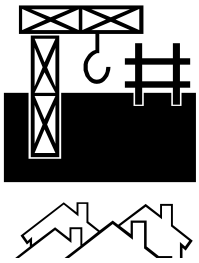
Marine Exhaust Emissions Quantification Study – Mediterranean Sea

FINAL REPORT

99/EE/7044



ENVIRONMENTAL ENGINEERING DEPARTMENT

Job Name	***Final Report***
Subject	***Marine Exhaust Emissions Quantification Study - Mediterranean Sea***
Client	***European Commission, DG XI Environment, Nuclear Safety and Civil Protection***
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REPORT SUMMARY
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Job Number

FINAL REPORT

Subject

Marine Exhaust Emission Quantification Study - Mediterranean Sea

On behalf of the European Community Directorate General for Environment, Nuclear Safety and Civil Protection, Lloyd's Register undertook a marine exhaust emission quantification study for the Mediterranean Sea. The study was based on a systematic methodology for the quantification of regional exhaust emissions from shipping which was developed as part of Lloyd's Register's Marine Exhaust Emissions Research Programme.

The methodology developed utilised ship movement data supplied by Lloyd's Maritime Information Services, ship particulars from the Register of Ships and emission data previously compiled by Lloyd's Register. The methodology has been designed to quantify emissions based on ship movement data and route information within the Mediterranean Sea.

Emission estimates were quantified on a per grid basis and spatially distributed throughout the study area using a gridded matrix, equating to the EMEP 50-km x 50-km grid system. From the results of the study, it was estimated that approximately 1,725 kilotonnes (kt) of oxides of nitrogen (NO_x), 1,246 kt of sulphur dioxide (SO_2), 147 kt of carbon monoxide (CO) and 35 kt of hydrocarbons (HC) were emitted from shipping operating in the Mediterranean Sea in 1990.

The emission estimates from this study were approximately 85-90% of the emission totals for the north-eastern Atlantic region, previously estimated by Lloyd's Register. Total annual emission estimates for NO_x and SO_2 were of a similar magnitude to those reported for France in 1990.

The spatial distribution of the emission estimates for each pollutant are presented in four graduated thematic maps of the study area as tonnes of pollutant/50-km x 50-km grid square. Emission estimates were also quantified on a per route basis.

This data has been provided on a floppy diskette as a Microsoft Excel 5 file.

A strong relationship between ship traffic density and pollutant emissions was evident, with the grid squares with the highest emissions lying along the Atlantic/Suez corridor, the Bosphorus/Volga transit, the coastal routes around the Gulfs of Valencia and Lion and the Ligurian, Tyrrhenian and Adriatic Seas.

With respect to further development of this work, the emission quantification model developed in this study could also be applied to assessing emission reduction strategies, such as fuel sulphur restrictions and engine NO_x reductions.

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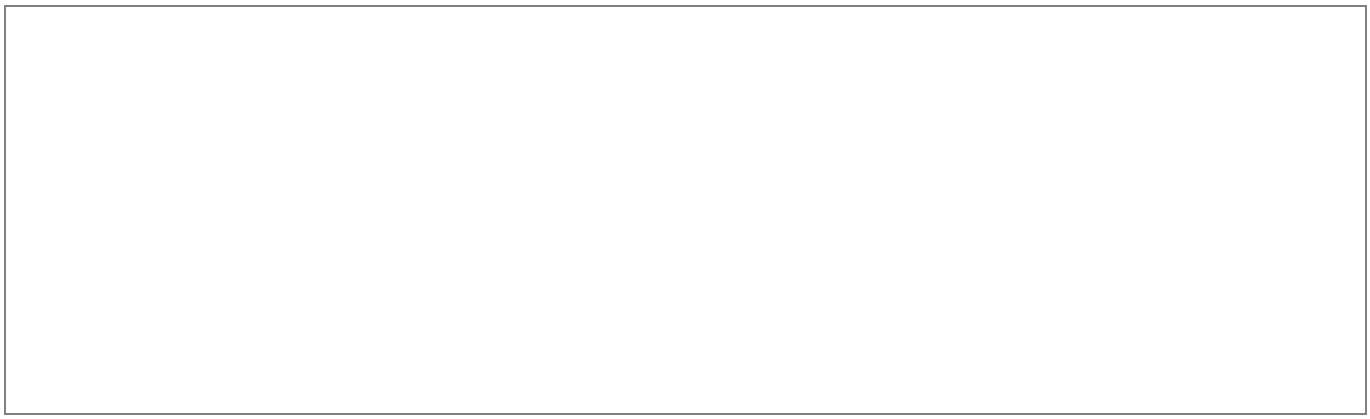


1. INTRODUCTION

At the request of the European Community Directorate General for Environment, Nuclear Safety and Civil Protection, Lloyd's Register undertook a desk based marine exhaust emissions quantification study for the Mediterranean Sea. The study was based upon a systematic methodology used to quantify regional exhaust emissions from shipping, which was developed as part of the third phase of work of Lloyd's Register's Marine Exhaust Emissions Research Programme [1]. The objective of the study was to quantify annual emissions from shipping operating within the Mediterranean and Black Seas and to spatially distribute these estimates on a grid based map of the study area.

2. METHODOLOGY

2.1 Overview

The methodology presented used available core data sets (Lloyd's Maritime Information Services (LMIS) ship movement data and the Register of Ships [2]) and commercially available computer software. Three key data components were used in the emission quantification process. These included: the details of all shipping movements in the study area over two periods in 1990; vessel specific data, such as engine power, used for the calculation of specific emission rates and emission factors previously defined by Lloyd's Register from in-service measurements. These three data sets were interconnected using a computer based relational database.

Route specific emission estimates were then calculated based upon ship movement data and shipping routes, which were manipulated onto a digitized map of the study area using a geographical information system (GIS) software package. For those routes either entering or exiting the Mediterranean Sea via the Straits of Gibraltar or the Suez Canal, emission estimates along each route were calculated only from the point of entry into/up to the point of exit out of the study area respectively.

These route based estimates were then spatially distributed using a GIS based 50-km x 50-km grid network (equating to the grid system adopted by EMEP[1]) to produce grid specific emission estimates. Maps were then generated for each pollutant quantified, indicating the magnitude and geographical distribution of oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC) and sulphur dioxide (SO_2) within the study area.

[1] Convention of Long-Range Transboundary Air Pollution, Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe

2.2 Study area

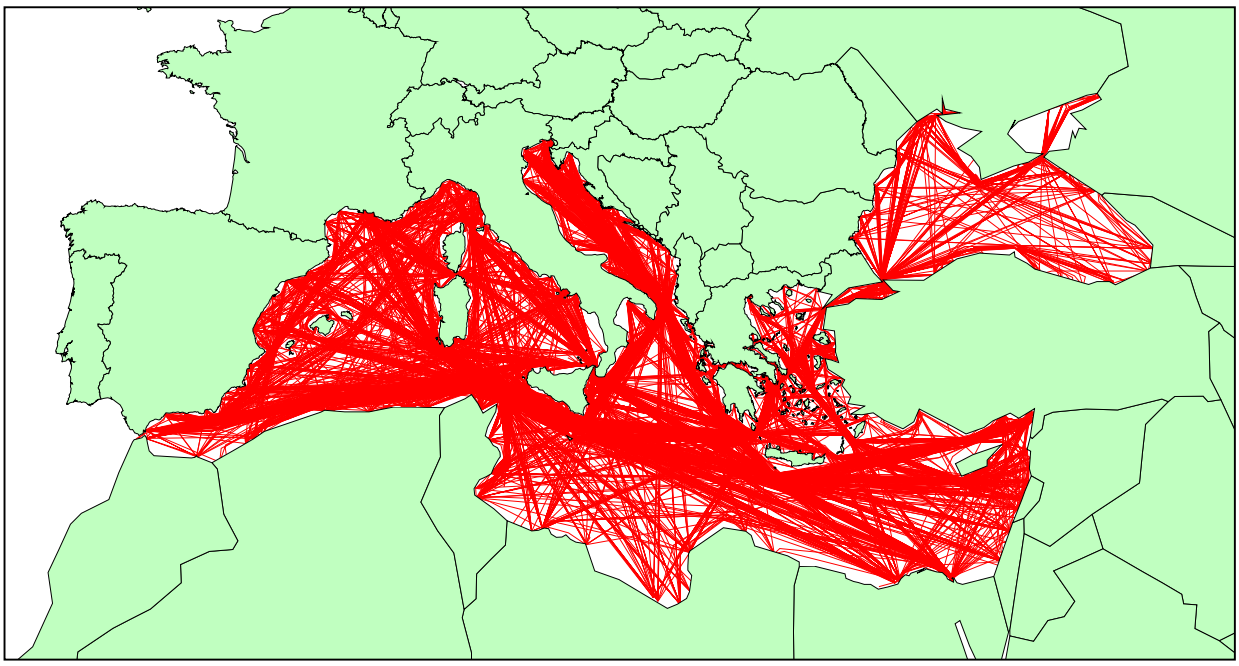
The area used in this study incorporated the Mediterranean Sea defined as "the Mediterranean Sea proper including the gulfs and seas therein, bounded to the west by the Straits of Gibraltar at the meridian 5° 36′ W" and the Black Sea. This definition has been taken from the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) [3]. The whole study area encompassed approximately 2,966,000 km^2 (Figure 1).

2.3 Study periods

The year 1990 was chosen as the base year for the emission estimates in this study as it was the year used in the marine exhaust emission quantification study for the north-eastern Atlantic Ocean previously undertaken by Lloyd's Register [1]. In addition, 1990 was the year chosen for a similar quantification study of the Baltic Sea undertaken by Lloyd's Register on behalf of Det Norske Meteorologiske Institutt (DNMI) [4]. Consequently, comparative evaluations could be undertaken with the results of these other studies.

Due to the size of the study area and the large number of vessel movements within the region (approximately 655,000 per year), two, two-week periods, 1-14 February and 1-14 August 1990, were focused upon. Emission estimates from these two periods were subsequently extrapolated to provide an annual estimate.

Figure 1: Map of the study area showing plotted shipping routes



2.4 Shipping movements

The latitude and longitude of departure and arrival ports, together with corresponding dates for all vessels greater than 250 gross tonnes travelling within the study area, during the two study periods were provided by LMIS. Vessels departing from or arriving at ports within the study area, one week before or after the period of interest were also included, to identify whether these vessels were traversing any part of the study area during that period. For those vessels entering or leaving the Mediterranean Sea, entry/exit points at Gibraltar and Suez, defined as 36°09'N, 05°20'W and 29°58'N, 32°33'E respectively, were incorporated into the ship movement database. These intermediate points were used in the plotting of all routes entering and exiting the study area.

A total of 34,055 vessel movements during the two periods in February and August were provided by LMIS. In addition, a further 16,376 ferry movements for the relevant periods were derived from operators' schedules or international timetables. Generally movements of naval vessels, small craft and fishing vessels were not recorded by LMIS and were, on the whole, excluded from the emissions estimate.

Only ships on passage or arriving at or departing from a berth were included in the study. Emissions from ships hotelling in port, or at anchor awaiting a berth, or awaiting orders, were not quantified.

2.5 Ship particulars

Ship particulars were provided by the Register of Ships [2] and LMIS. Data on ship type, gross tonnage, number of engines, main engine power and type (slow, medium speed or steam), generator power and, where available, service speed for each individual vessel were obtained on computer diskette.

A total of 7,050 individual vessels plus 212 ferries were included in the study. The ratio between the number of medium speed and slow speed vessels was in the region of 50:50; however, slow speed engines accounted for approximately 66% of the total installed propulsion power. Only 2.1% of vessels were steam powered, yet these ships represented approximately 8% of the total installed power.

Data on engine type are summarized in Table 1 below. Further detailed information regarding number of ships, total gross registered tonnage (grt), total power, number of shipping movements and total distance travelled, based upon ship type, is provided in Appendix 1.

Table 1: Ships categorized by engine type

Engine Type	No. of Vessels	%	Total Power (kW)	%
Medium Speed	3,675	50.6	11,809136	26.2
Slow Speed	3,434	47.3	29,686729	65.8
Steam	153	2.1	3,585,525	8.0
Total	**7,262**	**100**	**45,081,390**	**100**

2.6 Emission factors

Emission rates in kg/hour for oxides of nitrogen (NO_x), carbon monoxide (CO), hydrocarbons (HC) and sulphur dioxide (SO_2), for individual motor vessels, were derived from emission data obtained during the shipboard measurement programme [1]. These emission factors (Table 2) are based upon curves of engine rating against emission rate and adjusted to allow for an assumed engine load of 85% maximum continuous rating (MCR). The emission rate is dependent upon the number and type of engines (i.e. medium/slow speed diesel and steam) and the installed power of each vessel.

Table 2: Emission Factors (kg/h)

	Main engines		*Auxiliary engines*
	Medium speed	**Slow speed**	
NO_x	$4.25\times10^{-3}\times P^{1.15}\times N$	$17.50\times10^{-3}\times P\times N$	$4.25\times10^{-3}\times A^{1.15}$
CO	$15.32\times10^{-3}\times P^{0.68}\times N$	$0.68\times10^{-3}\times P^{1.08}\times N$	$15.32\times10^{-3}\times A^{0.68}$
HC	$4.86\times10^{-3}\times P^{0.69}\times N$	$0.28\times10^{-3}\times P\times N$	$4.86\times10^{-3}\times A^{0.69}$
SO_2 P <2,000 kW	$2.31\times10^{-3}\times P\times N$	-	-
SO_2 P >2,000 kW	$12.47\times10^{-3}\times P\times N$	$11.34\times10^{-3}\times P\times N$	
SO_2	-	-	$2.36\times10^{-3}\times A\times C$

P = maximum continuous engine power (kW) multiplied by engine load factor to give continuous service rating (85% MCR)
N = number of engines
A = auxiliary power (kW)
C = 1, 2, 3, 4 and 5 where vessel GT is <1,000, 1,000 <5,000, 5,000 <10,000, 10,000 <50,000 and 50,000 respectively

Emission rates for SO_2 are dependent upon the sulphur content of fuel burnt. In this study, it was assumed that slow speed engines and medium speed engines, greater than or equal to 2000 kW, were burning heavy fuel oil, with a sulphur content of 2.7% (by wt). Medium speed engines, less than 2000 kW, were assumed to be burning gas oil, with a sulphur content of 0.5% (by wt) [5].

Emission factors for steam ships were derived from data published by the United States Environmental Protection Agency [6].

It was assumed that auxiliary power was provided by medium speed diesel engines on all ships. Average auxiliary power estimates were based upon professional judgement and data within the Register of Ships [2] and are presented in Table 3. Emission rates were calculated following the same procedures as for the main engines, using the emission factors presented in Table 2. These factors assumed an MCR of 100% for auxiliary engines.

2.7 Emission quantification procedure

A computer based relational database was used to combine the vessel movement data with individual vessels and their corresponding emission rates. The latitude and longitude of each combination of departure port, arrival port and entry/exit point (i.e. Gibraltar or Suez) were entered into a GIS package which included a digitized map of the study area (Figure 1). The GIS package initially linked each combination of co-ordinates with a straight line. These straight-line routes were then manipulated to represent the most likely course between either the two internal ports, or the port and entry/exit point, using GIS tools and referring to ship routing guides [7,8]. A total of 5,525 routes were manipulated in this way.

A GIS based grid network of the study area was developed in parallel to the routing procedure. The origin of the grid system was equivalent to that used by EMEP. The GIS was then used to calculate the total distance of each individual route and the distance traversed across all the grid squares along each route. In order to assess the reliability of the routing information, eighty routes were selected and the calculated route distances were compared to those given in distance tables [9]. Estimated distances were found to be within ±5% of those quoted.

Since journey times were derived from departure and arrival dates given in the LMIS ship movement data, all movement times were rounded up to the nearest 24 hours. In addition, the LMIS data did not provide information as to when a ship entered or exited the study area. Therefore, it was necessary to assume average service speeds for specific vessel types to better estimate the actual journey time taken, to the nearest hour. These speed estimates were based upon marine engineering principles and data within the Register of Ships [2] and are presented by ship type in Table 3. The route distances were converted to total journey times for each vessel by application of vessel specific speed factors (excluding ferries, as times were taken from either operators' schedules or international timetables).

Table 3: Estimated auxiliary power (kW) and speed factor by ship type

			Average GRT				Speed
Ship Type	<500	500-999	1,000-4,999	5,000-9,999	10,000-49,999	>50,000	Factor (Knots)
Liquefied Gas Tanker	75	100	125	300	400	1,000	16
Chemical Tanker	40	50	165	300	435	-	15
Other Tanker	40	50	165	300	435	530	14
Bulk Dry Cargo	20	40	175	300	380	500	14
General Cargo	20	40	175	300	380	-	14
Passenger/General Cargo	20	40	175	300	380	-	18
Container	40	60	160	500	1,400	1,400	20
Refrigerated Cargo	40	140	180	455	580	-	20
Ro-Ro Cargo	100	150	350	1,000	2,500	4,000	18
Passenger/Ro-Ro Cargo	100	150	350	1,000	2,500	4,000	20
Passenger	100	150	350	1,000	2,500	4,000	20
Other Dry Cargo	20	40	175	300	380	500	15
Fish Catching	-	80	200	-	-	-	11
Other Fishing	40	105	180	550	550	-	15
Offshore	40	60	150	350	450	-	14
Research	40	60	150	400	400	-	14
Tug	40	60	150	-	-	-	11
Dredger	40	50	60	130	770	-	9
Cable	80	-	200	300	400	-	7
All other ship types	20	40	175	300	380	500	-

The time taken for each vessel to travel along a route and to transverse all individual grid squares along each route was calculated. Emissions per vessel per grid square were derived from the product of the time (in hours) a vessel was in a grid square and the emission rate (in kg/hour) of the individual vessel, as follows:

$$\text{Emissions/vessel/grid square, } E = et$$

where:

t is estimated time taken to traverse grid square (hours) = d/s

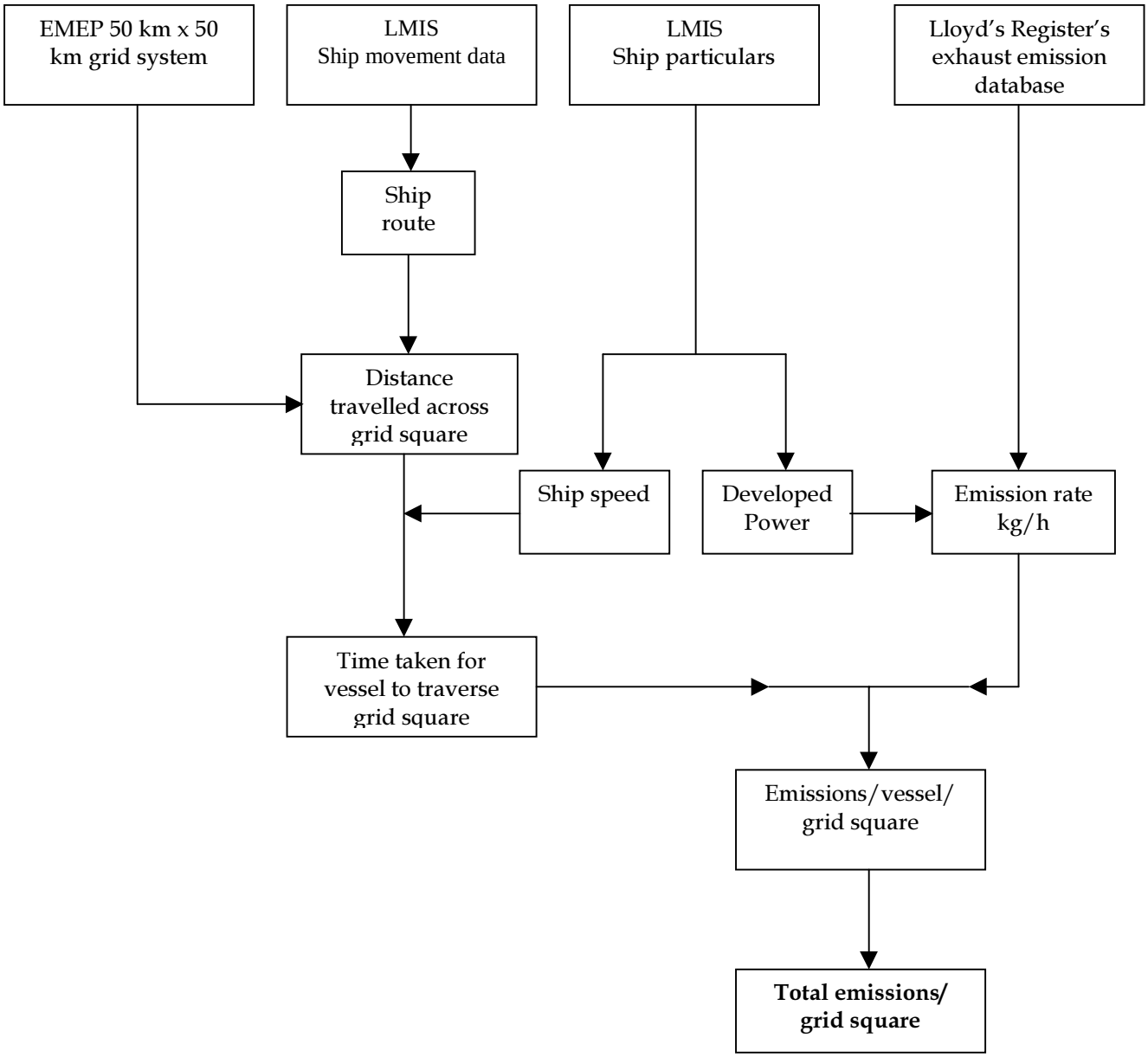
e is vessel specific emission rate (kg/hour)

d is distance traversed across grid square (nautical miles)

s is the estimated speed of vessel (knots)

The emissions per grid along each shipping route were then summed to give the total emissions per grid. These emission totals per grid were then summed and extrapolated to derive annual emission estimates. Both main and auxiliary engine emissions were calculated in this way. The GIS was then used to assign the emission totals to the relevant grid squares overlaying the study area to enable the spatial distribution of emissions to be plotted. The emission quantification procedure is outlined in Figure 2 below.

Figure 2: Summary of regional emission quantification procedure



2.8 Assumptions and Exclusions

As discussed above, certain key data parameters required for calculating ship emissions were either unavailable or unsuitable for incorporation due to limitations in time, resources and data handling capabilities. Therefore, it was necessary to make a number of assumptions and exclusions.

Assumptions were made about the following:

Engine Load - The main engines of all vessels were assumed to be operating at 85% MCR for all of the time whilst at sea.

Speed - It was necessary to assume average service speeds for specific vessel types in order to estimate actual journey times, to the nearest hour, from the plotted route distances in nautical miles. These speed estimates are presented in Table 3.

Auxiliary Power – It was assumed that auxiliary power was provided by medium speed diesel engines on all ships. Estimates were based upon information on ship type and gross tonnage (Table 3). Emission rates were calculated following the same procedures as for the main engines (assuming an MCR of 100%).

Exclusions were usually attributable to lack of basic information on vessel movements and include:

Ships in port - Routine quantification of harbour traffic was not considered feasible using the methodology presented here. Only emissions from shipping on passage or arriving at, or departing from a berth were included. Emissions from ships hotelling in port, or at anchor awaiting a berth or awaiting orders, were excluded.

Fishing vessels - Fishing vessels were not generally included in the LMIS data. Furthermore, data relating to fishing vessel fuel consumption or movements, which would enable regional emission quantification was not available. Therefore, other than the limited number included in the LMIS data, fishing vessels were excluded from this quantification study.

Naval vessels - Very little vessel movement or route data were available for naval ships. Therefore, other than the limited number included in the LMIS data, naval vessels were also excluded from this quantification study.

3. RESULTS OF THE STUDY

The results of the quantification study are presented in four thematic maps. Each map shows the spatial distribution of the annual emission estimates of NO_x, CO, HC and SO_2 produced by ships' main and auxiliary engines (Appendix 2). The emission estimates are presented as tonnes of pollutant/50-km x 50-km grid square.

As may be anticipated, a strong relationship between ship traffic density and pollutant emissions was apparent, with the grid squares with the highest emissions lying along the Atlantic/Suez corridor, the Bosphorus/Volga transit, the coastal routes around the Gulfs of Valencia and Lion and the Ligurian, Tyrrhenian and Adriatic Seas.

The estimated total annual emissions of NO_x, CO, HC and SO_2 emitted by shipping operating throughout the whole study area in 1990 are presented in Table 4 below.

Table 4 : Total estimated emissions from shipping operating in the Mediterranean and Black Sea areas in 1990 (tonnes/annum)

Emission	NO_x	CO	HC	SO_2
Main Engines	1,620,336	129,055	29,549	1,171,784
Auxiliary Engines	104,338	17,987	5,783	73,893
Total	**1,724,674**	**147,042**	**35,332**	**1,245,677**

The emission estimates have also been quantified on a per route basis. The 5,525 routes were divided into six distinct route categories; routes entering (181) or exiting (179) the Mediterranean Sea via the Straits of Gibraltar, routes entering (24) or exiting (86) the Mediterranean Sea via the Suez Canal, routes passing straight through the study area via the Straits of Gibraltar and the Suez Canal (2) and those routes lying entirely within the study area (5,053), which included all ferry routes.

There were a number of routes, which were in effect 'mirror images' of others. For example, of the 181 routes entering the Mediterranean Sea via the Straits of Gibraltar, 141 had a comparable route exiting the Mediterranean the same way. Similarly, there were 1,214 'mirror image' internal routes. Consequently, to determine the total emission estimates along these routes, the estimates for both routes were added together. A summary of the routes, showing the 'mirror images' and their respective emission estimates, as well as the total emission estimates per route for the whole study area, has been provided on a floppy diskette as a Microsoft Excel 5 file.

The total annual emission estimates from this study were compared with the results of the third phase of Lloyd's Register's Marine Exhaust Emissions Research Programme [1], together with national emission estimates for 1990, derived from the European Environment Agency Task Force [10]. These estimates are presented in Table 5 below.

Table 5 : Relative magnitude of shipping and national emission estimates in 1990 (x10^3 tonnes/annum)

	NO_x	CO	HC	SO_2
Shipping:				
Mediterranean & Black Seas region	1,725	147	35	1,246
NE Atlantic region [1]	1,935	172	40	1,371
National estimates: [10]				
Denmark	273	789	178	193
France	1,590	10,930	2,864	1,300
Germany	3,037	10,620	3,356	5,508
Netherlands	576	1,106	460	201
Norway	232	950	270	54
Spain	1,257	4,977	1,894	2,206
United Kingdom	2,773	6,701	2,682	3,787

The emission estimates from this study were approximately 85-90% of the emission totals for the north-eastern Atlantic region, previously estimated by Lloyd's Register. Total annual emission estimates for NO_x and SO_2 were of a similar magnitude to those reported for France in 1990.

4. CONCLUSIONS AND RECOMMENDATIONS

It was estimated that on an annual basis, ships emitted approximately 1,725 kilotonnes (kt) of NO_x, 1,246 kt SO_2, 147 kt of CO and 35 kt of hydrocarbons in the study area, based on 1990 ship movement data. This was approximately 85-90% of the emission totals for the north-eastern Atlantic region, previously estimated by Lloyd's Register. Total annual emission estimates for NO_x and SO_2 were of a similar magnitude to those reported for France in 1990.

A strong relationship was evident between ship traffic density and pollutant emissions, with the grid squares with the highest emissions lying along the Atlantic/Suez corridor, the Bosphorus/Volga transit, the coastal routes around the Gulfs of Valencia and Lion and the Ligurian, Tyrrhenian and Adriatic Seas.

With respect to further development of this work, the emission quantification model developed in this study could also be applied to assessing emission reduction strategies such as fuel sulphur restrictions and engine NO_x reductions.

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Appendix 1

Ship type and movement data

99/EE/7044
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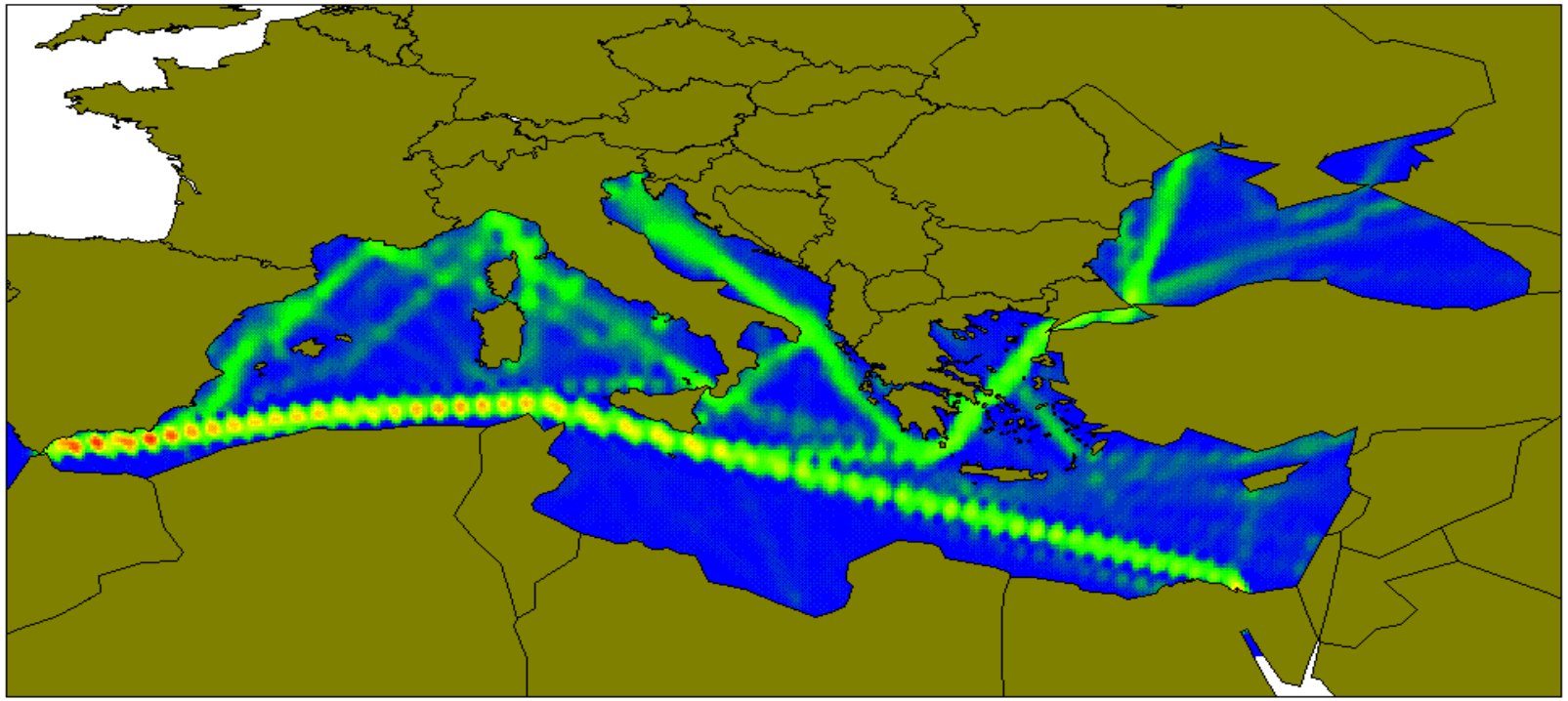
MARINE EXHAUST EMISSION QUANTIFICATION STUDY - MEDITERRANEAN SEA

MARINE EXHAUST EMISSION QUANTIFICATION STUDY - MEDITERRANEAN SEA

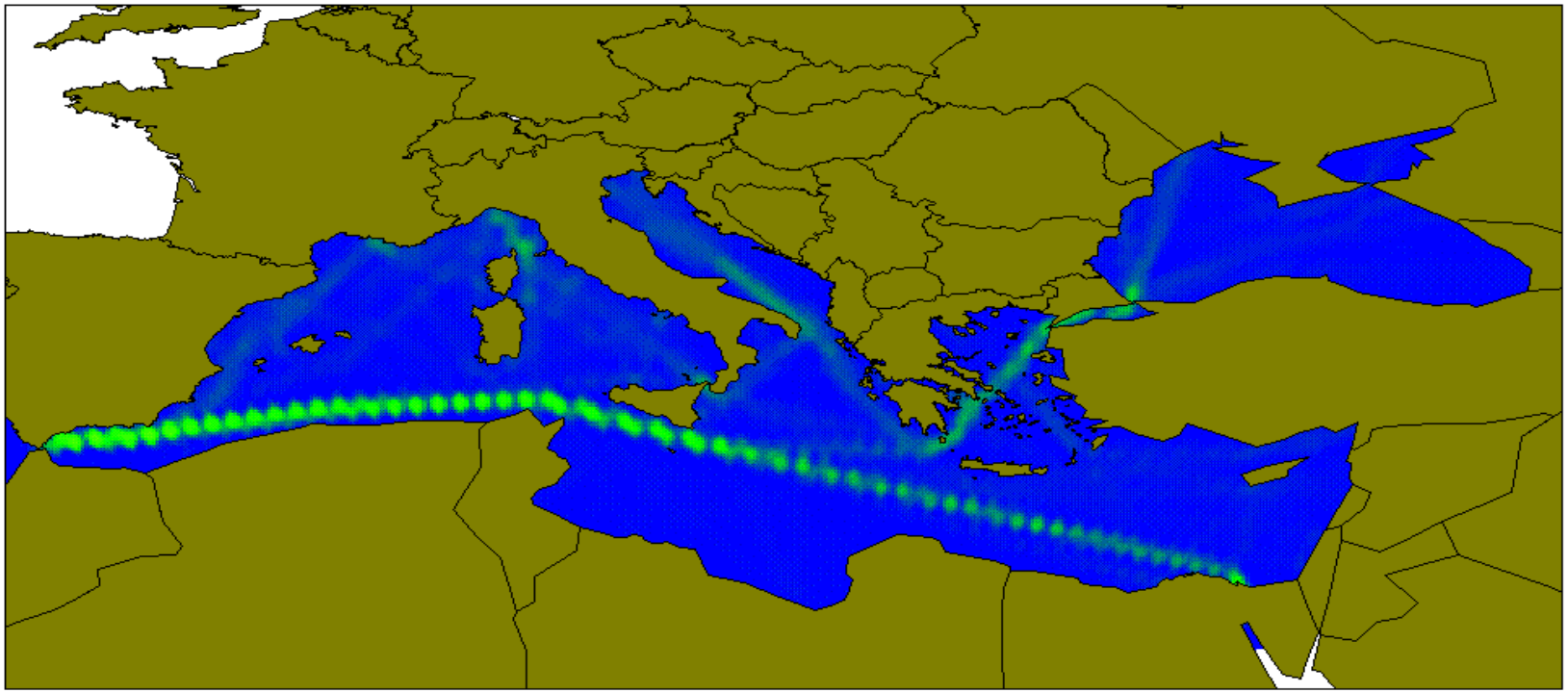
Appendix 2

Annual emission estimate maps

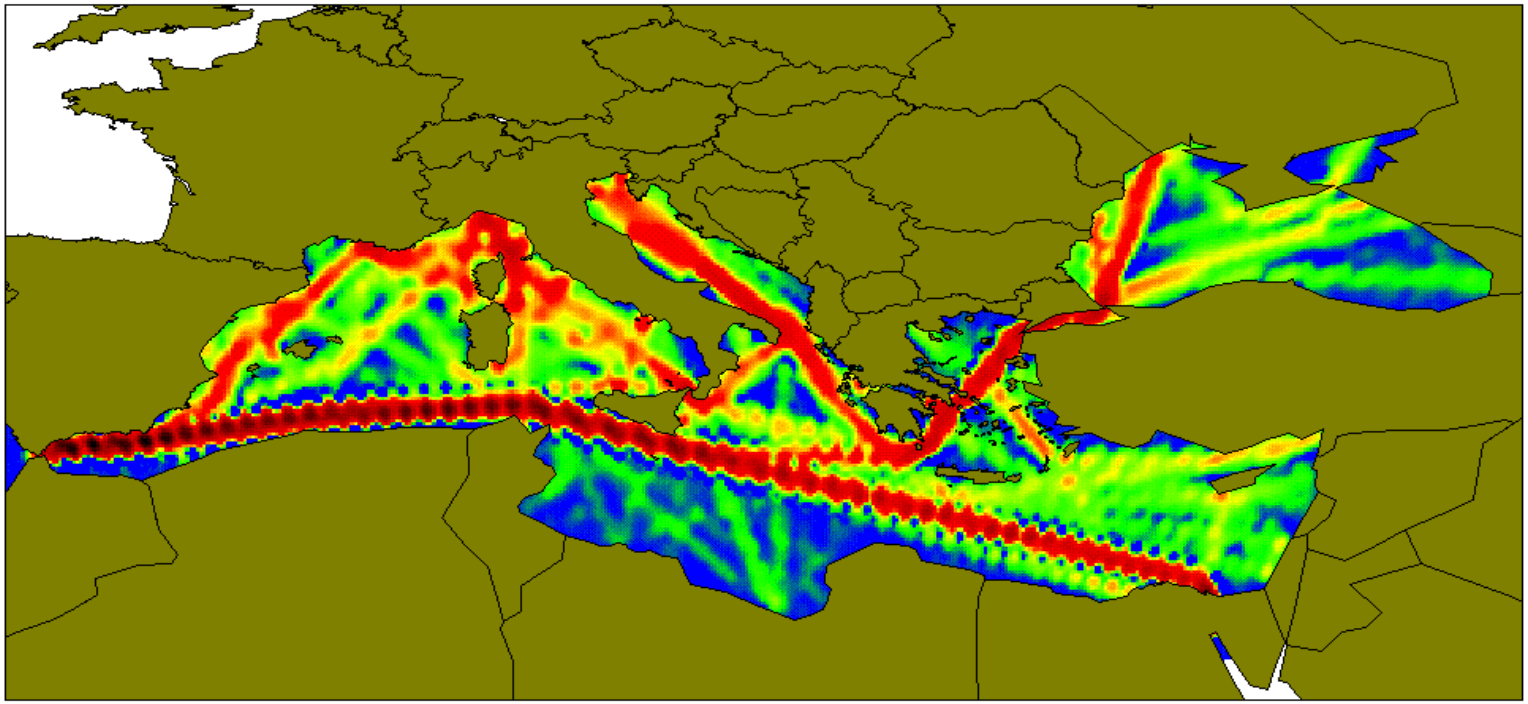
Estimated emissions of carbon monoxide from shipping operating in the Mediterranean & Black Sea regions, 1990



Estimated emissions of hydrocarbons from shipping operating in the Mediterranean & Black Sea regions, 1990



Estimated emissions of oxides of nitrogen from shipping operating in the Mediterranean & Black Sea regions, 1990



Estimated emissions of sulphur dioxide from shipping operating in the Mediterranean & Black Sea regions, 1990