Transactions on the Built Environment vol 36, © 1998 WIT Press, www.witpress.com, ISSN 1743-3509

Air Pollutant Emissions from ships: high Tyrrhenian Sea ports case study

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Abstract

In the paper is described, and applied in some case studies, a complete methodology for the estimate of air pollutant emissions from ships in port environment and in navigation.

The following pollutants are take into account: Nitrogen oxides, Sulfur oxides, and Carbon monoxide, Volatile Organic Compounds, Particulate matter, Carbon dioxide.

The paper introduces a schematic representation of ship traffic, from the point of view of consumption and emissions, subdividing the operation in: cruising, maneuvering, hotelling and tanker offloading. The emissions are estimated from daily fuel consumption, days spent in the different operations and average pollutants emission factors. The paper report regression formulas on fuel consumption at full power vs. gross tonnage (measured in line with the 1969 International tonnage convention) for each ship class and fraction of maximum fuel consumption in different operation mode.

The following classification of ships by type is used for fuel consumption evaluation: solid bulk, liquid bulk, general cargo, container, passenger/ro-ro/cargo, passenger, high speed ferries, inland cargo, sail ships, tugs, fishing, other.

Default emission factors are introduced for steam engines, high speed motor engines, medium speed motor engines, slow speed motor engines, inboard pleasure engines, outboard engines, tanker offloading engines.

Case studies of high Tyrrhenian Sea ports of Genoa, Savona, La Spezia, Imperia, Livorno, Marina di Carrara, Piombino and Portoferraio are discussed. The specific port studies has been realized in the frame of Regional Air Pollutant Management Plans.

Methodology

The methodology was developed in the framework of MEET Project (Methodologies for estimating air pollutant emissions from transport), project funded by the European Commission under the transport RTD program of the 4th framework program [1,2].
In shipping activity it is customary to distinguish between (a) approaching and docking in harbours; (b) hotelling in harbours; (c) departing from the harbour; (d) cruising. Phase (a) starts when the ship's deceleration begins and ends at the moment of the docking, while phase (c) starts with departure from the berth and ends when cruising speed has been reached.
From a consumption and emissions point of view, there are two manoeuvring phases (a) and (c), one hotelling phase (b) and one cruising phase (d). After its arrival in harbour a ship continues to emit at dockside (while in the hotelling phase). Power must be generated in order to supply the ship's lighting, heating, refrigeration, ventilation, etc. A few steam ships use auxiliary diesel engines to supply power but they generally operate one or more main boilers under reduced load. Ships powered by internal combustion engines normally use diesel powered generators to furnish auxiliary power.
For liquid bulk ships must be also take into account power requirements of the cargo pumps for tanker off-loading and of the ballast pumps for tanker loading. In smaller tankers the pumping power requirement will add to the electrical load whereas for larger tanks steam turbine driven pumps are generally used (even on motor tankers) with a consequent boiler load. As these power requirements can be relatively high the emissions will be separately estimated.
In order to estimate emissions in a detailed manner it is necessary to known:

- statistics on navigation (along a line and in ports) reporting GT and fuel use distribution of ships and average times spent in different mode;

when the previous ones are not available:

- statistics compiled directly from the register of single ship movements to obtain detailed estimate of emissions;

or

- approximate distribution of ships and general statistics of movements to obtain gross estimate of emissions.

From such information is then possible to estimate the number of working days in the different mode for each class of ships equipped with

different engines type and using different fuel.
The following pollutants are take into account: Nitrogen oxides, Sulfur oxides, Carbon monoxide, Volatile Organic Compounds, Particulate matter, Carbon dioxide.
The emissions are obtained as:

$$E_i = \Sigma_{jklm} E_{ijklm}$$
with
$$E_{ijklm} = S_{jkm}(GT) \cdot t_{jklm} \cdot F_{ijlm}$$

where:

i	pollutant
j	fuel
k	ship class for use in consumption classification
l	engines type class for use in emission factors characterization
m	mode (cruising, maneuvering, hotelling and tanker offloading)
E_i	total emissions of pollutant i
E_{ijklm}	total emissions of pollutant i from use of fuel j on ship class k with engines type l in mode m
F_{ijlm}	average emission factors of pollutant i from fuel j in engines type l in mode m (for SO_X, taking into account average sulfur content of fuel)
GT	gross tonnage
$S_{jkm}(GT)$	daily consumption of fuel j in ship class k in mode m as a function of gross tonnage
t_{jklm}	days in navigation of ships of class k with engines type l using fuel j in mode m

Emission factors

A complete review of all the emission factors available in literature is the basis of the following selected factors [3-19].
Table 1 reports on default emission factors proposed for the cruising phase, Table 2 proposes emission factors for the manoeuvring phase, Table 3 proposes emission factors for the hotelling phase (where inboard pleasure craft and outboard craft emissions are negligible) and, finally, Table 4 proposes emission factors for tanker loading and off-loading.

Table 1 – Proposed cruising emission factors (kg/ton of fuel)

Engine types	*NOx*	*CO*	*CO2*	*VOC*	*PM*	*SOx*
Steam turb. - residual oil	6.98	0.431	3200	0.085	2.50	20s
Steam turb. - distillate oil	6.25	0.6	3200	0.5	2.08	20s
High speed diesel engines	70	9	3200	3	1.5	20s
Medium speed diesel eng.	57	7.4	3200	2.4	1.2	20s
Slow speed diesel engines	87	7.4	3200	2.4	1.2	20s
Gas turbines	16	0.5	3200	0.2	1.1	20s
Pleasure – Inboard diesel	48	20	3200	26	neg.	20s
Pleasure – Inboard gasol.	21.2	201	3200	13.9	neg.	20s
Outboard gasoline engines	1.07	540	3000	176	neg.	20s

Table 2 – Proposed manoeuvring emission factors (kg/ton of fuel)

Engine types	*NOx*	*CO*	*CO2*	*VOC*	*PM*	*SOx*
Steam turb. - residual oil	6.11	0.19	3200	0.85	2.50	20s
Steam turb. - distillate oil	5.47	0.27	3200	5.0	2.08	20s
High speed diesel engines	63	34	3200	4.5	1.5	20s
Medium speed diesel eng.	51	28	3200	3.6	1.2	20s
Slow speed diesel engines	78	28	3200	3.6	1.2	20s
Gas turbines	14	1.9	3200	0.3	1.1	20s
Pleasure – Inboard diesel	48	20	3200	26	neg.	20s
Pleasure – Inboard gasol.	21.2	201	3000	13.9	neg.	20s
Outboard gasoline engines	1.07	540	3000	176	neg.	20s

Table 3 - Proposed hotelling emission factors (kg/ton of fuel)

Engine types	*NOx*	*CO*	*CO2*	*VOC*	*PM*	*SOx*
Steam turb. - residual oil	4.55	0	3200	0.4	1.25	20s
Steam turb. - distillate oil	3.11	0.6	3200	0.5	2.11	20s
High speed diesel engines	28	120	3200	28.9	1.5	20s
Medium speed diesel eng.	23	99	3200	23.1	1.2	20s
Slow speed diesel engines	35	99	3200	23.1	1.2	20s
Gas turbines	6	7	3200	1.9	1.1	20s
Pleasure – Inboard diesel	neg.	neg.	neg.	neg.	neg.	neg.
Pleasure – Inboard gasol.	neg.	neg.	neg.	neg.	neg.	neg.
Outboard gasoline engines	neg.	neg.	neg.	neg.	neg.	neg.

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Table 4 - Proposed tanker loading and off-loading emission factors (kg/ton of fuel)

	NOx	*CO*	*CO2*	*VOC*	*PM*	*SOx*
Tanker loading / off-loading	12	1	3200	0.01	2.11	20s

Specific fuel consumption

The entire world fleet consists of 86,000 vessels. Approximately 50% of these vessels are cargo carrying vessels (an estimated 40,000) whereas many of the other vessels are small non-cargo carrying vessels such as fishing vessels (over 22,000) and tugs (over 9,000).
In the database used by Lloyd's Maritime Information Services Ltd. there are approximately 15,000 vessels with fuel consumption data. Approximately 11,000 of these vessels have tonnage measured in concordance with the 1969 International Tonnage Convention and are those referred to in the statistical analysis.
The following elaborates data of fuel consumption at full power. In particular, a regression analysis has been made on fuel consumption vs. gross tonnage for each ship class with the exception of inland navigation (for which data on general cargo must be used). The data are highly correlated ($r > 0.68$ for all cases) and all regressions are significant on a confidence level greater than 99%. Table 5 contains the derived functions.

Table 5 - Consumption at full power (t/day) versus gross tonnage

Ship types	*Consumption*
Solid bulk	Cjk = 20.186 + .00049 * GT
Liquid bulk	Cjk = 14.685 + .00079 * GT
Gen.Cargo	Cjk = 9.8197 + .00143 * GT
Container	Cjk = 8.0552 + .00235 * GT
Passenger./RoRo/Cargo	Cjk = 12.834 + .00156 * GT
Passenger	Cjk = 16.904 + .00198 * GT
H.sp. ferry	Cjk = 39.483 + .00972 * GT
Inland cargo	Cjk = 9.8197 + .00143 * GT
Sail ships	Cjk = .42682 + .00100 * GT
Tugs	Cjk = 5.6511 + .01048 * GT

The effective fuel consumption can be obtained as:

$$S_{jkm}(GT) = C_{jk}(GT) * p_m$$

where:

$C_{jk}(GT)$ daily consumption at full power of fuel j in ship class k as a function of gross tonnage

p_m fraction of maximum fuel consumption in mode m

The default fraction of Table 6 can be used for the different mode. For tanker loading and off-loading a fuel consumption of 0.7 kg/ton of product or ballast offloaded can be used as default [9].

Table 6 - Fraction of maximum fuel consumption by different mode

Mode	fraction
Cruising	0.80
Manoeuvring	0.40
Hotelling default	0.20
passenger	0.32
tanker	0.20
other	0.12
Tug: ship assistance	0.20
moderate activity	0.50
under tow	0.80

High Tyrrhenian Sea case study

In the following the results of case study on high Tyrrhenian Sea ports and navigation lines are reported. In Table 7 the total emissions of main pollutants in 1995 are reported. In Figure 1 the distributions of total Nitrogen Oxides and Sulphur Oxides for ship types in ports are reported.

Table 7 – High Tyrrhenian Sea air pollutants emissions from ships movement in 1995 (t)

Pollutant	*Ports*	*Navigation lines*
Nitrogen oxides	3,852.7	6,626.8
Sulphur oxides	3,108.3	2,253.4
Carbon monoxide	14,484.9	858.9
Volatile organic compounds	3,361.9	279.9
Particulate matter	216.4	139.9
Carbon dioxide	546,600.0	360,500.0

Figure 1 Nitrogen Oxides emissions for ship types in ports (t)

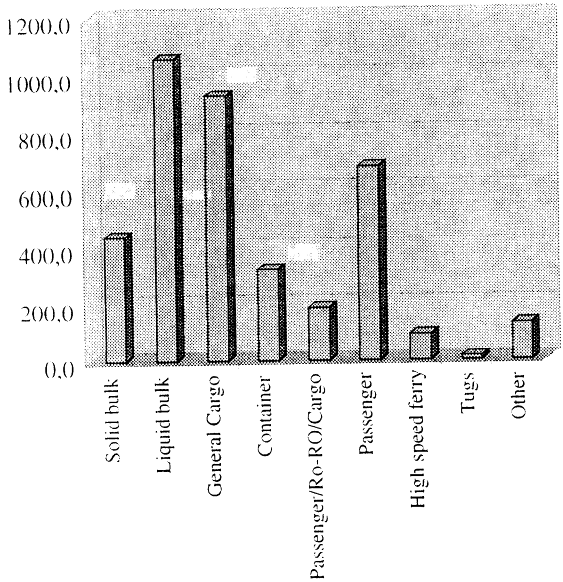
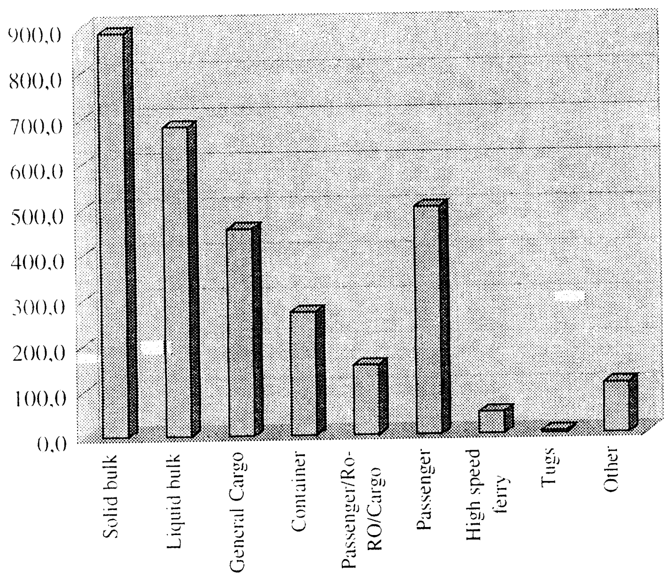
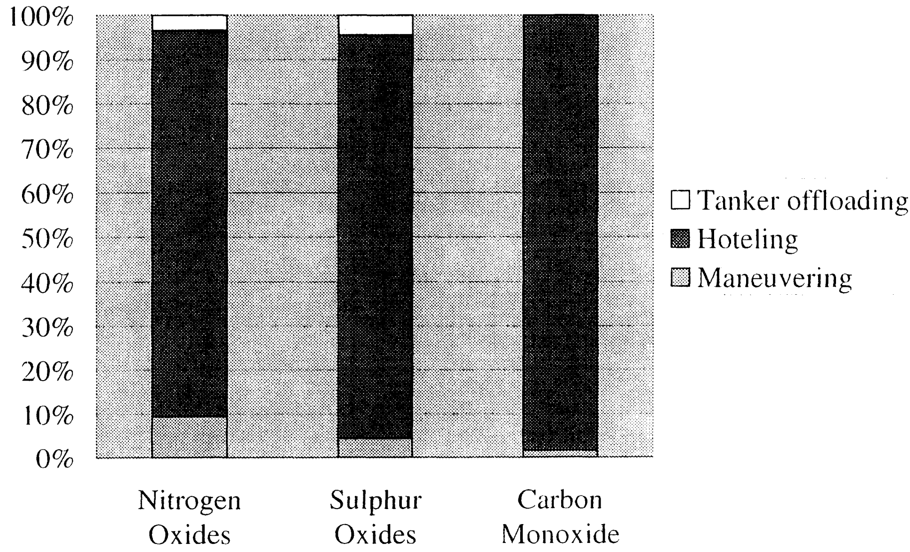


Figure 2 Sulphur Oxides emissions for ship types in ports (t)



The distributions of emissions by mode of operation in port are reported for Nitrogen Oxides, Sulphur oxides and Carbon Monoxide in Figure 3.

Figure 3 – Emissions of Nitrogen Oxides, Sulphur oxides and Carbon Monoxide by mode of operation in port



As regards ports, Figure 4 reports on thematic map of nitrogen oxides emission and, as regards navigation lines, Figure 3 reports on thematic map of nitrogen oxides emissions.

Figure 4 – High Tyrrhenian Sea ports - Nitrogen oxides emissions (t)

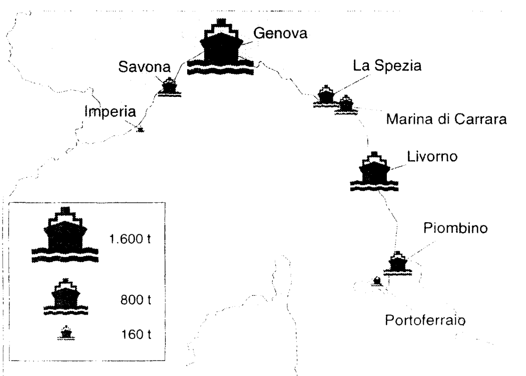


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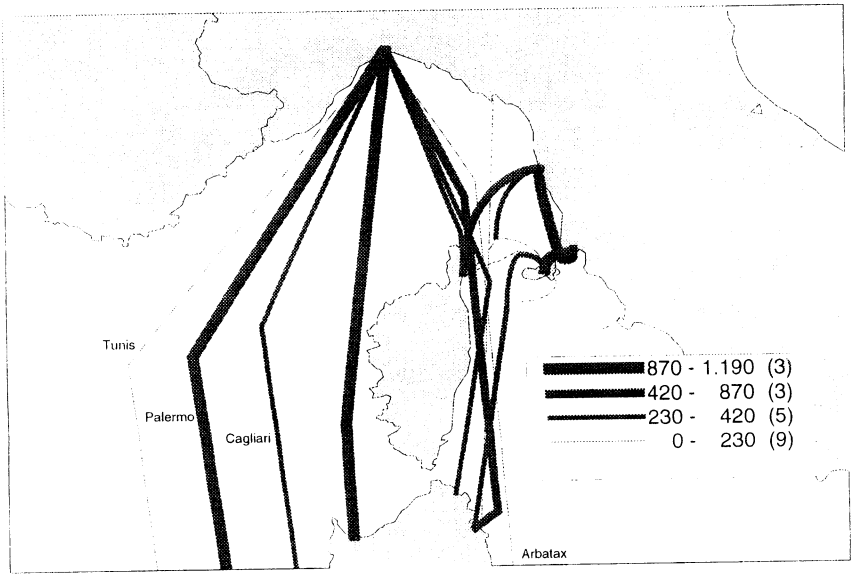
Figure 5 – High Tyrrhenian Sea navigation lines - Nitrogen oxides emissions (t)



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