_2, NO_x, CO, HC och partikelutsläpp i Finland och närbelägen havsområden åren 2000 och 2015. Fartygutsläppen år 2000 har uppskattats utgående från statistik över fartygstrafik på hamnar i Finland, Sverige, Estland och Ryssland. Kombinerad med uppskattad mängd utsläpp på farlederna och utsläppskoefficienter har den totala mängden utsläpp beräknats. 2015 års fartygutsläpp har uppskattats med hjälp av tillväxtprognoser över trafiken. Fyra olika scenarier har använts.

SO_2-utsläppen som uppstod i farlederna år 2000 var ungefär 36000 ton och NO_x-utsläppen ungefär 107000 ton. De gällande internationella utsläppsgränserna har ingen betydande inverkan på mängden fartygsutsläpp i det område som undersöktes. Efterlevnaden av gränserna förutsätter reglering av motorernas förbränningsprocess och begränsning av bränslet svavelhalt till maximalt 1,5 procent.

Resultatet av scenarieundersökningen pekar på att utsläpp av SO_2 och NO_x kommer att öka med 20 % respektive 40 % på havsområdena nära Finland innan år 2015, om inte mer effektiva reduktionstekniker tas i bruk. Med sådana reduktionstekniker är det möjligt att minska utsläppen betydligt. Dylika tekniker är minskning av bränslets svavelhalt, tillsättning av vatten i förbränningsprocessen, återcirkulering av avgaser och selektiv katalytisk reduktionsteknik. I synnerhet den potential som fraktfartyg har att minska NO_x-utsläpp är betydande, ungefär 90 % jämfört med 2015 års nivå.</td></tr>
<tr><td>Nyckelord</td><td colspan="4">luftförorening, fartygstrafik, utsläpp, miljöteknologi</td></tr>
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