M. Kroon, R. Smit and J. van Ham (Editors), Freight Transport and the Environment
© 1991 Elsevier Science Publishers B.V., Amsterdam. Printed in the Netherlands

EMISSIONS FROM INLAND AND COASTAL SHIPPING AND POTENTIAL FOR IMPROVEMENT

L. Kolle[a], Ø. Melhus[a], K. Bremnes[a] and G. Fiskaa[b]
[a]*Marintek – Sintef Group, P.O. Box 4125, N-7002 Trondheim, Norway*
[b]*Norwegian Institute of Technology, Trondheim, Norway*

1. BACKGROUND

In comparison with other transport forms, the energy consumption in sea transportation in terms of kWh/ton km is favourably low, as shown in figure 1.

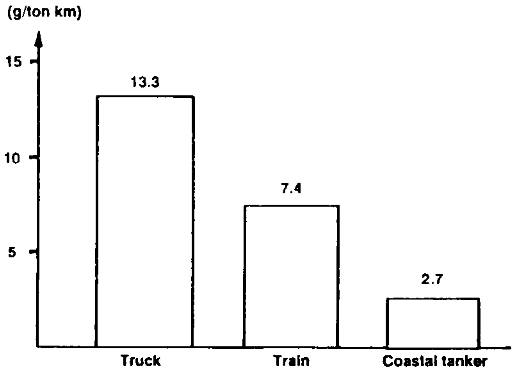


Fig. 1: Fuel consumption for various transport forms.
(Source : Svensk Sjøfartstidning).

Due to the near relationship between the amount of burnt fuel and air pollution, sea transportation represent an environmental-friendly form of transportation. With todays concern about air pollution, this should result in giving sea transportation a competitive edge, as well as emphasising the importance of further reduction of harmful emissions from ships.

The NO_x emission from shipping presented in this paper might seem high, but one should bear in mind the dominating role shipping plays in domestic and international transportation.

In this paper we will concentrate on describing methodology and results from a Norwegian study, performed on contract for the Norwegian State Pollution Control Authority in order to determine the current levels of exhaust gas emissions from international shipping.

2. METHODOLOGY

Probably the only method capable of charting exact figures for exhaust gas emissions and inventories would be to install equipment for continuous emission registration on all ships combined with a detailed registration of each specific ship's movement on a world–

wide basis. According to Lloyd's Statistical Tables the total world fleet contains 75.680 ships of 100 gross tons or more, and the amount of work will be prohibitive.

In the Norwegian study the exhaust gas emissions from ships in international trade and the global distribution have been computed on the basis of the ships' bunker consumption combined with the transport pattern of the sea-borne cargo. The stipulated bunker consumption figures have been compared with the statistical figures for bunker deliveries, and adequate corrections have been made.

The basic input data for the computations are as follows :

1. International sea-borne transport pattern.
   The distribution of bunker consumed on international ship routes has been constructed in accordance with the international sea-borne trade statistics.

2. Ships' bunker consumption.
   The consumption of bunker for each category of ships and ship size has been stipulated on the basis of world fleet statistics and ship data given in ship register books. Ships' total bunker consumption has been corrected in accordance with international energy statistics.

3. Exhaust gas emission.
   Bunker consumption has been converted to emission of NO_x and SO_2 in accordance with the latest established emission factors.

For each main type of goods (general cargo, liquid bulk, dry bulk etc.) moved between given coastal regions, the consumed bunker has been calculated in accordance with the volum carried, voyage length and the type and size of ships employed for the relevant trade.

The bunker consumed has been converted into emission of NO_x and SO_2, and these figures have been marked on ocean charts in accordance with the main international ship routes.

3. THE PATTERN OF INTERNATIONAL SEA-BORNE TRANSPORT

The pattern of the international seaborne trade has been drawn up on the basis of data given in "International Sea-borne Trade Statistics Yearbook 1884-1985" issued by United Nations Organization.

In this statistic, goods traded internationally are classified into 37 categories under 5 main groups (dry bulk, liquid bulk, type of general cargo etc.) according to the general characteristic of their ocean carriage.

The coastlines of the world are divided into 30 regions compatible with geographical and national constraints.

Quantities are shown in metric tons and the transport distances (average length of haul) in nautical miles.

3.1 Export/Import regions

Unfortunately, only a condensed version consisting of 15 regions was available for electronic data processing at the start of this study. These regions are:

1 East Coast North America
2 West Coast North America
3 Central America
4 East Coast South America
5 West Coast South America

6 British Isles
7 Northern Europe
8 Atlantic Coast West Europe
9 Mediterranean Area
10 West Africa
11 South- and East Africa
12 Red Sea and Persian Gulf
13 South and Southeast Asia
14 Far East Asia
15 Oceania

The traffic between these 15 regions give a total number of 105 ship routes, internal traffic in the regions not included. The Cross ocean routes are far less in numbers because many routes are combined.

4. SHIPS' BUNKER CONSUMPTION

The specific bunker consumption expressed as "units per ton per nautical mile" varies greatly with the category of ships and the size of ships. This information is not readily available, and it has been necessary to carry out a fleet survey to establish the average ship size as well as the average bunker consumption, for each category of ships of the world fleet.

Ship data and specifications from 50 - 80 ships of each category have been used to stipulate the consumption factors. The essential input data for this survey have been collected from Lloyds' Statistical Tables, Lloyds' Register of Ships and other specialized Ship Register Books.

In addition to ship sizes and bunker consumption the fleet survey also contain engine data and power consumption factors. Calculation factors for bunker and power consumption have been corrected for ballast voyages, bunker supply, load factors, engine loads etc. The result of the fleet survey is given in table 1. (next page).

4.1 Bunker consumption statistics

The only available statistics which give bunker consumption on world wide basis is the "Energy Statistics Yearbook", issued by United Nations. This statistic only includes bunker deliveries to "international marine transport". National consumption for marine activities are not specified, but included in other inland consumption of bunker oils.

International Energy Agency (IEA) issues energy statistics for the OECD area, but none of these statistics specifies national consumption of bunker oils for marine purposes. The figures for international marine bunkers from IEA correspond fairly well with the UN energy statistics.

4.2 International consumption

For the years 1982 - 1986 world international consumption of bunker type oils and total consumption are given in table 2.

According to the figures in table 2. the consumption of bunker fuel oil for international transport is approximately 6,5% of the world total consumption of bunker type oils (residual fuel, gas- and diesel oils) and approximately 3% of total consumption of liquid energy products.

Table 2. shows a decrease in total bunker deliveries to international transport from 98.7 mill.tons in 1982 to 83.7 mill.tons in 1984, increasing to 87.5 mill. ton in 1986.

Table 1. World Fleet Data - Cargo Vessels (Average figures)

TYPE OF SHIP	SHIP DATA						POWER CONSUMPTION				BUNKER CONSUMPTION		
	SIZE GRT	SIZE DWT	MAIN ENG. KW	SPECFIC CONS.	SPEED KNOTS	CONSUMP. TONS/DAY	ENGINES KW/GRT	ENGINES KWH/T-M	CORREC. "F"	CORRECTED KWH/T-M	CONSUMP. KILO/T-M	CORREC. "U"	CORRECTED KILO/T-M
DRY BULK:													
Bulk & Combo Carriers													
Steam (4,5%)	75,384	144,730	19,650	281	15.2	132,0	0.2607	0.0089	1.72	0.0154	0.0025	63%	0.0040
Motor (95,5%)	28,221	51,482	9,795	202	14.6	47.4	0.3471	0.0130	1.67	0.0217	0.0026	65%	0.0040
Coastal and Short Haul Bulk Carriers	8,100	12,356	4,410	203	13.5	19.6	0.5444	0.0250	1.61	0.0403	0.0050	68%	0.0074
LIQUID BULK:													
Crude Carriers													
Steam turb.(62%)	131,313	276,430	26,280	276	16.0	174.2	0.2001	0.0063	1.96	0.0123	0.0016	55%	0.0029
Motor (38%)	73,539	141,242	17,662	191	15.4	80.1	0.2402	0.0090	1.96	0.0176	0.0015	52%	0.0029
Product tankers	21,745	36,714	8,207	205	15.0	39.8	0.3774	0.0168	1.85	0.0311	0.0030	60%	0.0050
Coastal tankers	1,983	3,413	1,777	210	12.1	9.0	0.8961	0.0430	1.69	0.0727	0.0090	63%	0.0143
Gas Carriers													
Turb. L.H. (68%)	72,232	57,741	25,583	280	19.2	171.8	0.3542	0.0231	1.92	0.0444	0.0065	55%	0.0119
Motor S.H. (26%)	20,272	23,218	9,247	195	16.1	42.5	0.4561	0.0339	1.92	0.0651	0.0066	56%	0.0119
Coastal (6%)	1,269	1,432	1,368	200	12.0	8.4	1.0780	0.0799	1.82	0.1454	0.0159	60%	0.0265
GENERAL CARGO - (incl. refrigerated food)													
Cargoship for overseas trade													
Steam (4,3%)	27,105	31,045	24,273	268	22.0	156.0	0.8955	0.0355	1.69	0.0600	0.0095	70%	0.0136
Motor (95,7%)	11,963	14,142	10,935	208	17.3	54.7	0.9141	0.0383	1.78	0.0682	0.0093	60%	0.0155
Cargoship for coastal- and Short Sea trade	4,200	5,800	4,490	204	15.5	22.0	1.0690	0.0502	1.85	0.0929	0.0102	58%	0.0176

(GRT = Gross Register Tons, DWT = Dead Weight Tons, ENG. = Engines, CONS. = Consumption, KW/GRT = Kilowatt per gross register ton,
KWH = Kilowatt-hour, T-M = ton-mile (nautical). - L.H. = Long haul, S.H. = Short haul)

"F" = Correction factor for ballast voyages, bunker supply, load factor, engine load, etc.

"U" = Utilization ratio (Correction of ship capasity due to ballast voyages, load factor etc.)

Year:	1982	1983	1984	1985	1986
For international trade:					
Residual fuel	82,444	73,225	68,068	69,331	70,711
Gas/Diesel oil	16,214	15,476	15,614	16,042	16,812
Total	98,658	88,701	83,682	85,373	87,523
World total consumption:					
Residual fuel	680,535	669,817	658,736	605,017	621,840
Gas/Diesel oil	670,231	670,413	683,447	697,292	707,113
Total	1,150,766	1,340,230	1,342,183	1,303,309	1,328,953
World consumption of liquid energy:					
All commod.	2,513,104	2,787,329	2,830,522	2,807,539	2,955,266

(Figures in 1,000 metric tons) Source: UN Energy Statistics Yearbook 1986

Table 2. - International consumption of bunker oils.

The consumption of light bunker oils (gas/diesel oils) for marine purposes in relation to heavy bunker oils, has been constantly growing during the period covered by the above named statistics. Light oil consumption increased from 16% of the total consumption of marine bunker in 1982 to 19% in 1986.

4.3 National bunker consumption

As mentioned above the consumption of bunker oils for coastal and other national marine purposes are not specified in international statistics.

In some countries the national consumption of marine bunker may be considerable.

The Norwegian deliveries of bunker oil for marine consumption (1986) are given in table 3. This table shows that deliveries to fishing- and coastal vessels represent 69% of total consumption, while 31% are deliveries to ships in international trade.

Of the total consumption of bunker type oils in Norway 80% is landbased consumption, while fisheries and coastal transport each represent 10%.

Due to a very long coastline and extensive activities in the fishing sector, Norway is in a special situation compared with most other countries, but national consumption of marine bunker oil may be considerable also in some other countries.

Only national statistics or other national information will contain the necessary data for stipulation of the total emissions of exhaust gasses from all ships.

	Heavy fuel oil	Gas & diesel oil	Total
Coastal transport	156	262	418
Fisheries	5	428	433
Total	161	690	851
International bunker deliveries	210	170	380
Total	371	860	1231

(Figures in 1.000 metric tons) Source: Norsk Petroleumsinstitutt

Table 3. - Norwegian bunker deliveries 1986.

5. EMISSION FACTORS

MARINTEK has performed studies regarding emission factors and especially NO_x emission, for marine diesel engines for several years. Various medium speed and high speed engines have undergone laboratory tests. During the latest months additional comprehensive emission measurements on bord Norwegian coastal vessels have been performed.

5.1 Measurements on laboratory engines.

In the machinery laboratories at the Marine Technical Center (MTS) in Trondheim, NO_x emissions from four marine, medium speed diesel engines have been established. These engines have been operated both according to the propeller law and at constant speed.

The reason for establishing NO_x emission at different operating modes, is that in the coastal trade fleet some ships use propellers with fixed pitch and some propellers with variable pitch.

NO_x Emissions from the engines operating according to the propeller law are shown in table 4.

Engine type	NO_x emission factor (g/kg fuel)			
	100% load	80% load	50% load	20% load
4 stroke	80	77	83	98
2 stroke	60	66	86	96

Table 4. NO_x emission factors from marine diesel engines (medium 4 speed) operated according to the propeller law .

NO_x emissions from engines operating at constant speed are shown in table 5.

Engine type	NO_x emission factors (g/kg fuel)		
	100% load	60% load	20% load
4 stroke	82	94	89
2 stroke	60	70	51

Table 5. NO_x emission factors from marine diesel engines (medium speed) operated at constant speed.

The differences in NO_x emissions on different engine loads, are due to differences in engine speed and process conditions.

5.2 Measurements on operating vessels.

During the winter 1989/1990 NO_x emissions from main engines on operating vessels in Norwegian coastal trade were established. Both 2 stroke and 4 stroke diesel engines and both fixed and variable pitch propeller were covered by this investigation. The age of the engines varies from more than 30 to less than 5 years while the size ranged from some hundred and up to several thousand kilowatts. The results are shown in table 6.

Engine	NO_x emission factor (g/kg fuel)	
type	Mean value	Standard deviation
4 stroke	55.9	9.5
2 stroke	72.8	8.2
Total	62.6	12.2

Table 6. NO_x emission factors from operating vessels in Norwegian coastal trade.

The results shows that the NO_x emissions established from laboratory engines and engines installed in ships differ quite much. Some of the reason for this is that all the laboratory engines are new or upgraded engines with high efficiency, while many of the engines on the vessels are old engines with lower efficiency. Further more, some of the vessels with propeller with variable pitch did not operate at constant speed.

6. CALCULATED NO_x EMISSION FROM SEA TRANSPORT

Table 7. shows the world total emission from international transport. This calculation is based on the bunker consumption for 1986 and the following conversion factors.

Motor Ships: 70g/kg fuel oil NOx
Steam Ships: 8g/kg fuel oil NOx

Ship type	Consumed bunker Mill. tons	Emission NO_x
Motor Ships	53,916 Hvf 16,812 Mdo*	3,774 1,177
Steamships	16,795 Hvf	134
Total	87,523	5,085

Table 7 - World total NO_x emission from international sea-borne transport.

Figure 2. shows the emission from international shipping relative to the total global emissions.

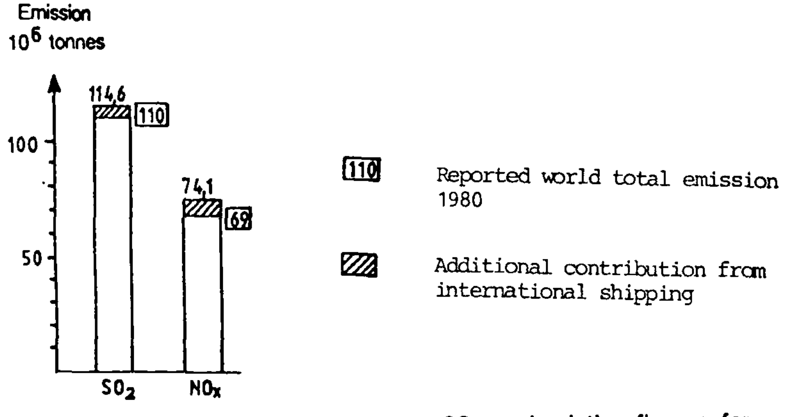
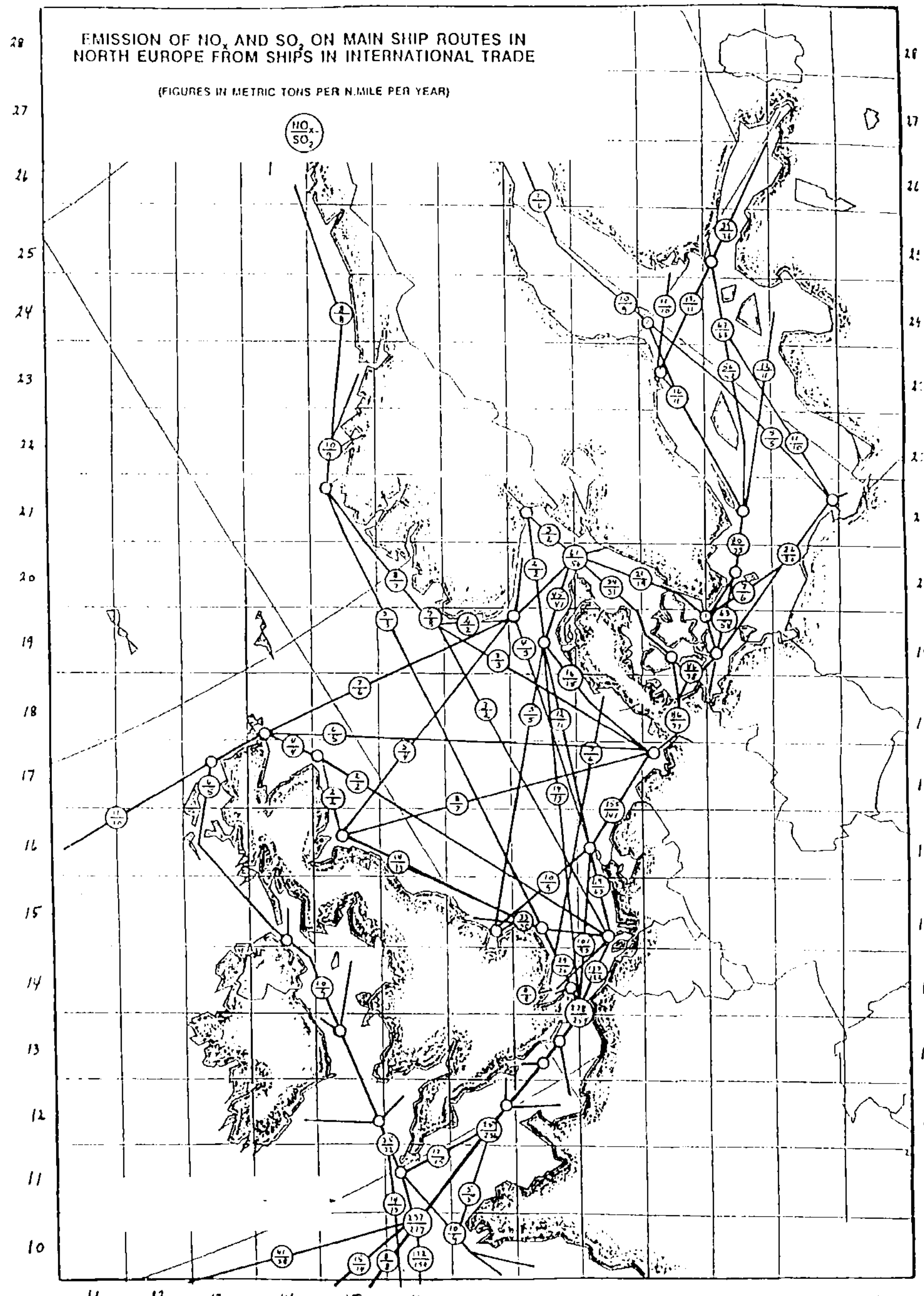


Figure 2. Total global emissions of NO_x ans SO_2 and relative figures for international shipping.

Fig. 3: - Emission of NO_x and SO_2 in North European Waters



From the calculated results may be summarized :

International shipping contributes about **7%** of the total NO_x emission on a global scale.

6.1 Emissions of NO_x and SO_2 in North European waters

A special survey has been carried out for the North Sea, Baltic and English Channel. To be able to chart the bunker consumption and exhaust gas emission on the main ship routes within this area it has been necessary to use national export/import statistics, manual calculations and estimates based on experience in addition to the basic figures computed on the basis of the UN sea-borne transport statistics.

Due to some uncertain factors, the figures must only be regarded as approximate. A more extensive use of national export/import statistics, port statistics etc. will be necessary to produce more correct figures. From the results may be summarized :

4% of the total emissions of NO_x and SO_2 from international shipping are emitted in the North Sea and the English Channel. This amount is comparable with the discharges in countries like Belgium, Denmark, the Netherlands and Norway. Area emissions varies considerably, and may represent significant local and regional emission problems.

The result of this survey is given on EMEP map in figure 3 (next page). The emissions are especially high in the narrow waters of the English Channel by Dover. The discharges are also high in the southern part of the North Sea, especially along the coastline of Belgium, the Netherlands and West Germany.

Figure 4. shows area emissions (tonnes per square kilometer per year) for the North Sea and some European countries. As can be seen, the area emissions in most European countries are much higher than in the North Sea and the English Channel. Local variations in the density of traffic on the sea will, however, result in area emissions that represent local or regional emission problems of significance.

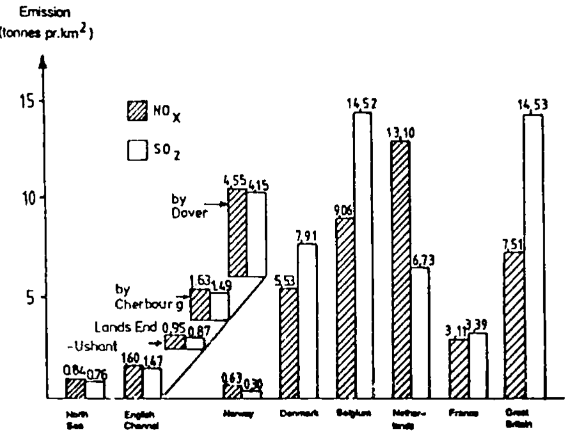


Figure 4. Emission in tonnes per square kilometer of NO_x ans SO_2 in the North Sea, the English Channel and some European countries. Figures from 1985.

7. UNCERTAINTIES

The employed method for calculation of emissions is dependent of several parameters. Uncertainties in the transport pattern, fleet composition, bunker consumption and emission factors will all influence the calculated total emissions as well as their geographic distribution.

The sea transport pattern is based on figures from the UN statistics. This statistics does not cover data from coastal transport, inland water ways, fisheries and other national marine activities. Therefore, only emissions from ships in international trade are included in this study. Only national statistics will contain the necessary data for estimation of those sources.

The study has not included details regarding ship routes, and hence the calculated emissions are distributed on the most important international ship routes.

The emission factors are based on the latest information from major engine builders as well as Norwegian measurements on operating vessels and laboratory engines.

8. POSSIBLE MEANS OF NO_x REDUCTION

Several methods may be applied to reduce NO_x emissions from ships, such as :

- alternative fuels/techniques
- engine modifications
- exhaust gas cleaning
- better utilication of existing transport capacity
- energy optimized vessels

Of these, only the first three will be further dealt with here.

8.1 Alternative Fuels.

Alternative bunker fuil qualities imply only minor alterations in NO_x emission, and normal fuel oil additives have marginal effects. Emulsion of higher rates of alcohols, for instance methanol show more promising results, but might not be realistic in marine application. Another technique, which has been used on landbased applications, is by water emulsion or water injection in the cylinder units. By these methods, NO_x emissions may be reduced as much as 30%, with minor increase in fuel oil consumption.

By using natural gas fuel, NO_x reduction of 20–30% may be achieved. For smaller engines (5000 kW) "Otto-lean burn" engines may be applied, resulting in NO_x reduction of ab. 80%.

8.2 Engine Modification.

Considerable reductions of NO_x emissions can be achieved by optimizing the engines for low emissions. With contemporary technology it is possible to reduce the NO_x emission from modern engines by approximately 50%. A reduction of 25% may be achieved without a significant increase in fuel oil consumption. Efforts for higher NO_x reductions will, with todays technology, increase the fuel consumption in the range up to 10%. This fuel consumption penalty will reduce the effect of the emission reduction and at the same time increase the CO_2 emission. There is a potential in new techniques in the future for reduction or elemination of the fuel consumption penalty, and possibly also for a reduction below the 50% figure.

8.3 Exhaust Gas Cleaning.

Existing technology for landbased applications is able to reduce both SO_2, particles and NO_x. Common for these process plants is that they are voluminous and therefore not easily applicable on existing ships. Only NO_x-reducing SCR plants have so far been installed in newbuilt ships.

The most promising process for exhaust gas treatment is the deNO_x-ing Selective Catalytic Reduction (SCR) technology. This process is adopted from the power generating industry, and the first ships with this NO_x-reducting equipment are built in 1989. The SCR plant is claimed able to reduce the NO_x emission 80 – 90% with the use of ammonia (NH_3) to give pure N_2 and H_2O. In addition HC emission can be reduced by as much as 60%. Investment cost depends on engine size. For a pilot plant installed on a power station with a 20 MW diesel generator the price is reported to be 80.000 US$/MW, and two ships with 4MW main engines are under construction with SCR plants for 130.000 US$/MW. Operational costs are estimated to be $2\text{–}3 \cdot 10^{-3}$ US$/kWh. Also regarding this technique further improvement should be anticipated.

9. FINAL REMARKS

For a period, technical improvements in ships and ship engines have compensated for the increase in sea transport volume, and the energy consumption and polluting emissions have been contant for some years.

This technological achievement has been powered by high fuel prices and the economic competition in the transport sector, resulting in very efficient ships and engines. These improvements will slow down, however.

These days there are signs indicating that international trade will increase even faster than before, and the energy consumption can not be kept constant by increased efficiency. Polluting emissions will increase unless the emission problem is addressed directly. Economic competition is, however, not a natural force to propel technological developments in this field.

Within reasonable economic frames it is possible to reduce the NO_x emission by 50 to 80 percent. In order to achieve this it will be necessary to have international regulations, stipulating permissible emission levels from the various sources of pollution. The regulations should make reasonable allowances for technology and costs, so that their implementation will not result in unfortunate social consequences, such as penalizing either sea or road transport. The regulations should be enforced after a time interval, allowing for the development of necessary know how and technology.