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Ship Emissions and Their Externalities at the Container Terminal of Piraeus – Greece

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ABSTRACT: Ship exhaust emission inventories and their associated externalities constitute valuable information resources towards policy making and management of the influence exerted by shipping on air quality. To this extent, the container terminal at the Greek Port of Piraeus by virtue of its shipping significance and its urbanised character was selected in order to provide an estimation of the emissions produced by the ship activity within the terminal and to monetarise their adverse effects upon the environment and the local population in particular. With reference to the year 2006, the relevant annual emission inventory generated during in-port ship manoeuvring and at berth was found to be equal to 16,104 tons, divided into 294, 264, 15,504, 16.5 and 26.4 tons of NO_x, SO_2, CO_2, HC and PM, respectively. The overall damage of these emissions was estimated to be around 7.5 million euro, comprised by 2.15, 3.35, 0.6, 0.003 and 1.35 million euro of NO_x, SO_2, CO_2, HC and PM, respectively. The findings of this work, along with similar studies recently conducted in neighbouring locations, provide useful information towards the completion of a detailed and accurate picture of ship exhaust emissions and their externalities within the region of the eastern Mediterranean.

Key words: Maritime, Shipping, Air Pollution, Emission, Environmental Costs

INTRODUCTION

With regard to the environmental performance of transport, shipping compares favourably to other transport modes both in terms of consumed energy and produced pollution (including air pollution) per unit of transport work performed (UNCTAD, 2009). However, with regard to the adverse effects of ship exhaust emissions upon the environment, it is important to mention that marine engines produce significant exhaust quantities mainly due to their sizable power and the use of low-grade fuels.

Ships generally have one or two main diesel engines which cater for the propulsion of the ship and a diesel generator set for auxiliary services such as lighting, pumping, ventilation, cooling, loading and unloading of cargo etc. For example, a modern Ultra Large Container Ship (ULCS), by virtue of her size and speed, requires a propulsion power just in excess of 100 thousand hp and, despite the excellent fuel efficiency of modern large marine diesel engines (of around 115 g/bhp), a daily consumption of about 275 tons of heavy fuel oil is recorded, corresponding to the daily exhaust of almost 850 tons of CO_2.

Although this is an example of very fuel "thirsty" ship, it demonstrates the fact that even a much lower propulsion power requirement when accumulated over the world's merchant fleet is bound to produce massive quantities of exhaust emissions.

In order to estimate their associated impact upon air quality several global, regional and local emission inventory studies have been recently performed. In line with increasing global seaborne trade between 1990 and 2007, the annual emissions of NO_x, SO_2, PM and GHGs (mainly CO_2) from global shipping have increased from 585 to 1096 million tons, whereas CO_2, NO_x and SO_2 emissions were found to correspond to 3%, 11% and 4% of the overall anthropogenic emissions, respectively (Buhaug *et al.*, 2009). With respect to GHGs, recent research estimates that CO_2

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emissions from global shipping in 2007 were 943.5 million tons (Psaraftis and Kontovas, 2009). For the exhaust pollutants from global shipping, the level of SO_2, NO_x and PM emissions was found to be 16.5, 24.3 and 1.9 million tons, respectively (Cofala *et al.*, 2007). In terms of their environmental impact, the engine exhausts of NO_x, SO_2, HC and PM constitute the main air pollutants, whereas CO_2 is a main contributor to climatic change. These emissions have been associated to various damages, such as mortality, morbidity, diminishing crops yield, acidity of the built and natural environment, ecosystem eutrophication etc, as well as the detrimental effects of global warming. The health effects of ship exhaust emissions in ports may include asthma, other respiratory diseases, cardiovascular disease, lung cancer and premature death (EPA, 2003; Sharma, 2006). All these impacts reveal that shipping has remarkable global, regional and local adverse effects on air quality and consequently on the overall quality of life on earth. Therefore, the control of atmospheric pollution and climatic change from shipping stood and continues to stand highly on the international and European environmental agenda. To this extent, the international regulations for the “Prevention of Air Pollution from Ships” were adopted in the 1997 Protocol to MARPOL 73/78, as Annex VI of the Convention, which was later amended in 2008 to form the Revised Annex VI, both mainly aiming at and succeeding in reducing the SO_2 and NO_x emissions from shipping. In November 2003, IMO adopted resolution A.963(23) “IMO Policies and practices related to the reduction of greenhouse gas emissions from ships”, but the control of Green House Gases (GHGs) from shipping remains unregulated despite attracting the interest of the most recent UN conferences on climate change. The last United Nations Climate Change Conference (COP 16/CMP 6) – meeting in Cancun, Mexico, from 29 November to 10 December 2010 – has once again invited IMO to continue informing future Conferences and their subsidiary bodies of the Organization’s progress on its work plan to limit or reduce the emissions of greenhouse gases from international shipping. On the other hand, the Directive/2005/33/EC of the European Parliament and of the Council issued in July 2005 aimed at limiting the sulphur content of marine fuels used by ships operating within the European seas and ports and consequently led to the reduction of ship generated SO_2 emissions in these areas.

Although within this regulatory framework significant improvement has been made over the last five years, it becomes imperative to implement more effective measures in order to respond to the difficulties associated with the closing margin on emission reduction, in conjunction with the anticipated increase in seaborne trade, past the current global economic crisis. The polluting effects of ship exhaust emissions are inevitably more profound in coastal zones, narrow channels and straits, gulfs and ports, where the dense maritime traffic is in close proximity to sensitive ecosystems and human populations. Amongst these areas, urbanized ports are the most recognizable receptors of ship exhaust pollutants, mainly due their impact upon the local population.

Irrespective of location, however, in order to exercise effective emission control, it is necessary to know the magnitude of the problem. In this respect, emission inventories which are based upon the in-port ship activity are extremely valuable towards developing effective emission control policies, since they provide the ability to accurately predict the effectiveness of proposed emission control measures. According to this approach, an in-port ship activity may be divided into a manoeuvring phase (port approach and departure) and a berthing phase (during which the ship is securely moored or anchored in the port while loading, unloading or hotelling, including the time spent when not engaged in cargo operations).

The in-port emission inventory is estimated through the utilization of appropriate emission factors which relate the amount of emitted pollutants per ton of fuel consumed during each activity phase, for all ship port calls. Furthermore, the estimation of the exhaust emission externalities through the utilization of appropriate external cost factors (which relate damage costs per ton of emission) constitutes a valuable step in the assessment of the cost effectiveness of proposed emission control measures. With reference to exhaust emissions from shipping in restricted waters and ports several studies have been conducted within the last decade. With regard to ports of north Europe, ship emissions were estimated by Isakson et al.(2001) for the harbour of Goteborg, by Saxe and Larsen (2004) in three Danish ports and by De Meyer et al.(2008) in Belgian ports.

Within the region of the eastern Mediterranean, ship emissions of NO_x and SO_2 have been estimated for the Sea of Marmara (Deniz and Durmusoglu, 2008). However, since the lack of activity data of ships, emissions from ships in this study were highly underestimated (Kilic, 2009). Also, ship emission estimations were provided by Kilic and Deniz (2009) for Izmit and Candarli Gulf – Turkey, and Ambarli Port in Marmara Sea (Deniz C. et al, 2010; Deniz and Kilic, 2010). Most recently, research by Tzannatos (2010) produced an annual emissions inventory and an evaluation of their associated externalities for the ship traffic within the main (passenger) Port of Piraeus and proceeded with a cost assessment of ship emission reduction methods for ships while at berth (Tzannatos, 2010).

In the present study, with reference to the year of 2006, the in-port exhaust emissions and associated externalities produced mainly by oceangoing container ships (as well as bulk carriers, general cargo ships and Ro-Ro vessels) calling at the container terminal of the port of Piraeus were estimated.

The Port of Piraeus is the largest port in Greece and in the south-eastern region of the European Union (Fig. 1). It is the hub port of coastal passenger shipping, connecting the Greek mainland with the islands of the Aegean. It is the main import/export freight gate of Greece. It also serves as an international cruising and freight hub for the eastern Mediterranean Sea. The container terminal is positioned within a short distance from the centre of the city of Piraeus. It is comprised by two piers which stretch over a total dock length of 2.8 km, cover a total area of around 900 thousand m2 and provide a maximum berthing depth of 18 m, sufficient for the accommodation of the largest post-panamax container ships (Fig. 2).

Its maximum annual throughput capacity stands at 1.6-1.8 million TEU and in 2006 a throughput of around 1.4 million TEU was recorded (Url-1).

According to the records kept by Piraeus Port Authority, in 2006, the container terminal recorded 1641 port calls which were made by 291 ships. The relevant port calling data was provided in the form of vessel's name and date of call. On the basis of the vessel's name, the online Lloyd's Register of Ships (LRS) was utilized in order to obtain all ship particulars necessary for the estimation of the in-port ship exhaust emissions generated by all port calls (Url-2 and Url-3). These particulars were ship type, year of build (YoB), gross tonnage (GRT), deadweight tonnage (DWT), sailing speed (knots), number of main engines (ME), type of main engines (two- or four-stroke), main engine power (kW), main engine speed (RPM), number of auxiliary engines (AE), auxiliary engine power (kW), fuel type used and daily fuel consumption

Although, the majority (75.1%) of 1641 port calls made at the container terminal in 2006 involved container ships other ship types were also recorded. More specifically, one port call was made by a con-bulk carrier, whereas container ships, general cargo ships and Ro-Ro ships made 1233, 206 and 201 port calls, respectively. The port calling characteristics at the container terminal by ship type and flag are shown in Table 1.

BC: Bulk Carriers, CS: Container Ships, GC: General Cargo Ships, RR: Ro-Ro Ships, U: Unknown.

With respect to the (eleven) vessels of unknown type, the assumption that they were container ships was considered reliable, due to the terminal type. Furthermore, the year of build of these ships was assumed to be equal to the average year of build of all the other (known) container ships which called at the terminal, namely the year 1995. Similarly, gross tonnage, deadweight, sailing speed and engine specifications of these ships were assumed to be equal to the average value of these particulars for all container ships. The missing values of service speed for two Ro-Ro ships

Fig. 1. Location of Port of Piraeus

Fig. 2. View of the container terminal of the Port of Piraeus

Table 1. Ship types and flags

FLAG	BC	CS	GC	RR	U	Σ
Unknown	-	72	8	10	2	92
Albania	-	-	-	-	1	1
Antig. & Bar.	-	19	14	-	3	36
Bahamas	-	3	3	-	-	6
Bulgaria	-	4	1	-	-	5
China	-	1	1	-	-	2
Cyprus	-	3	2	-	-	5
Denmark	-	-	-	1	-	1
Germany	-	2	1	-	-	3
Gibraltar	-	1	-	2	-	3
Greece	-	5	-	5	-	10
Holland	-	-	2	-	-	2
H.Kong	-	5	-	-	-	5
Israel	-	15	-	-	1	16
Italy	-	-	3	1	-	4
Liberia	-	19	2	-	-	21
Malta	1	15	5	-	1	22
Mars. Is.	-	4	-	-	-	4
Panama	-	35	1	-	3	39
Portugal	-	1	1	-	-	2
St Vin.&Gran.	-	1	-	-	-	1
Turkey	-	6	-	2	-	8
UK.	-	2	1	-	-	3
TOTAL	**1**	**213**	**45**	**21**	**11**	**291**

and the general cargo ship were assumed to be equal to the average service speed values of the corresponding ship types. Similarly, the missing values for the number and type of main engines (two- or four-stroke), engine power and speed were completed according to ship type.

As shown in Table 2, 95% of all ships calling at the container terminal of Piraeus had a single main engine and 75% of all ships were equipped with two-stroke diesel engines.

A more detailed statistical summary of the technical and operational particulars of ships calling at the container terminal of Piraeus is presented in Table 3a and Table 3b.

As it can be shown in the following box plots, with the exemption of Ro-Ro ships, the median values are higher than the mean and the negative skewness for the YoB indicates that most of the ships calling at the container terminal of Piraeus are relatively young, i.e. less than 15 years old. The distribution of the YoB and GRT of all ships according to ship type is shown in Fig. 3 and Fig. 4, respectively.

The correlation coefficients of ship particulars are shown in Table 4. Although the high coefficients between GRT-DWT, GRT-ME power and GRT-AE power are expected, the significant correlation observed between GRT and YoB for Ro-Ro ships implies that the younger vessels are larger than the older ones.

Emitted mass depends upon fuel consumption which is a function of engine power and engine running time. Thus, deviation between the exact and default values of engine power affects the accuracy of emission estimations. In literature, there are some studies which determine ME and AE power as a (step) function of ship type and gross tonnage.

In Fig. 5, the exact values for ME power are compared to those provided by Lloyds Register of shipping emission inventory guidebook (Lavender *et al.*, 2006). As seen in this figure, the engine power of container ships above 50 thousand GRT is under-

Table 2. Main engines ships

Ship Type	1 ME	2 ME	3 ME	4 ME	2 Str	4 Str	Σ
BC	-	1	-	-	1	-	1
CS	214	9	1	-	190	34	224
GC	45	-	-	-	15	30	45
RR	15	5	-	1	11	10	21
Σ	**274**	**15**	**1**	**1**	**217**	**74**	**291**

Table 3a. Summary of ship particulars

Year of Build (YoB)					
	Max	Min	Mean	Med.	Std Dev.
BC	1985	1985	1985	1985	0.00
CS	2007	1970	1995	1996	9.46
GC	2006	1954	1991	1993	9.53
RR	2005	1973	1986	1981	10.54
Σ	**2007**	**1954**	**1993**	**1995**	**9.81**
Gross Tonnage (GRT) x 10^3					
	Max	Min	Mean	Med.	Std Dev.
BC	24.7	24.7	24.7	24.7	0.00
CS	109.2	4.0	34.1	33.2	22.8
GC	17.3	0.5	6.6	6.1	3.6
RR	52.5	2.3	25.7	14.8	18.5
Σ	**109.2**	**0.5**	**29.2**	**25.7**	**22.9**
Sailing Speed (knots)					
	Max	Min	Mean	Median	Std Dev.
BC	14	14	14	14.0	0.00
CS	27.4	13.5	21	21.0	3.08
GC	18.5	10	15	15.5	1.89
RR	20.5	12.5	17	18.0	2.01
Σ	**27.4**	**10**	**20**	**19.7**	**3.63**

Table 3b. Summary of ship particulars

Main Engine (ME) Power (kW) x 10^3					
	Max	Min	Mean	Med.	Std Dev.
BC	6.2	6.2	6.2	6.2	0
CS	74.8	3.3	25.5	23.3	17.3
GC	11.2	0.2	5.1	5.1	2.5
RR	16.0	1.1	9.8	9.4	4.7
Σ	**74.8**	**0.2**	**21.2**	**16.6**	**17.2**
Auxiliary Engine (AE) Power (kW)					
	Max	Min	Mean	Med.	Std Dev.
BC	480	480	480	480	0
CS	3,250	185	1,283	1,282	549
GC	1,072	14	566	566	242
RR	1,800	270	1,001	1,001	418
Σ	**3,250**	**14**	**1,149**	**1,200**	**568**

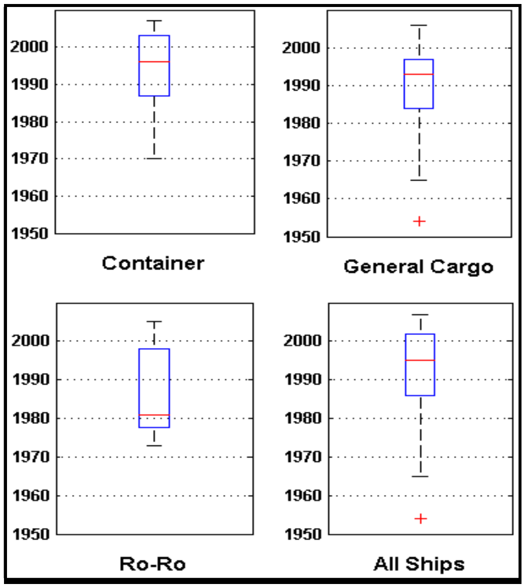

Fig. 3. Distribution of year of build according to type of ship

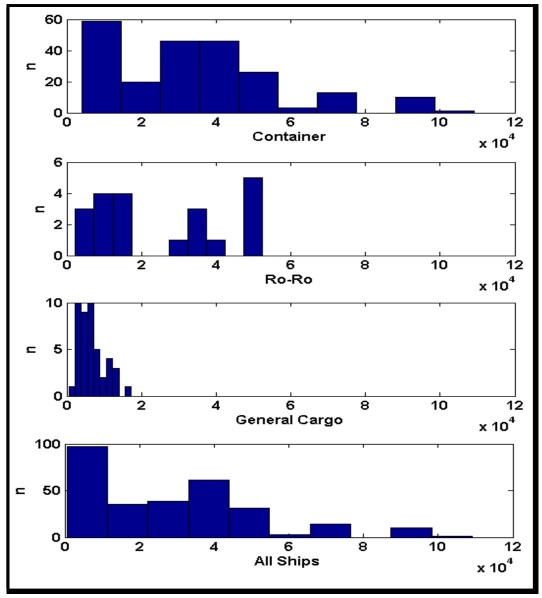

Fig. 4. Distribution of gross tonnage according to ship type

Table 4. Correlation coefficients of ship particulars

	Correlation Coefficients			
Ship Type	Grt-Dwt	Grt-Me Power	Grt-Ag Power	GRT-YoB
CS	0.98	0.97	0.68	0.43
GC	0.98	0.91	0.53	-0.01
RR	0.79	0.93	0.80	0.85
All Ships	**0.91**	**0.96**	**0.74**	**0.44**

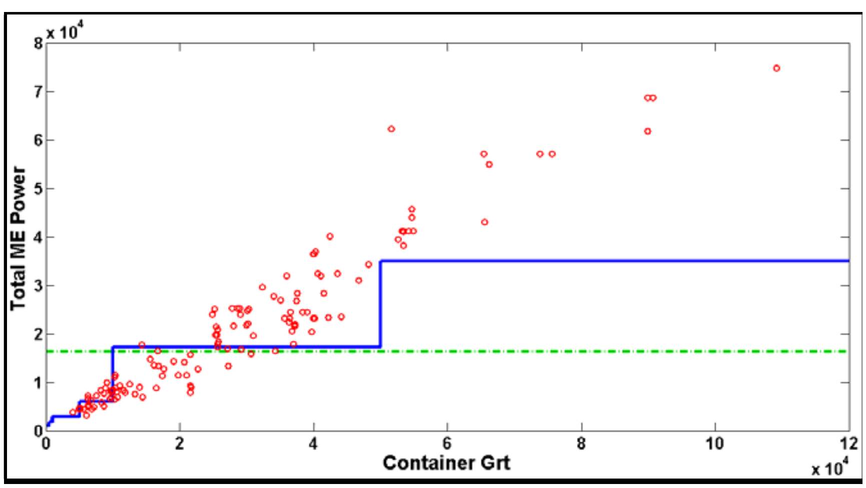

Fig. 5. Comparison of exact values and step function values of ME power vs GRT for container ships

estimated. The default average main engine power in the literature is equal to 16,300 kW for container ships which is indicated as dotted line. Nevertheless, mean engine power of ships called to Piraeus was 25,555 kW as indicated in Table 3b. In the current work emission estimation is based on exact engine power values.

MATERIALS & METHODS

In-port exhaust emissions from ships are produced by their main and auxiliary engines, while ships manoeuvre in and out of port and stay at berth, respectively. Therefore, taking also into consideration the operation of their engines while at sea, merchant ships are considered to be continuous emission sources throughout their entire economic lives. Ship exhaust emission inventories can be estimated by applying a fuel-based or an activity-based methodology, which are also known as a top-down or bottom-up approach, respectively. The former methodology relies upon figures of overall fuel consumption in order to estimate the quantities of emissions. The activity-based methodology, being a bottom-up approach, is by far more accurate since it utilizes emission factors which express the amount of emitted gases per unit of developed power and time. Furthermore, being an engine (rather than a fuel) specific methodology, is also capable of capturing the engine efficiency improvement through appropriate updating of the emission factors. Therefore, an activity-based methodology which caters for changes in the mode of ship operation and consequently changes in the engagement of engine type (in conjunction with fuel type) and load, while the ship is manoeuvring in and out of port and during its stay at berth, is considered to be the most suitable approach for estimating in-port ship exhaust emission inventories. The ship exhaust emissions generated while at berth and during manoeuvring are estimated according to the following expression:

Ei,m (g) = Tm . EFi,m,t (PME . LFME, m .%TME,m + #AE,m . PAE . LFAE,m)

where; Ei,m is emitted mass of pollutant (i) in grams from all engines at the operation mode (m), Tm is the total time spend in operation mode, EFi,m,t is the emission factor of the pollutant for ship type (t), PME is the total power of all main engines at %80 MCR (Maximum Continuous Rating), LFME, m is the main engine load factor at the operation mode, %TME,m is the percentage of time where the main engine runs, #AE,m is the number of AE (Auxiliary Engine) running at the operation mode, PAE is the power of one AE, LFAE,m is the load factor of one AE. The engine load factors and operational time are shown in Table 5 (ENTEC, 2005). In the cruising mode, ships use one auxiliary generator or a shaft generator. Modern ships are equipped with a shaft generator which is driven by the main engine and produces the necessary electricity in open sea cruising thus avoiding auxiliary engine operation and fuel consumption. In general, ships have at least two or three auxiliary generators for electricity production. In manoeuvring, they use two synchronized generators for covering the increased energy demand and ensuring the safety of critical ship operations. During berthing at port, most ships use one auxiliary generator unless cargo loading/unloading is performed by the ship's equipment.

Table 5. Engines load factors and operational time (%)

Activity Phase	ME load	Time of ME operation	AE load
At berth	20	5	40
Maneuvering	20	100	50

Time spent at berth is comprised by cargo handling time and preparation time prior to cargo handling and ship departure. The usual cargo handling practise was observed to involve the engagement of two gantry cranes per ship working at an average productivity of 25 TEU per hour. Also, two extra hours were added to cargo handling time for paper work, survey, port clearance etc. It is also assumed that there is no loss of time. For the ships having more than one record for a day, the number of TEUs was added and grouped by the date by using SQL (Structured Query Language) in order to determine the total TEU capacity handled per port call. The ship manoeuvring times were provided by port pilots and were found to be on average equal to 30 minutes for departure and 45 minutes for arrival to port.

The International Maritime Organization (IMO) regulates the sulphur content of marine fuels according to sailing area and NO_x emissions according to engine power. The Mediterranean Sea is not an Emission Control Area (ECA), hence IMO's global limits apply. More specifically, the maximum sulphur content of fuel will be reduced from 4.5% to 3.5% in 2012 and a reduction of NO_x emissions will come into effect after 2011. This is important because although ENTEC (2005) offers the use of emission factors for the year 2010, those corresponding to the year 2000 were considered to be the appropriate choice for the cargo ships which called at the Piraeus Port in 2006. The ENTEC emission factors expressed in g/kWh were used as shown in Table 6. These emission factors are based on an average sulphur content of 2.7% for heavy fuel and 0.2% for distillate fuel.

All types of emissions have some adverse effects on the human health, as well as on the natural and built environment. These effects cause damage costs which are known as external costs.

Table 6. Emission factors (grams/ton of fuel)

Operation	Ship Type	NO_x	SO_2	CO_2
Maneuvering	BC	14.0	11.9	698
	CS	13.8	12.0	705
	GC	13.2	12.1	715
	RR	12.8	12.2	719
At Berth	BC	13.5	12.2	718
	CS	13.5	12.3	720
	GC	13.4	12.2	721
	RR	13.3	12.3	722
Operation	**Ship Type**	**HC**	**PM**	**SFC***
Maneuvering	BC	1.30	1.84	220
	CS	1.19	1.73	222
	GC	1.03	1.59	225
	RR	1.06	1.68	226
At Berth	BC	0.50	1.00	226
	CS	0.50	0.90	226
	GC	0.50	0.90	227
	RR	0.50	0.90	227

* Specific Fuel Consumption

Holland and Watkiss estimated external costs for NO_x, SO_2 and $PM_{2.5}$ for various European countries, based upon the application of the willingness-to-pay (WTP) principle (Holland and Watkins, 1998). These estimates were categorized according to region of exposure in rural and urban. It is specified that for SO_2 and $PM_{2.5}$ emissions at ports, the external cost factors are equal to the urban value as applied to a city of equal size to the port city under consideration plus the rural value of the host country. Furthermore, the external cost factor for in-port emission of NO_x is specified to be equal to the rural value.

This difference in the treatment of SO_2 and $PM_{2.5}$ versus NO_x externalities reflects the significance of the damages produced by the former polluters at the local scale in comparison to the more regional by the latter. For the year 2000, the external cost factors in rural areas of Greece were found to be equal to 6000, 4100 and 7800 euro per ton of emitted NO_x, SO_2 and $PM_{2.5}$, respectively, whereas the urban values of SO_2 and $PM_{2.5}$ for a city of 100,000 people were estimated at 6000 and 33,000 euro per ton, linearly increasing up to a population of half million people. With respect to other engine emissions, MINTC (2003) reports that in-port HC and CO_2 cost 148 and 32 Euro per emitted ton, in year 2000 prices.

Since all these external cost factors refer to the year 2000, it is necessary to correct them for the year 2006. To this extent, the damage costs are assumed to follow the change in the Consumer Price Index (CPI), which according to the Bank of Greece records between 2000 and 2006 was found to increase by 22% (Url-4).

RESULTS & DISCUSSION

In Table 7, standard deviation and the difference of means of real and default engine energy consumptions are indicated. Although there is huge difference between real and default values of engine powers, both the negative values and time factors together reduce the error term.

The estimated annual ship exhaust emissions in the container terminal of Piraeus are presented analytically in Table 8. The overall emission inventory stands at 16,104 tons, of which 15,504 (96.3%) are CO_2 emissions. NO_x, SO_2, HC and PM emissions represent 1.82%, 1.64%, 0.1% and 0.16% of the total.

It was found that container ships contribute to the overall in-port generated emissions by 92.6% on average, which contributes to 92.5%, 92.4%, 92.2%, 93.7% and 92.3% of all NO_x, SO_2, CO_2, HC and PM emissions, respectively. Also, fuel consumption accounted for 92.1% of the fuel consumed by all ships. Berth emissions of SO_2, CO_2, HC and PM produced by all ships were found to be equal to 61.2%, 62.1%, 61.8%, 37.5% and 46.1% of the overall emissions, respectively. It is important to note at this point that part load operation of main engines during manoeuvring leads to poor combustion and increased

Table 7. Standard deviation and diference of real and default engine energy consumption (kW-h)

	std dev			
Ship Type	ME Man	ME Berth	Aux Man	Aux Berth
BC	651	53	125	81
CS	2422	4526	703	5471
GC	484	88	520	780
RR	644	84	2095	1939
All Ships	2119	3924	971	4799
	Difference of means (real-default)			
Ship Type	ME Man	ME Berth	Aux Man	Aux Berth
BC	-651	-53	125	81
CS	602	1039	-74	-12
GC	302	45	462	637
RR	-132	-17	-1464	-1192
All Ships	473	784	-177	-75
	% of total kWh ((defaul-real)/real)			
Ship Type	ME Man	ME Berth	Aux Man	Aux Berth
BC	42	42	-21	-21
CS	-13	-28	6	0
GC	-23	-17	-60	-56
RR	6	7	122	103
All Ships	-12	-27	14	1

Table 8. Annual ship exhaust emissions (tons)

		ME Man.	**ME Berth**	**AE Man.**	**AE Berth**	**Σ**
NO_x	BC	0	0	0	0	**0**
	CS	77	63	23	109	**272**
	GC	4	1	2	3	**10**
	RR	6	1	3	3	**12**
	Σ	**87**	**64**	**28**	**116**	**294**
SO_2	BC	0	0	0	0	**0**
	CS	67	57	20	100	**244**
	GC	3	1	2	3	**9**
	RR	5	1	3	3	**12**
	Σ	**76**	**59**	**25**	**105**	**264**
CO_2	BC	1	0	0	0	**2**
	CS	3946	3354	1160	5831	**14291**
	GC	195	39	114	168	**516**
	RR	318	35	174	167	**695**
	Σ	**4461**	**3429**	**1448**	**6167**	**15504**
HC	BC	0	0	0	0	**0**
	CS	7	2	2	4	**15**
	GC	0	0	0	0	**1**
	RR	0	0	0	0	**1**
	Σ	**7**	**2**	**2**	**4**	**16**
PM	BC	0	0	0	0	**0**
	CS	10	4	3	7	**24**
	GC	0	0	0	0	**1**
	RR	1	0	0	0	**1**
	Σ	**11**	**4**	**4**	**8**	**26**
FC	BC	0	0	0	0	**1**
	CS	1243	1053	365	1830	**4491**
	GC	61	12	36	53	**162**
	RR	100	11	55	53	**218**
	Σ	**1405**	**1076**	**456**	**1936**	**4873**

HC and PM emissions which is reflected in the lower share of HC and PM emissions at berth. Furthermore, while at berth, auxiliary engines produced almost double the emissions of main engines, whereas during manoeuvring the emissions generated by the main engines were almost threefold to those of the auxiliaries.

Estimated emission inventories in various ports and regions are presented in Table 9. Although these inventory figures may prove meaningful in terms of the (absolute) impact shipping exerts upon the atmospheric environment, a comparative assessment of the impact amongst the different locations will require to consider the influence of time and place upon fuel operating conditions, as well as the port calling frequency characteristics for each case. For example, in the passenger terminal of Piraeus NO_x, SO_2 and PM were found to be emitted at the rate of 0.17, 0.07 and 0.009 tons per port call , whereas (according to this study) the emission rates in the container terminal are 0.18, 0.16 and 0.016 tons per port call, respectively (Tzannatos, 2010).

The significant lower SO_2 and PM emission rates for the passenger terminal reveals (amongst other ship related parameters) the influence of the use of low sulphur heavy fuel (max. 1.5%) by all passenger ships operating on regular services to or from EU ports, as enforced by Directive/2005/33/EC on the 11th of August 2006, in the absence of a similar restriction on the operation of other ship types in this location over this period.

SO_2 emissions depend directly upon the sulphur content of the fuel used. Reducing the sulphur content will also result in the indirect reduction of PM, VOC and NO_x emissions. Therefore, with reference to the in-port ship activity currently examined, the use of fuel oil with 1.5% sulphur content (instead of 2.7%) would have produced annual NO_x, SO_2, CO_2, HC and PM emissions of 265, 252, 15,105, 16 and 21 tons, respectively. This reveals that when sulphur content reduction is related to the fuel used by the main engines only, the overall emission reduction is highly disproportional, because the load contribution of the main engines of cargo ships (as opposed to passenger ships) during manoeuvring is low and their operating time during the emission dominant berthing phase is minor. Hence, the observation is made that for a 45% reduction in the sulphur content of fuel oil (2.7% to 1.5%), the overall SO_2 reduction is merely 9%.

The container terminal of Piraeus is bordering the Perama and Keratsini municipalities. These municipalities are inhabited by 26,684 and 78,474 people (Url-5). Due to their vicinity and concentration around the container terminal, it is assumed that all of the population of these municipalities is directly exposed to the adversities of the ship exhaust emissions generated within the terminal.

Applying the updated for the year 2006 external cost factors as proposed by Holland, M. and Watkiss (1998) and MINTC (2008) for the port cities of Perama and Keratsini, the external costs of ship generated exhaust emissions at the bordering container terminal of the port of Piraeus are shown in Table 10.

Table 9. Comparison of annual ship exhaust emission inventories at various locations (in ktons)

	Ambarli Port, Turkey (1)	Ports in Candarli Gulf, Turkey (2)	Ports in Izmit Gulf, Turkey (3)	Danish Ports (4)	Marmara Sea (5)	Passenger Port of Piraeus (6)	Container Terminal of Piraeus(7)
NO_x	0.7	0.5	2.0	48	111.0	1.8	0.3
SO_2	0.2	0.5	1.9	19	87.2	0.7	0.3
CO_2	71.0	30.0	111.0	-	5,451.0	-	16.0
HC	-	<0.1	0.1	-	-	-	<0.1
PM	<0.1	<0.1	0.2	0.83	4.8	0.1	<0. 1

(1) Maneuvering and at berth emissions, for the year 2005, Deniz (2010,b).
(2) Maneuvering and at berth emissions of 10 ports, for the year 2007, Deniz (2010, a).
(3) Maneuvering and at berth emissions by all ships at 37 ports in 9 port regions, for the year 2005, Kilic (2009).
(4) Maneuvering and at berth emissions by container and mixed cargo ships, in Copenhagen and Kope Ports. PM emission is 75% of TSP (Total Suspended Particules), for the year 2003, Saxe (2004).
(5) Total emissions from all ships based on fuel consumption, for the year 2003, Deniz (2008).
(6) Maneuvering and at berth emmisions by coastal passenger ships and cruise ships, for the year 2009, Tzannatos (2010, a).
(7) For the year 2006, this study.

Table 10. Annual damage costs of emissions

Emissions	Damage cost (€)
NO_x	2,152,080
SO_2	3,352,685
CO_2	605,276
HC	2889
PM	1,348,168
Σ	**7,461,098**

For the year 2006, the overall cost of the damages caused by the generated exhaust emissions of port calling ships at the container terminal of Piraeus is estimated at around 7.5 million euro, analyzed into 2.15, 3.35, 0.6, 0.003 and 1.35 million euro for NO_x, SO_2, CO_2, HC and PM, respectively.

The polluting emissions of NO_x, SO_2, HC and PM represent 91.4% of the overall damage costs, whereas the CO_2 accounts for the remaining 8.6%. Finally, it was found that the use of fuel oil with 1.5% sulphur (instead of 2.7%) would lead to NO_x, SO_2, CO_2, HC and PM damages of 1.94, 3.2, 0.59, 0.003 and 1.09 million euro respectively, totalling 6.8 million euro. Again, the reduction in sulphur is disproportional to the improvement in damage costs, due to the minor influence of the quality of main engine fuel upon the overall emission inventory.

CONCLUSION

The annual exhaust emissions of NO_x, SO_2, CO_2, HC and PM generated by ships calling at the container terminal of Piraeus were estimated, based upon actual and modelled in-port activity of the ships during manoeuvring and while at berth.

It was found that NO_x, SO_2, HC and PM accounted for 91.4% of the overall damage costs although they represented only 3.7% of the overall emission inventory, thus highlighting the direct polluting influence of these emissions upon the local environment in comparison to the indirect impact of CO_2 through its global climatic change influence. In addition, it was found that although PM emissions represented 0.16% of the overall inventory, they accounted for 18.1% of the overall damage costs, thus providing a clear indication of their strong polluting and hence damaging influence upon the environment and specifically upon the health of local human population.

Finally, it was found that in-port ship exhaust emissions are not significantly affected by main engine operation and to this extent policy making should be mostly concentrated towards improving the quality of fuels used by the ship's auxiliary engines, i.e. upon the quality of distillate fuels. However, bearing in mind the high cost of ultra-low sulphur fuel, the option of the shore side electricity supply (through the conventional power grid or renewable power sources) does not only presents a minimum emission option for the ships while at berth, but may offer a more economically viable alternative too.

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