Exhaust emissions from ships at berth

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Abstract

Emission measurements have been carried out on board six ships at berth during normal real-world operation (hotelling, unloading and loading activities). The study included three passenger ferries, one transoceanic container/ro-ro, one transoceanic car/truck carrier, and one chemical tanker. Emissions were measured from 22 auxiliary engines (AEs, medium and high-speed marine diesels) covering seven engine models and ranging in size from 720 to 2675 kW maximum output. The fuels varied from low sulphur gasoils (2.91 cst viscosity) through to residual oils (411 cst viscosity). Both specific emission factors (g kWh^{-1}) at a given engine load and total emissions (kg) of nitrogen oxides (NO$_x$), sulphur dioxide, carbon monoxide, hydrocarbons, carbon dioxide, particulate matter (PM) and polyaromatic hydrocarbons during actual harbour stops were determined. In addition, some preliminary measurements to investigate PM size distributions were undertaken.

The specific emissions showed significant variations between the different engine models and also within the same engine model on board the same ship. For example NO$_x$ emissions varied between 9.6 and 20.2 g kWh$_{corr}^{-1}$ between all engines and 14.2–18.6 g kWh$_{corr}^{-1}$ between engines of the same model and fuel. Other emissions from boiler use and possible main engine warm-up prior to departure were in general expected to be considerably less than those from the AEs. The results obtained for the three passenger ferries demonstrate that empirically derived, emission formulae using dead weight tonnage can prove to be a cost-effective and accurate tool for harbour emission inventories.
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Keywords: Ship emissions; Diesel exhaust; Auxiliary engine; Harbour

1. Introduction

Over the past decade, several reports have outlined exhaust emissions from the growing marine transport sector as a significant air pollution source (Lloyd's Register Engineering Services, 1995; Corbett et al., 1999; Skjølsvik, 2000; European Commission, 2002a). The European shipping fleet, using fuels with an average sulphur content of 2.7% m/m, emitted approximately 2578 thousand tons of SO$_2$ for the year 2000 within the European monitoring and evaluation programme (EMEP) domain (European Commission, 2002a). This can be compared to 5750 thousand tons arising from European Community land-based sources and domestic

sea traffic (European Environmental Agency, 2002). In light of the considerable emission reductions and tighter legislation for land-based sources that have progressed since the 1960s, further emission reduction scenarios will most certainly include the relatively untapped marine sources. Thus, an accurate assessment and control of ship emissions will play key roles in providing cost-effective solutions to achieve regional and global environmental targets in the future. Different regulatory strategies including for example, fuel sulphur capping and new engine nitrogen oxides (NO$_x$) emission limits (International Maritime Organisation, 1998), environmentally differentiated fairways dues (Swedish Maritime Administration, 1998; Norwegian Ministry of Fisheries, 2000) and emission trading schemes (Swedish Shipowners Association, 2002) are gaining acceptance. For more local-scale benefits, however, a focus on emissions

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from ships while in port areas has been highlighted (Colvile et al., 2001). The European Commission has recently put forward a proposal to enforce a 0.2% sulphur limit on fuel used by ships at berth in European ports (European Commission, 2002b). This is despite the fact that in-port sulphur dioxide (SO_2) emissions have been estimated to account for only 6% of the total European shipping fleet emissions (European Commission, 2002a).

Although main engines (MEs) used for ship propulsion at sea, create the largest emissions, emissions from the smaller auxiliary engines (AEs), used for generating electrical power on board, cannot be entirely ignored. This is especially so when ships are stationary (with MEs shut down) and at berth in ports close to population centres. In general, AEs are used continuously except when shaft generators coupled to MEs are available at sea, or when a shore-side electricity link is provided at berth. Almost all AEs are four-stroke marine diesel engines operating at engine speeds of 500–2500 rpm (i.e. so-called medium- and high-speed diesels) with power output in the range of 30–3000 kW. The AE power requirement on board a ship can vary. A short-term maximum is often encountered when bow and stern thrusters are operated during departure from or arrival at a port. Once in port, however, the power requirement is usually less but can still vary depending on the type of ship activity, e.g. hotelling, loading operations.

Since most marine emission studies have been directed towards ME operation, there is a general lack of knowledge regarding AE operation and their emissions. Real-world emission data, i.e. actual emissions measured during normal service as oppose to those at engine manufacturers test beds, and associated uncertainty evaluations are especially valuable in this context (Corbett, 2002). Bearing this in mind, the present investigation was initiated with the primary aim of providing an improved reference material for air emissions from AEs used on ships while at berth. Besides the determination of specific emissions, case

studies for actual harbour stops by the ships were investigated. In the latter case, relative contributions from boiler use (oil burners) for hot-water supply and when MEs are set at idling (short, warm-up period just prior to departure) were also estimated.

2. Experimental

2.1. Strategy and measurement ships

Initially, it was hoped that the choice of measurement ships and their AEs would reflect the shipping fleet in general, i.e. in terms of engine type (engine speed and power output), fuel used, engine age and mode of operation. Besides obtaining a representative selection of ships for the study however, consideration was given to the practicalities involved with the measurements, i.e. duration of harbour stops, locality of ports, etc. Furthermore time and economic constraints weighed heavily and not least finding shipowners willing to participate in the project. Thus, the chosen ship/engine combinations represent a compromise of these factors. An overview of the specifications of the measurement ships, AEs and fuels used are presented in Tables 1–3. Regarding AE fuels, most were classed as low-sulphur marine gasoils (MGO) although ships B and E used heavier residual oils (RO). The fuel from ship D was classed as a marine diesel oil (MDO) of type DMB (International Organisation of Standardisation, 1996a), although the subsequent analysis proved to be very similar to MGO grade except with a higher sulphur content. Since ship B uses both RO (AE1–AE4) and MGO (on AE5), this provided an opportunity to observe how emissions from the same engine model (also age and similar service history) vary for the two fuels. Regarding engine type, all the AEs were marine diesel engines where the torque load is varied at a constant speed to provide a power output range coupled to an electric generator which is typical for AEs of the

Table 1
Specifications of the six measurement ships

	Ship A	Ship B	Ship C	Ship D	Ship E	Ship F
Type	Pass. ferry	Pass. ferry	Pass. Ferry	Car/truck carrier	Container/ ro-ro	Chemical tanker
Length and width (m)	155 × 29	175 × 29	185 × 27	199 × 32	292 × 32	115 × 18
Gross register tonnage (t)	28727	39178	22528	52288	58438	5698
Dead weight tonnage (t)	2953	3938	3335	29213	51157	8245
Passenger capacity	2274	2400	1524	n. a.	n. a.	n. a.
Vehicle capacity	555	550	379	5870	[a]	[b]
No. of MEs and AEs	4 + 5	4 + 5	4 + 6	1 + 2	1 + 4	1 + 3

[a] Cargo capacity: 1000 Automobile units, 1850 TEU (20/ft Equivalent Unit) Containers and 1000 TEU ro-ro.
[b] Cargo capacity: 10 separate tanks providing a total of 8988 m^3.

Table 2
Specifications of the auxiliary engines (AEs, constant speed, four stroke marine diesel engines)

Ship	Engine model/max. output (kW)	Engine speed (rpm)	Measured AEs	Fuel type[a]
A	Sulzer 6ASL 25/30/960	750	AE1, AE2, AE3, AE4, AE5	MGO
B	Sulzer 8ASL 25/30/1270	750	AE1, AE2, AE3, AE4, AE5	RO, MGO
C	Wärtsila 824 TS/940	720	AE1, AE2, AE3, AE4, AE5, AE6	MGO
D	Wärtsilä 4R32D/1480	720	AE1, AE2	MDO
E	Wärtsilä 8R32/2675	720	AE1	RO
	Wärtsilä 6R32/2005	720	AE3	RO
F	Caterpillar 3508/720	1800	AE1, AE2	MGO

[a] MGO refers to marine gasoil, MDO as marine diesel oil, and RO as residual oil.

Table 3
Analyses of the AE fuels ("—" indicates analysis not performed)

	Ship A	Ship B	Ship B	Ship C	Ship D	Ship E	Ship F
Type	MGO[a]	RO	MGO[a]	MGO	MDO	RO	MGO
Dens. at 15°C (g cm^{-3})	0.876	0.936	0.881	0.891	0.866	0.992	0.848
Net cal. value (MJ/kg)	42.60	41.73	42.49	41.85	42.21	40.15	42.65
Viscosity at 50°C (cst)	9.4	168	10.0	3.71	3.16	411	2.91
Total PAH (% m/m)[b]	—	—	—	—	2.1	18	1.5
Carbon (% m/m)	87.0	87.5	87.5	86.7	88.6	87.5	86.3
Hydrogen (% m/m)	13.4	12.5	13.5	12.9	13.0	10.9	13.8
Nitrogen (% m/m)	<0.05	0.19	<0.05	<0.05	<0.05	0.41	<0.05
Oxygen (% m/m)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphur (% m/m)	0.08	0.53	0.09	1.2	0.23	2.2	0.06
Ash (% m/m)	<0.005	<0.05	<0.005	—	<0.01	0.06	<0.01

[a] Fuel also classed as wide range distillate (WRD). For ship B, only AE5 operated with MGO/WRD fuel.
[b] Given as phenanthrene equivalents.

shipping fleet in general. The crankcase engine speeds of the measured AEs were largely medium speed but some could be classed as high speed (ship F).

All measurements were conducted over the period January–December 2002. Of the 22 AEs on board the six ships, the number and scope of sampling events were reduced in several cases especially regarding engines of the same model due to time and budget limitations. Since the study focused on real-world operating conditions, so-called emergency engines on board the ships, which are not normally used, were excluded from the measurements. For ships normally using only one or two AEs continuously during a harbour stop out of a larger number of available AEs, arrangements were made so that measurements could be made on all AEs. So for example, on board ships A–D, some AEs were stopped and other started to enable emission measurements on all engines. Since this procedure did not alter the total power requirement for the ships, the measured emissions still reflected real-world operation. The engine loads applied during the measurements were entirely dictated by the operational requirements and thus measurements at specific engine load settings (as in standard test cycles) were not undertaken.

2.2. Exhaust sampling location

Sampling locations along the exhaust channels were chosen with regard to obtaining a representative sample and practical considerations, i.e. available space for the gas analysers, ambient temperatures, and safety regulations. The most suitable solution was often to choose a site in the engine casing within the funnel housing although an engine room location on the lower decks was also used. In all cases, an adequate number of straight exhaust channel diameters were present upstream (>5) and downstream (>2) of the sampling holes, thus minimising error from uneven cross-sectional concentration profiles. On most exhaust channels two sample holes with threaded plugs were used ($2''$ and $2\frac{1}{2}''$ size).

2.3. Measurement parameters and methodology

All measurements were based on international standard procedures where possible (International Organisation of Standardisation, 1996b, 2000; International Maritime Organisation, 1998). Thus, some measurements (e.g. NO_x, carbon monoxide (CO), hydrocarbons

(HC), carbon dioxide (CO_2), oxygen (O_2)) relied on continual sampling with data logged on-line with a computer, while other parameters were based on grab samples (particulate matter (PM) and polyaromatic hydrocarbons (PAH)) taken over a given time period. In addition to those at the exhaust channel sampling sites, other periodic measurements of air temperature, humidity and pressure were undertaken at the air intake of the engine in the engine room. Furthermore, AE generator power was periodically (5–10 min intervals) registered from the existing instrumentation in the engine control room. An overview of the measurement parameters, methods and instrumentation together with relative uncertainty is presented in Table 4.

Concentration measurements of NO_x, CO, HC, CO_2 and O_2 were carried out using a continual emission monitoring system (CEMS) based on automatic gas analysers. Data collection, calibration and determination of NO_x and PM correction factors for ambient conditions are described elsewhere (Cooper and Andreasson, 1999; International Organisation of Standardisation, 1996b). In view of the relationship between theoretical (from fuel sulphur content) and measured exhaust SO_2 (Lloyd's Register Engineering Services, 1995), SO_2 emissions were calculated indirectly from fuel sulphur content and fuel consumption.

Total PM was sampled using a partial flow dilution system with CO_2 concentration measurement for determination of dilution ratio and fractional sampling (Cooper, 2001; International Organisation of Standardisation, 1996b). In most cases, two or three 20-min grab samples were taken during steady engine load conditions and the average value used in the subsequent evaluation. In addition to total PM sampling, other techniques were tested to investigate PM size fractions. Thus for one sample on board ship D, the glass fibre collection filter used in the dilution system was replaced by a polycarbonate filter which was then submitted for sweep electron microscopy analysis (SEM). On board ship A, an in-stack, eight-stage cascade impactor was tested where PM sizing was obtained by gravimetric analyses of the different filters. In this case, two samples were taken (one on AE5 using MGO and one on ME3 using RO of grade IF180 with 0.5% m/m sulphur content) to investigate fuel dependency on PM size. It should be borne in mind that the PM sizing exercises were carried out only as preliminary tests prior to a more thorough investigation planned.

Bearing in mind the time and equipment required for PM sampling following international standard procedure, some investigations have relied on much simpler soot number scales based on darkening of filter paper after exhaust exposure to indicate trends in emissions (Hountalas, 2001). In order to compare these types of measurements, a Bacharach soot tester (oil burner scale from 0 to 10 corresponding to filter colouration) was used directly after the PM measurements with the dilution system.

Following previous experience of PAH sampling on board ships (Cooper et al., 1996; Cooper, 2001), the

Table 4
Measurement parameters, equipment used and relative uncertainty (all gas parameters were measured in the dry exhaust gas except for HC and PM in the wet exhaust gas)

Parameter	Equipment (analysis method)	Uncertainty
NO_x (ppm)	Ecophysics CLD 700EL gas analyser (chemiluminescence)	$\pm 5\%$[a]
CO (ppm)	Maihak multor 610 gas analyser (infra-red absorption)	$\pm 8\%$[a]
CO_2 (vol%)	Maihak multor 610 gas analyser (infra-red absorption)	$\pm 6\%$[a]
O_2 (vol%)	Maihak multor 610 gas analyser (paramagnetic)	$\pm 5\%$[a]
HC (ppm C)	J. U. M. model VE7 gas analyser (flame ionisation)	$\pm 11\%$[a]
PM (mg nm^{-3})	Partial flow dilution system (gravimetric analysis)	$\pm 5\%$[b]
Soot No.	Bacharach oil burner scale (0–10) (darkening of filter paper)	n. a.
PAH (μg nm^{-3})	In-stack filter, absorption on PUF/XAD-2 (GC-MS analysis)	$\pm 10\%$[b]
Exhaust temp. ($^{\circ}$C)	Fischer–Rosemount thermoelement 244P-MV1 (in situ)	$\pm 1\%$[b]
Ex. flow (wet $nm^3\ h^{-1}$)	Calculation using carbon balance	$\pm 5\%$[b]
Barom. pressure (kPa)	Vaisala analogue barometer model PTB 101B	$\pm 0.1\%$[b]
Air temp. ($^{\circ}$C)	Nordtec testo 600	$\pm 2\%$[b]
Rel. air humidity (%)	Nordtec testo 600	$\pm 2\%$[b]
Engine load (kW)	From ship instrumentation for generator power[c]	$\pm 5\%$[b]
Fuel consumption (g kWh^{-1})	From engine test protocol and corrected for fuel calorific value	$\pm 10\%$[b]
SO_2 (g kWh^{-1})	From S content in fuel analysis and fuel consumption data	$\pm 10\%$[b]

[a] Accredited method with uncertainty at the 95% confidence interval defined by the Swedish Board for Technical Accreditation (SWEDAC).
[b] Estimated error or specified by instrument manufacturers (assumed as one standard deviation or at 68% confidence interval).
[c] Brake power calculated by assuming a 5% energy loss up to the generator or as specified by engine manufacturer.

PAH measurement technique used was based on the in-stack filter method which corresponded to sampling variant B in International Organisation of Standardisation (2000). Exhaust samples were drawn and filtered through a quartz fibre filter held inside the exhaust channel using borosilicate glassware. Thereafter, the sample was cooled and passed through a cartridge containing PUF (polyurethane foam) and XAD-2 (polyvinylbenzene resin) as PAH adsorbents. Rather than using a continual supply of cold water or portable compressor cooler equipped with a circulation pump, cooling of the sample gas was achieved by passing the sample gas through a series of glass condenser traps cooled in an ice bath. Since diesel PM are mostly sub-micron (Section 3.3), conditions for isokinetic sampling could be relaxed. Instead, the sample flow could be chosen with respect to analysis detection limits and maintaining the sample temperature $<20°C$ prior to the adsorbent cartridge. This approach for sample cooling during PAH sampling significantly simplified time, location, and equipment factors without impairing measurement quality. In practice, grab samples of 1–2 h were taken with sample volumes of 0.12–0.33 nm^3 dry gas. PAH analyses were undertaken at the IVL laboratory in Gothenburg using gas chromatography and mass spectrometry (GC–MS). All PAH sample fractions, in particular, gas and liquid phase (in condense and acetone wash) PAH, were combined after

extraction. An internal standard was used in the GC–MS analysis procedure and the results corrected for recovery of the standard.

Since AE operation was at a reasonably stable engine load for most of the time, exhaust gas flow, and thus specific emissions, could be calculated reliably via the carbon balance method (i.e. carbon input from the fuel balanced against carbon output in the form of measured CO_2) (International Maritime Organisation, 1998).

3. Results and discussion

For conciseness, a general overview of the concentration and emission intervals measured is shown in Table 5 and Fig. 1. Relative uncertainty (at the 95% confidence level) associated with the emission factors in $g\,kWh^{-1}$ are estimated as $\pm10\%$ (SO_2, CO_2), $\pm17\%$ (NO_x, CO), $\pm20\%$ (PM, HC), and $\pm30\%$ (PAH). It can be noted that emissions expressed as $g\,kg\,fuel^{-1}$ can be obtained by dividing the $g\,kWh^{-1}$ emission factors by the fuel consumption in $g\,kWh^{-1}$ multiplied by 0.001 given in Table 5.

3.1. NO_x, SO_2, CO, HC, CO_2 and PM emissions

Fuel-dependent specific emissions of CO_2 and SO_2 are a direct reflection of the carbon and sulphur contents of

Table 5
AE measurement results at steady-state engine load operation

Ship/engine	A/AE1–AE5	B/AE1–AE4	B/AE5	C/AE1–AE6	D/AE1–AE2	E/AE1	E/AE3	F/AE1–AE2
Load (% of max.)	45–63%	47–58%	59%	36–50%	43%–48%	41%	39%	63%
Fuel type	MGO	RO	MGO	MGO	MDO	RO	RO	MGO
NO_x (ppm)	930–1393	1002–1232	1559	967–1278	901–926	1225	1005	1502–1620
CO (ppm)	69–102	121–216	—	43–67	139–144	118	97	101–102
CO_2 (vol%)	4.52–5.20	5.61–6.13	6.29	4.78–5.40	6.52–6.66	5.74	5.57	5.98–6.32
O_2 (vol%)	13.29–14.59	12.64–13.28	12.34	13.63–14.47	12.08–12.51	13.11	13.76	12.73–12.10
HC (ppm C)	30–48	17–32	107	42–61	58–68	46	47	81–87
PM (mg nm^{-3})	27–56	62	45	40–57	29–31	98	79	21–26
PM (Bach. soot scale)	4–6	6–7	7	3–5	7	6	6	6
PAH (µg nm^{-3})	—	170–220	—	23–29	370–400	1810	1400	250–290
Ex. flow (wet $nm^3\,h^{-1}$)	3290–4400	4520–4990	4970	2620–3320	3580–4150	7150	5310	2640–2790
Ex. temperature (°C)	301–405	315–335	359	273–340	372–381	361	335	342–363
Fuel cons. (g kWh^{-1})	205–219	238–251	240	216–223	213–214	216	217	214
Charge air temp. (°C)	30–43	33–43	33	30–40	46–49	48	53	—
Charge air press. (bar)	—	—	—	0.20–0.50	7.0–8.5	0.6	0.6	—
NO_x (g kWh_{corr}^{-1} [a,b])	14.9–19.2	13.3–17.5	20.2	14.2–18.6	9.6–9.9	15.2	12.9	17.5–17.9
CO (g kWh^{-1})	0.57–0.97	1.06–1.71	—	0.33–0.57	0.92–0.98	0.90	0.77	0.69–0.73
CO_2 (g kWh^{-1})	653–699	763–803	768	686–708	691–694	691	697	676
HC (g kWh^{-1})	0.12–0.21	0.07–0.14	0.41	0.19–0.25	0.19–0.23	0.17	0.19	0.29–0.30
PM (g kWh_{corr}^{-1}) [a]	0.21–0.45	0.48	0.31	0.30–0.44	0.17–0.19	0.67	0.54	0.14–0.16
PAH (mg kWh^{-1})	—	0.9–1.5	—	0.15–0.19	1.9–2.0	11	9.5	1.4
SO_2 (g kWh^{-1})	0.33–0.35	2.5–2.7	0.4	5.2–5.3	1.0	9.5	9.6	0.26

[a] Corrected for ambient conditions according to International Organisation of Standardisation (1996b).
[b] NO_x emissions expressed as $g\,NO_2\,kWh_{corr}^{-1}$.
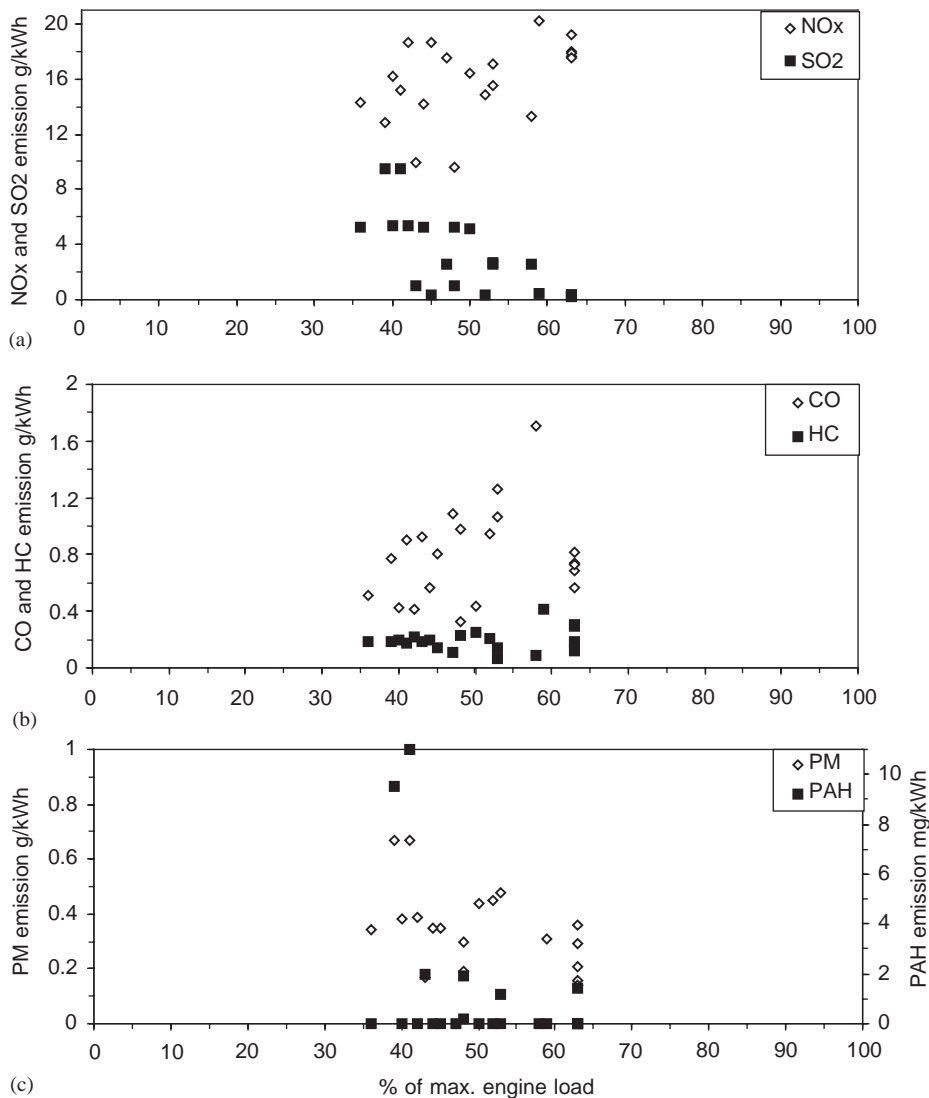
Fig. 1. Measured specific emissions against engine load.

the fuel used combined with the fuel consumption of the AEs. Since the variations in fuel carbon content (Table 3) and fuel consumption (Table 5) are small, CO_2 emissions are relatively well defined and similar for most AEs. For SO_2, significantly reduced emissions are evident when fuels with low sulphur contents are used (compare ships E and F). In view of the fuels used on the measurement ships and those of the fleet in general (European Commission, 2002a) where fuels of higher sulphur content are used, the SO_2 emissions reported in this study are probably lower than for the world fleet in general.

NO_x, CO and HC emissions varied considerably across the data, i.e. between 9.6–20.2 g kWh_{corr}^{-1}, 0.33–1.71 g kWh^{-1}, and 0.07–0.41 g kWh^{-1}, respectively.

Smaller variations were also apparent between engines on the same ships (similar model, age, and fuel). For example, the six AEs on ship C had emission ranges of 14.2–18.6 g kWh_{corr}^{-1} (NO_x), 0.33–0.57 g kWh^{-1} (CO), and 0.19–0.25 g kWh^{-1} (HC). These emissions are more dependent on the local combustion conditions and, therefore, individual maintenance and service history. Higher nitrogen contents in the fuel will theoretically promote higher NO_x emissions but in the present data other factors have a greater influence (compare ships E with F and also the AEs on ship B in Tables 3 and 5). Similarly, NO_x emissions have been correlated with engine speed (International Maritime Organisation, 1998), i.e. the slower the engine speed, the longer the time period at high temperatures and, therefore, greater

thermal fixation of nitrogen in the combustion air occurs giving higher NO_x emissions. In the present data, however, the two high-speed engines on ship F had some of the highest NO_x emissions. Thus, due to the numerous differences between engines operating in the real world, the validity of accepted NO_x correlations can be questioned for a limited group of engines.

The corrected PM emission levels measured varied between 0.14 and 0.67 g kWh_{corr}^{-1}, for the entire data set and the variation between engines on the same ship appeared to be similar to that observed for CO and HC. Generally, PM emissions from marine diesels can be categorised as being both fuel dependent (sulphates and metal oxide ash constituents) and also dependent on combustion conditions (unburnt HC and carbon residue constituents). Thus higher fuel sulphur and ash contents as for AE1 and AE3 of ship E for example gave rise to higher PM emissions. Fuel dependency on PM emissions is however less pronounced than for CO_2 or SO_2 emissions, since combustion conditions can greatly affect PM emissions. The obtained soot number values (Bacharach oil burner scale) or black smoke index and the measured uncorrected PM concentrations by the dilution system for 19 measurements, varied between 3–7 and 23–103 mg nm^{-3}, respectively. No clear correlation between the entire data set and between AEs with the same fuel could be observed, i.e. a low Bacharach oil burner soot number does not necessarily imply a low PM concentration and vice versa. For individual engines, however, a correlation between soot number index and PM concentrations may exist (not investigated in this work).

Although instantaneous specific emissions were not determined in this study, the concentrations measured at start-up of AE3 on ship A (Fig. 2a), clearly indicate elevated CO and HC emissions with engine ignition. For this start-up, the engine (shut down for the previous 11 h) was operated to give a step increase up to 57% of maximum load, which was then maintained for approximately 4 h thereafter. The elevated emissions appear to be quite short lived and within a 1-min period the CO and HC concentrations stabilised to their steady-state levels. In contrast, NO_x emissions increased steadily at start-up. Similarly the rapid engine load changes associated with engaging bow thrusters prior to ship departure, gave rise to only very short-term increases in CO and HC emissions (Fig. 2b). Thus relative to the length of the harbour stops, the periods with abrupt engine load changes, e.g. start-ups, appear to be minor and thus no significantly excessive HC or CO emission cases can be identified.

Previous marine emission measurement studies have dealt mostly with those emissions arising from MEs for ship propulsion. A set of AE emission factors has, however, been reported in a recent review (European Commission, 2002a). In general, the present data are in good agreement with the review factors, although lower HC and PM emissions have been measured for ships A–F. Two other investigations have reported universal emission factors based on empirical functions from a very limited experimental data set (each on four diesel AEs) (Lloyd's Register Engineering Services, 1995; Trozzi and Vaccaro, 1998). For a sample of 10 measurements from ships A–F in this work, the Lloyd's function overpredicted NO_x emissions on average by 64%, CO emissions by 323% and HC emissions by 522% while the Trozzi and Vaccaro function is not applicable since this empirical function was restricted to engines only in the 20–500 kW size interval.

3.2. PAH emissions

The speciated and total PAH emissions determined are presented in Table 6 and Fig. 1c. Where concentrations were analysed as below the detection limit, half of the detection limit has been used in calculating the sum of total PAH. The data compare well with previous PAH measurements on marine diesel engines (Cooper et al., 1996; Cooper, 2001; Lloyd's Register Engineering Services, 1995). Between 63% and 92% of the total PAH emission in each sample is accounted for by the five napthalenes and the two phenanthrenes, which is typical of diesel exhaust (Khalili et al., 1995). Total PAH emissions were mostly in the range 0.15–2.0 mg kWh^{-1} except for two samples from ship E (9.5 and 11 mg kWh^{-1}) which used an RO fuel with a significant PAH content (Table 3). Although PAH analyses are lacking for some of the fuels in this study, the results obtained in this study indicate that fuels with higher PAH contents (typically RO) are likely to give higher PAH exhaust emissions. This type of correlation has also been established for diesel road vehicles which are driven increasingly with Environmental Class 1 diesel fuel (maximum PAH content 0.02% m/m) (Wingfors et al., 2001).

Total PAH is defined above as the sum of the 29 species listed in Table 6. It should be borne in mind, however, that the definition of "total PAH" is a rather loose term and can vary. For example, French authorities list seven components (not including naphthalene) while the American EPA list includes 16 species (including naphthalene) (European Commission, 2001). The International Standards Organisation choose not to list specific PAH species but merely define PAH as "compounds that contain two or more fused aromatic rings made up only of carbon atoms" (International Organisation of Standardisation, 2000). For national emission reporting of PAH, the United Nations Economic Commission for Europe (UNECE) require the sum of only 4 species (see UNECE species in Table 6) (United Nations, 2002).
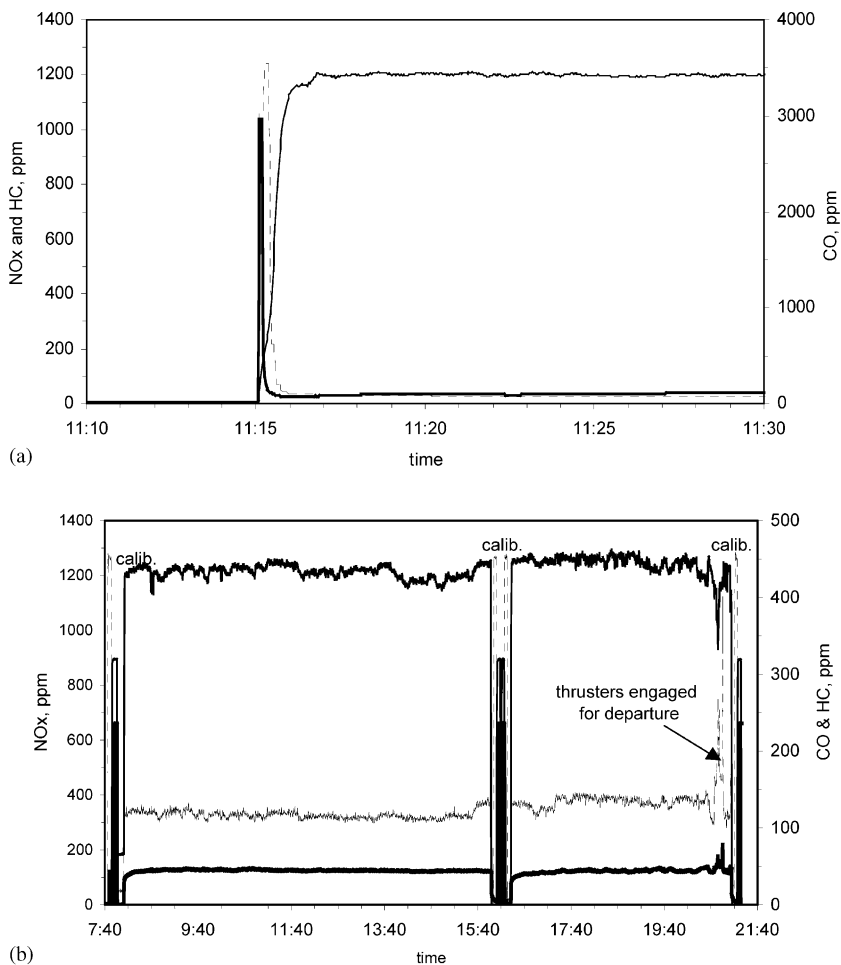
Fig. 2. NO_x (top line), HC (bold line) and CO (dashed thin line) concentration profiles during: (a) start-up of engine (AE3 on board ship A), and (b) loading/unloading activities over a 14-h period prior to departure for AE1 on board ship E (three calibration periods included).

3.3. PM sizing experiments

The results from the PM sizing experiment using the dilution tube and SEM analysis for ship D are presented in Table 7. The number of particles in % of total at different size intervals was counted and calculated at suitably chosen magnifications while PM as % m/m were calculated assuming uniform density ($1 \, g \, cm^{-3}$) and an average diameter for a given size interval. Although this technique for PM size distribution is relatively simple to perform, the drawback when compared to other techniques (impactors, etc.) is that all particles are collected on one filter with risk for agglomeration (i.e. biased towards larger particles).

The results from the particle sizing experiment using the cascade impactor on board ship A are presented in Table 8. The disadvantage with this technique is that a proportion of the fine particulates formed from conden-

sing HC compounds (nuclei mode) will be missed since the impactor was mounted in the hot exhaust. This can be compared with the temperature in the dilution tube which is kept $< 52°C$ to prevent these losses (International Organisation of Standardisation, 1996b). In comparing the data in Tables 7 and 8, the larger particles account for more of the total PM mass in the ship D sample which may however be a consequence of agglomeration. Although the data are far too few to draw any firm conclusions, the smaller particles ($< 1 \, \mu m$) appear to dominate in number but may only account for 10–50% of the total mass.

Since PM size distributions from operating marine diesel engines on board ships are lacking in the literature, the present results, although preliminary, provide a first assessment that needs to be verified. One previous study has however reported PM size data in exhaust plumes 0.6–1 km downwind of passing ships

Table 6
Speciated PAH emissions ($\mu g\ kWh^{-1}$) and total PAH emissions ($mg\ kWh^{-1}$)

Ship/engine Load (% of max.)	B/AE1 55%	B/AE1 43–58%	B/AE1 56%	C/AE1 51%	C/AE1 48%	D/AE1 43%	D/AE2 48%	E/AE1 41%	E/AE3 39%	F/AE2 32%	F/AE2 63%
Naphthalene	560	670	420	98	72	740	490	4740	5850	550	300
2-Methyl-naphthalene	250	310	160	38	31	540	510	1230	1080	260	190
1-Methyl-naphthalene	150	190	92	19	15	280	290	810	670	230	160
Biphenyl	16	14	8	3	4	95	73	1060	1460	78	56
2,6-Dimethyl-naphthalene	52	81	36	12	12	69	100	190	170	50	53
Acenaphthylene	2.1	3.4	0.7	0.4	0.4	<1.3	<2.1	<2.0	<4.0	4	3
Acenaphthene	5.4	7.9	2.6	0.3	0.3	<1.1	<1.8	30	25	26	22
2,3,5-Trimethyl-naphthalene	11	18	10	1.1	1.1	14	23	34	34	25	21
Fluorene	45	72	30	1.6	1.1	33	42	150	150	91	56
Dibenzothiophene	8.9	14	12	0.2	0.1	28	31	73	110	24	18
Phenanthrene	88	130	80	0.7	0.5	150	179	810	980	420	280
Anthracene	0.9	1.3	<0.5	<0.2	<0.2	<1.4	<2.3	14	<5.0	27	14
2-Methyl anthracene	3.5	<0.7	<1.3	<1.5	<0.1	<1.1	<1.9	<1.0	<3.0	<0.1	<0.1
1-Methyl-phenanthrene	<0.2	<0.2	<0.3	<0.3	<0.3	28	76	140	130	<0.2	<0.2
1-Methyl anthracene	1.8	2.2	<1.1	<0.1	<0.1	8	22	37	33	106	67
Fluoranthene	2.2	1.0	<1.2	<0.1	<0.2	8	14	10	99	150	49
Pyrene	<1.0	<0.3	<0.2	<0.1	<0.1	6	13	56	33	190	67
Retene	<0.3	<0.1	<0.1	<0.1	<0.1	<0.6	<1.0	<1.0	<2.0	32	17
Benz(a)anthracene	<0.9	<0.4	<0.5	<0.6	<0.6	<1.0	<1.6	8	6	19	7
Chrysene	<0.2	<0.2	<0.3	<0.3	<0.4	<0.8	10	27	32	42	15
Benzo(b)fluoranthene (UNECE)	<0.3	<0.3	<0.4	<0.4	<0.4	<0.9	<1.6	<2.0	<5.0	22	7
Benzo(k)fluoranthene (UNECE)	<0.5	<0.5	<0.7	<0.7	<0.7	<0.8	<1.4	<2.0	<4.0	6	2
Benzo(e)pyrene	<0.5	<0.2	<0.2	<0.2	<0.2	<0.9	<1.4	6	<4.0	12	4
Benzo(a)pyrene (UNECE)	<0.5	<0.5	<0.7	<0.7	<0.8	<1.5	<2.5	<4.0	<9.0	4	2
Perylene	<0.4	<0.4	<0.6	<0.6	<0.6	<1.2	<2.0	<3.0	<8.0	<0.2	<0.2
Indeno(1,2,3-c,d)pyrene (UNECE)	<1.2	<1.1	<1.5	<1.7	<1.7	<11	<15	<17	<44	16	3
Dibenzo(a,h)anthracene	<1.5	<1.4	<1.9	<2.1	<2.1	<10	<15	<16	<43	16	18
Benzo(g,h,i)perylene	<0.5	<0.5	<0.7	<0.7	<0.7	<11	<15	<17	<44	21	3
Coronene	<1.1	<1.0	<1.4	<1.5	<1.6	<18	<27	<29	<76	<0.3	<0.3
Sum of above 29 PAH ($mg\ kWh^{-1}$)	1.2	1.5	0.9	0.18	0.14	2.0	1.9	9.5	11.0	2.4	1.4
Sum 4 PAH (UNECE) ($mg\ kWh^{-1}$)	<0.001	<0.001	<0.002	<0.002	<0.002	<0.007	<0.01	<0.01	<0.03	0.047	0.013

using a differential mobility particle sizer (DMPS) (Isakson et al., 2001). This work presented only submicron PM number and mass size distributions, i.e. nuclei and accumulation modes. Previous particle size distributions from large stationary diesel engines have been reported as 77% m/m as <1 μm, 0.2% m/m in the range 1–3 μm, 2.7% m/m in the range 3–10 μm, and 20% m/m as >10 μm (US Environmental Protection Agency, 1996). Heavy-duty diesel road vehicles have exhaust PM number size distributions which have been described as being trimodal, i.e. three peaks, which may or may not overlap, are observed in the mass distribution (Brown et al., 2000). These are denoted nuclei mode (condensing HC volatiles) 0.01–0.1 μm, accumulation mode (carbon species and adsorbed material) 0.1–1 μm, and the coarse mode (re-entrained particles) 1–10 μm. For heavy-duty diesel road vehicles, the number distribution has been shown to be dominated by the nuclei mode while for the mass distribution the accumulation mode dominates.

3.4. Auxiliary engine operation and emissions from case studies

For most of the time spent at berth, power requirements of the ships were fairly constant and considerably less (9–49%) than the total installed AE power. This means that some AEs were not operated and the power output for individual AEs was usually only 25–60% of maximum. A questionnaire study targeting ME and AE operation for 81 ships (Flodeström, 1997) confirm that these AE power outputs for normal operation appear to be representative.

Procedure for standard emission test measurements ought to consider real-world operation in assigning engine load set points. Current Swedish legislation for

Table 7
PM size data from AE1 of ship D (dilution tube and SEM analysis)

Size interval (μm)	Number of particles (%)	PM (% m/m)
<0.5[a]	60.6 ± 4.0	0.4 ± 0.1
0.5–1	37.0 ± 4.0	7.3 ± 2.5
1–2[b]	1.1 ± 0.3	1.8 ± 0.8
2–5	1.1 ± 0.2	22.7 ± 1.2
5–10	0.1 ± 0.05	25.1 ± 3.6
10–20	0.0	30.7 ± 5.6
> 20[a,b]	0.0	12.0 ± 6.5
Sum	100.0	100.0

[a] Average diameters in these intervals taken as 0.25 and 21 μm, respectively, for calculation purposes.
[b] Number of counted particles in this interval was <10.

Table 8
PM size data from AE5 and ME3 of ship A (in-stack cascade impactor)

Size interval (μm)	PM (% m/m) AE5 (MGO fuel)	PM (% m/m) ME3 (RO fuel)
0–0.59	39.1 ± 4.6	32.5 ± 3.6
0.59–0.86	7.8 ± 0.9	6.0 ± 0.7
0.86–1.4	10.9 ± 1.3	6.0 ± 0.7
1.4–2.8	12.5 ± 1.5	9.6 ± 1.1
2.8–4.3	6.3 ± 0.7	14.5 ± 1.7
4.3–6.3	9.4 ± 1.1	7.2 ± 0.8
6.3–9.3	4.7 ± 0.5	10.8 ± 1.3
9.3–14.9	6.3 ± 0.7	8.4 ± 1.0
> 14.9	3.1 ± 0.4	4.8 ± 0.6
Sum	100.0	100.0

determination of the NO_x reduction certificate specifies, however, emission measurements at the 75% engine load set point for both MEs and AEs (Swedish Maritime Administration, 1998). Based on this work and others (Det Norske Veritas, 2000), a 50% AE load set point would be more appropriate. Similarly, the D2 weighting factors used for constant speed AEs in the IMO technical NO_x code (International Maritime Organisation, 1998) are biased towards higher loads, i.e. 0.05 for 100% and 0.25 for 75%.

An example of the AE load observations on board ship F for two harbour stops (one unloading and one loading cargo) is shown in Fig. 3. In this case, the power requirement was significantly greater during unloading cargo since the on board cargo pumps were in use. For loading operations, however, the pump power is normally supplied by a shore-side source. Such differences in AE operation and consequently emissions, however, are mostly limited to tankers and other self-unloaders carrying dry bulk products, e.g. cement,

which have these operational alternatives at berth. In general, these type of ships will often utilise ME power (equipped with a shaft generator) while in berth if the installed AE power is insufficient.

For the other five ships studied, the AE load operation was reasonably stable, and according to the chief engineers, the power requirement very similar for all harbour stops. Thus, the measured exhaust component concentrations showed little variation (see Fig. 2b) and the resulting emission factors could be assumed valid for most harbour stops. For a short, approximately 5-min period after arrival at the quayside, however, and approximately 15 min before departure, the power requirement for all the ships studied increased to 40–56% of the total installed AE power when bow and stern thrusters used for manoeuvring the ship were engaged. Since these time periods were relatively small compared to the total time spent in berth, their emissions can be approximated using the same emission factors measured at slightly lower and more constant engine loads. Emissions were measured at partial engine loads of 39–63% of maximum, and in some cases where time allowed, specific emissions were determined at two different loads. For example, emissions were measured from AE2 on board ship F at approximately 32% and 63% engine load. The latter case was the predominant engine load used while unloading cargo (Fig. 3).

By using the emission factors determined for each AE combined with the periodic engine load observations, an estimate of the emissions from the AEs during actual harbour stops (at two Swedish and two German ports) could be calculated (Table 9). Relative uncertainty (at the 95% confidence level) associated with the calculated total emissions in kg are estimated as ±14% (SO_2, CO_2), ±20% (NO_x, CO), ±22% (PM, HC), and ±32% (PAH). Note that these emissions are only from the AEs, covering the time from when the ship is stationary at berth and up to the point of departure from the quayside. These time periods appear representative of the respective ship type in view of results from 14 European port authorities (European Commission, 2002a). Median times for hotelling and loading/unloading operations were reported from a questionnaire as 18 h (chemical tankers), 13.6 h (passenger ferries), and 38.5 h (general cargo).

Other emissions from boiler use and possible warm-up of MEs whilst in berth were not measured due to budget limitations but estimated based on operational information from the chief engineers and universal emissions factors in the literature (European Commission, 2002a; US Environmental Protection Agency, 1998). It should be noted that ships with a fixed propeller shaft (e.g. ships D and E) do not have the ability to warm up MEs whilst stationary in berth. This type of propulsion system is common for larger cargo ships but virtually absent in, for example, passenger ferries. For the six ships, average
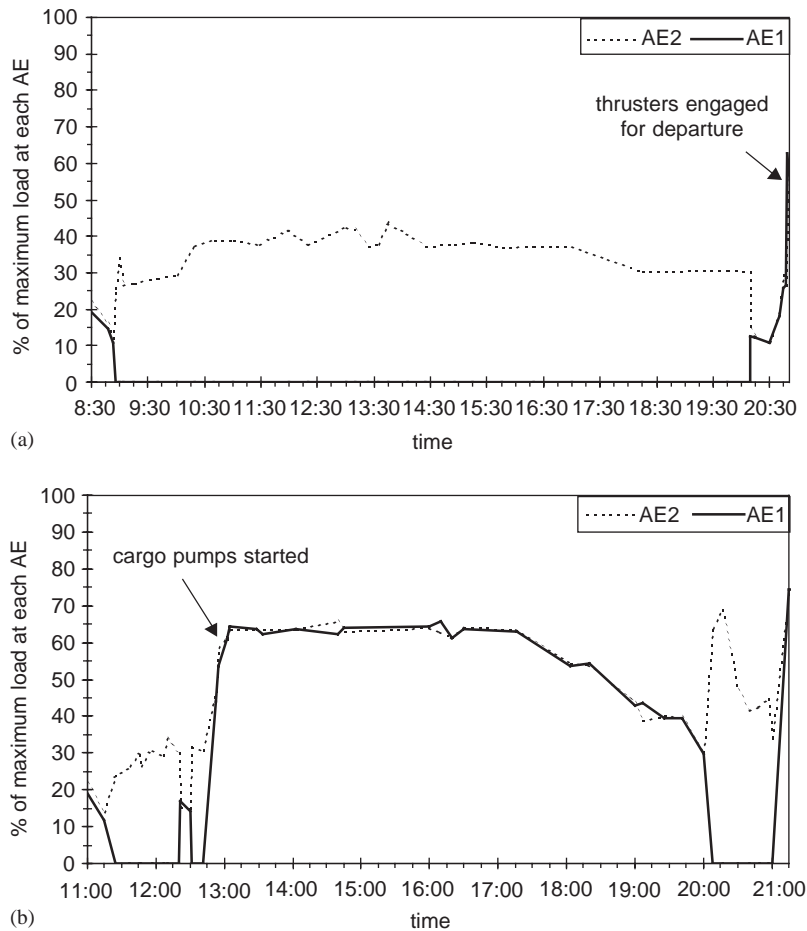
Fig. 3. AE power output for ship F: (a) harbour stop loading cargo, and (b) harbour stop unloading cargo. AE3 was not operated in either case.

Table 9
Estimates of total AE emissions (kg), fuel consumption (kg) and total power requirement (kWh) for the six measurement ships during actual harbour stops

Ship	A	B	C	D	E	F[a]	F[b]
Time in berth (h:min)	7:15	10:30	14:30	13:00	54:00	11:00	12:00
NO_x	131	260	303	178	652	133	50
CO	5.0	16	8.3	17	39	5.7	3.3
CO_2	5224	12050	13180	12650	31800	5250	2390
HC	2.6	2.3	3.9	3.8	8.2	2.3	1.1
SO_2	2.6	35	100	18	437	2.0	0.9
PM	1.2	6.2	6.8	3.3	28	1.2	0.51
PAH	0.0091	0.019	0.0032	0.036	0.48	0.012	0.007
Fuel consumption	1642	3754	4150	3890	9925	1660	756
Total power	7410	15420	18500	17960	45800	7550	3240

[a] Refers to chemical tanker unloading cargo (91% of max. capacity) using on board pumps.
[b] Refers to chemical tanker loading cargo (92% of max. capacity) not using on board pumps.

boiler emissions calculated as per cent of the AEs emissions were 1.1% (PAH), 2.8% (NO_x), 5.6% (HC), 7.1% (CO), 25% (PM), 48% (CO_2) 85% (SO_2). Generally, boilers are in continual use while in berth and the amount of fuel used was estimated to vary from 18 to 106% of the AE fuel consumed (48% as average value). Similarly, ME emissions during warm-up before departure were calculated as per cent of the AEs emissions for the four ships (A–C, and F) as 1.2% (NO_x), 1.6% (CO_2), 4.5 (PAH), 6.4% (HC), 6.8% (CO), 15% (PM), 33% (SO_2). No in-berth ME emissions could be attributed to ships D and E due to the fixed propeller power arrangement. Summarising, ME and boiler emissions can give significant emissions of SO_2 relative to those from the AEs. This is especially so in cases where AEs are run on low sulphur MGO while the boilers and MEs use RO (with higher fuel sulphur contents).

Interestingly, the emissions for ship B could be compared with emissions from an identical stop (in terms of time and operations) at a different port where a shore-side power link was used instead of AEs to supply electric power. In this case a Swedish power mix (including 48% hydroelectric power, 44% nuclear power, and 3% biomass power) and their emissions kWh^{-1} were used in the calculation (Stripple, 2002; Vattenfall, 1996). Thus for the shore-side link, emissions as per cent of the AE case were estimated as 0.2% (NO_x), 0.7% (SO_2), 1.1% (CO), 1.7% (PM), 2.4% (CO_2) and 7.6% (HC).

Since different ship types have widely different power requirements which reflect their purpose and equipment on board, no simple correlation between power requirement at berth and gross register or dead weight tonnage could be determined within the data for the six ships studied. For the three passenger ferries, however, the average power requirement correlated reasonably well with dead weight tonnage. Using this relationship and mean values for the measured emission factors from the 16 AEs on board the passenger ferries, formulae for calculating AE emissions from these passenger ferries at berth can be derived (Table 10). By comparing with the actual emissions in the case studies in Table 9, a level of uncertainty is obtained for the model. Thus, for a 10 h 30 min harbour stop for ship B, the model predicts a total NO_x emission of 254 kg (i.e. $0.00616 \times 3938 \times 10.5$) which is only a 2% underprediction of the measured emission of 260 kg (Table 9). Bearing in mind the uncertainty in the measurements, these formulae may give a useful and cost-effective emission prediction from fundamental input parameters for similar sized passenger ferries. It is possible that given an extended experimental data set, similar empirical formulae for other ship classifications may be derived thus simplifying harbour emission inventories.

Table 10
Universal functions for predicting AE emissions in kg from in berth passenger ferries based on their deadweight (Dwt in ton), time in berth (t in h) and AE fuel sulphur content (S in % m/m)

| Emission (kg) = $k \cdot$ Dwt $\cdot t$ | k | % Difference with case studies[a] | | |
		Ship A	Ship B	Ship C
NO_x	0.00616	0	2	2
CO	0.00029	−18	35	−40
CO_2	0.26345	−7	11	3
HC	6.63×10^{-5}	82	−16	23
SO_2	0.001651[b]	−7	16	4
PM	0.000131	−56	15	8
PAH	2.52×10^{-7}	69	78	−74
Fuel consumption	0.08257	−7	10	4
Total power	0.36716	−6	2	4

[a] Per cent difference between emissions measured in the three case studies for ships A, B and C in Table 9 and those predicted by the functions are shown. Negative values indicate an overprediction of the model.
[b] Emission (kg) = $k \cdot$ Dwt $\cdot t \cdot$ S.

4. Conclusions

To improve the limited knowledge regarding ship emissions while in berth, both specific (g kWh^{-1}) and total emissions (kg) of NO_x, SO_2, CO, HC, CO_2, PM and PAH were determined on board six ships during actual harbour stopovers, i.e. real-world emissions. The results obtained for the three passenger ferries demonstrate that empirically derived, emission formulae using dead weight tonnage can prove to be a cost-effective and relatively accurate tool for estimating total emissions from similar ferries in berth. Besides AE emissions, other emissions from boiler use and possible ME warm-up prior to departure were in general considerably less than those from the AEs, but can be significant especially for SO_2 if different fuel qualities are used. In light of eventual EU legislation to enforce low sulphur fuels in port areas, i.e. predominantly through increased MGO use, these results indicate that besides SO_2 and PM, PAH emission reductions may be expected. The measurements in this study show, however, that the variations in condition between engines in the real world and other factors affecting NO_x emissions, can hide, at least for individual engines, any expected improvements in these emissions due to the lower fuel nitrogen content of MGOs. Generally, the power consumption of the ships at berth was fairly constant and considerably less (9–49%) than the total installed AE power. Relative to the total time spent at berth, periods with abrupt engine load changes and higher loads (engagement of thrusters prior to departure) were insignificant. The observed AE operation on board the ships indicate that legislative

emission testing ought to focus on an engine load set point of 50% of maximum for AEs. A significant difference in power requirement was observed for the chemical tanker when loading and unloading (on board cargo pumps engaged) where the power requirement increased approximately by a factor of 2.5.

Acknowledgements

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