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Continual NO_x emission monitoring on board *Manon* and *Stena Jutlandica*

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RAPPORTSAMMANFATTNING
Report Summary

Projekttitel/Project title

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Rapportens titel och undertitel/Title and subtitle of the report

Continual NO_x emission monitoring on board *Manon* and *Stena Jutlandica*

Sammanfattning/Summary

IVL Swedish Environmental Research Institute Ltd. has carried out continual NO_x emission monitoring on board two ships equipped with NO_x reduction abatement technologies. The study was aimed to provide a practical demonstration of the feasibility of using continual emission monitoring to determine marketable NO_x emission reductions at sea.

Firstly, measurements were undertaken on the Pure Car/Truck Carrier, *Manon*, on a 17-hr voyage from Malmö (Sweden) to Drammen (Norway) during 18^{th}-19^{th} July, 2003. The low-NO_x slide fuel valves installed on the main engine of *Manon* were shown to achieve a marketable NO_x reduction of 660 ±106 kg NO_x for the test voyage within EU waters (based on a general baseline methodology set at the IMO NO_x emission limit curve, i.e. 17 g/kWh_{corr}).

The second demonstration was performed on the passenger ferry, *Stena Jutlandica*, for six 3 hr 15-min crossings each between Gothenburg (Sweden) and Fredrikshavn (Denmark) during 13^{th}-14^{th} August, 2003. The ship is equipped with Selective Catalytic Reduction (SCR) on all diesel engines for reducing NO_x emissions. In this exercise, a multi-engine measurement system was used to follow the NO_x emissions from main engines 2 and 4. For the two engines studied, a marketable, "real" NO_x reduction of 1737 ± 347 kg NO_x for the six voyages was determined (based on a ship specific baseline methodology i.e. separate measurements on the engines without SCR in operation).

In general, the measurement equipment and calculation routines outlined in the Phase 1 draft report of this project (the DEMO Project) were shown to be suitable on board the two measurement ships.

Nyckelord samt ev. Anknytning till geografiskt område eller näringsgren/Keywords

Ship emissions, NO_x, continual emission monitoring, marketable reduction

Bibliografiska uppgifter/Bibliographic data

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Contents

1 Introduction

1.1 Background

PriceWaterhouseCoopers AB have initiated a multi-phase project financed by several stakeholders in the shipping industry aimed at demonstrating that monitoring and verification of nitrogen oxides (NO_x) emission reductions and sulphur dioxide (SO_2) emission reductions from ships are feasible. In turn, the Swedish Environmental Research Institute has been contracted to outline suitable shipboard emission measurement techniques and calculation routines (Phase 1), and secondly to provide a practical demonstration at sea (Phase 2). Thus this work (Phase 2a) focuses on the first emission monitoring exercises in the project, on board two ships using two different kinds of NO_x abatement methodology.

1.2 Objective

The objective of these measurements was to demonstrate the functionality of the measurement equipment and methodology suggested in the draft Phase 1 report (Hansén *et al.*, 2003) for two ships using two different types of NO_x abatement technology. Specifically, the work focuses on determining the marketable[1] NO_x emission reductions for the ships during typical voyages.

2 Methodology

2.1 Technical ship data

Technical data for the measurement ships are presented in Table I.

Table I Technical data for the measurement ships

Ship name	***Manon***	***Stena Jutlandica***
NO_x abatement technology	low-NO_x fuel slide valves on ME	SCRs on all 8 diesel engines
Length and width, m	199,1 x 32,3	184 x 28
Dead-weight, tonnes	22 526	6 300
Int. GRT, reg. t	57 018	29 691
Pass./ car capacity	5 850 cars	1500 / 550
Engines	1 ME and 2 AEs	4 MEs and 4 AEs
Service speed, knot	19	21,5
Year of delivery	1999	1996
Main engines (ME)	Hanjung MAN B&W 8S60MC, 14710 kW (2 stroke slow speed diesel)	MAN B&W 9L 40/54, 6480 kW (4 stroke medium speed diesel)
Auxiliary engines (AEs)	Wärtsilä 4R32LNE, 1 620 kW (4 stroke medium speed diesel)	MAN B&W 8L 28/32H, 1740 kW (4 stroke medium speed diesel)
Fuel type	ME use Heavy Fuel Oil (HFO/IF380) AEs use Marine Diesel Oil (MDO/DMB)	MEs and AEs use Low Sulphur Heavy Fuel Oil (HFO/IF180)

2.2 Measurement site

Measurements on board *Manon* were carried out on the ME using a sampling hole (2½" size) at deck level 6. Gas analysers were located in the engine room, ca. 4 m below the sample hole at deck level 5 (see Figure 1). ME measurements were made during the 17-hr voyage from Malmö to Drammen (departure 22:00 18th July, arrival 14:40 19th July). The weather conditions during the voyage were favourable; little swell, light winds, and air temperature of ca. 20 – 25 ^{o}C.

[1] In this report the word "marketable emission reduction" is used in the sense that in a potential future emission trading system (or other market based instrument) the achieved emission reduction (achieved emission level below an assigned baseline), will after third party verification have an economic value to the ship owner.

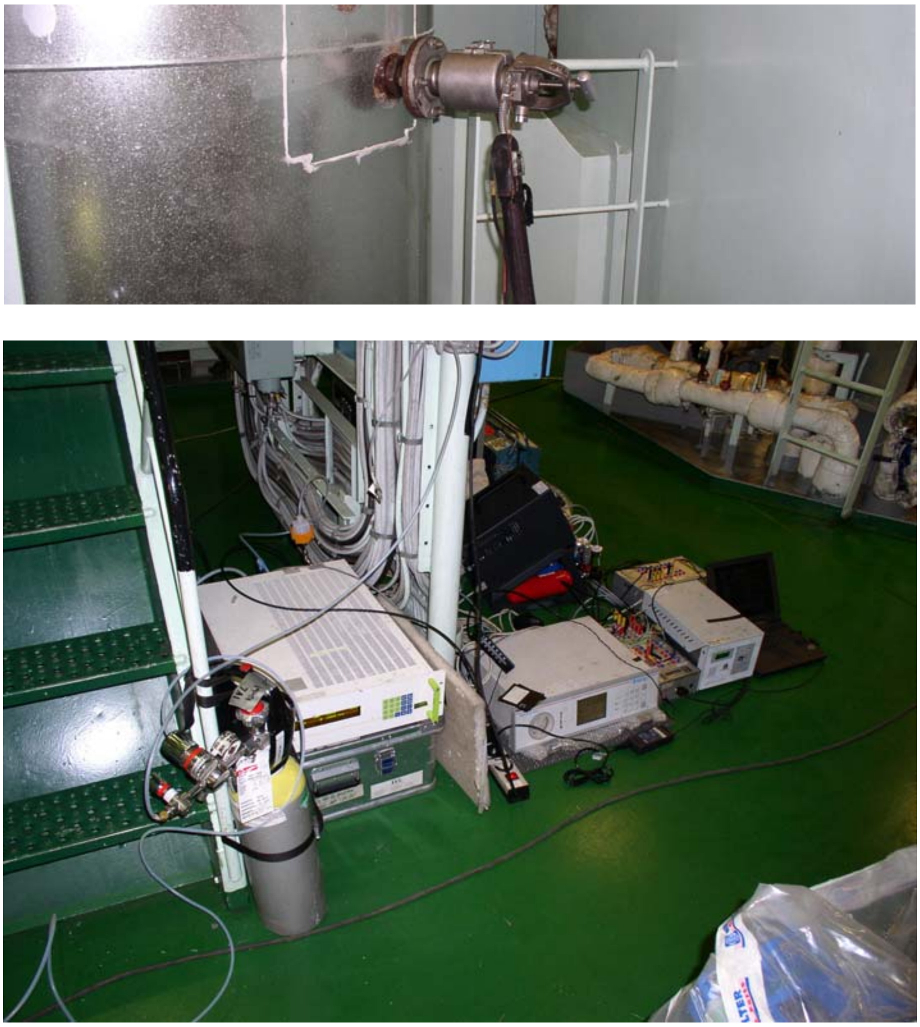


Figure 1. Measurement equipment set-up on board *Manon*.

Measurements on board *Stena Jutlandica* were carried out on ME2 and ME4 using sampling holes (2½ " size) at deck level 8 and in the starboard engine casing. By using two gas probes and heated lines and a valve switching system at the gas conditioning system, exhaust gas was sampled every 6 minutes in turn from each engine. Gas analysers were also located in the engine casing, ca. 10 m below the sample holes at deck level 7 (see Figure 2). Due to a malfunction of a cooling fan on the starboard side and the relatively high ambient temperatures in the casing (35 – 46 ^{o}C), the gas conditioning system was periodically lifted out on deck to avoid over heating. The measurements were made during six 3 hr 15-min voyages between Gothenburg (Sweden) and Fredrikshavn (Denmark). The total measurement period was ca. 24 hours; from the Fredrikshavn departure at 11:50 13th August, to the arrival in Fredrikshavn at 11:15 14th August. The weather conditions during the voyage could be characterised by little swell, light winds, but air temperatures of up to 28 ^{o}C and occasional rain showers.

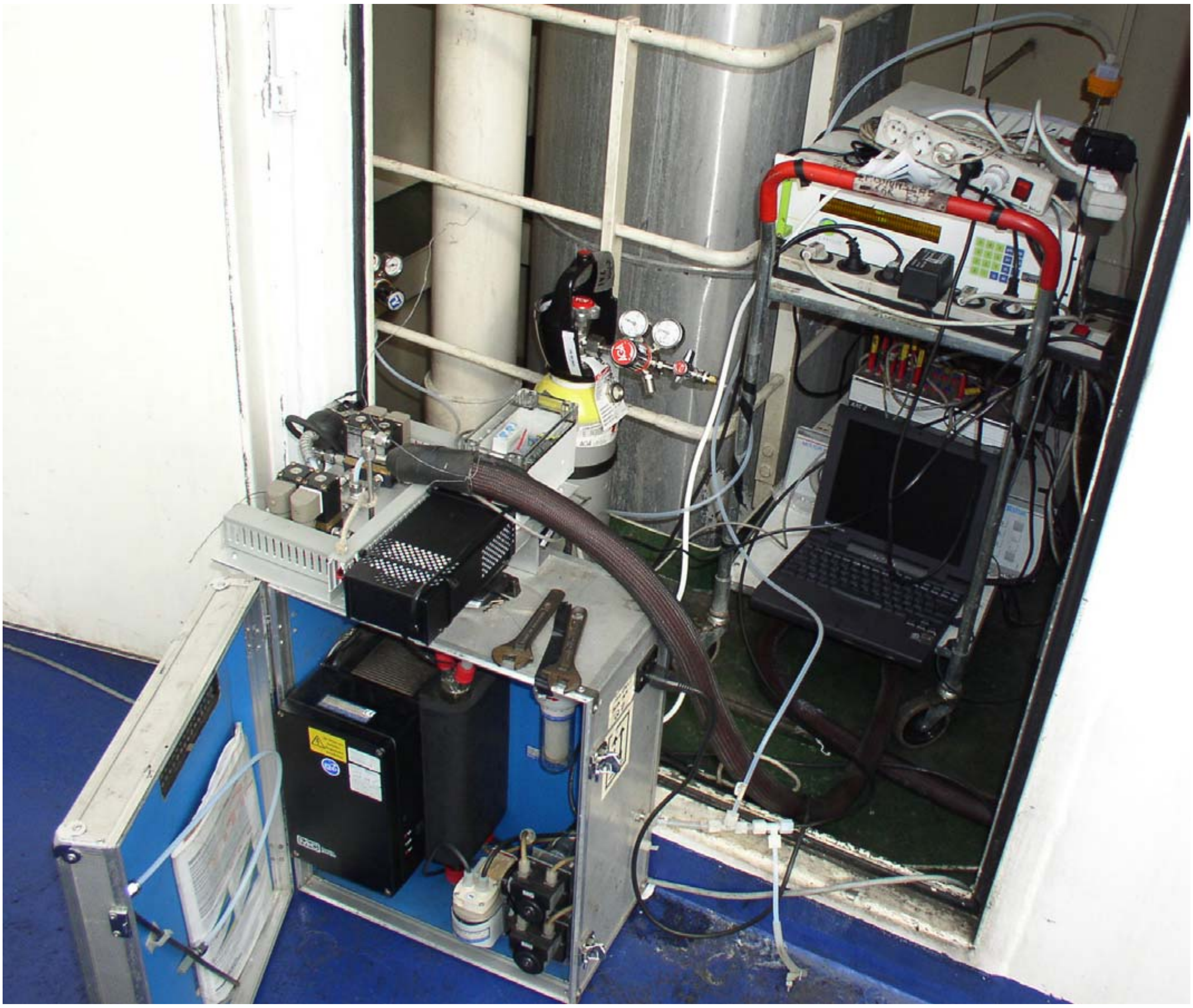


Figure 2. Measurement equipment set-up on board *Stena Jutlandica*

Normal engine operation occurred for all voyages except on board *Manon* where a 75% engine load set-point was required for ca. 2 hours (from 00:30 to 02:30 on 19th July). Since this represented no significant deviation from normal operation it has very little effect on the total marketable NO_x emission reduction measured.

2.3 Measurement parameters and techniques

A summary of the six primary measurement parameters (in red) and constants used (in blue) in the emission calculations are presented in Table II.

Table II Measurement parameters and constants, techniques and instrumentation

Parameter	Technique
NO_x ($NO + NO_2$), *NO_x in dry ppm*	Ecophysis CLD 700EL, chemiluminescence (continual) [1)]
CO_2, *CO2D in dry vol-%*	Maihak Multor 610, infra-red (continual) [1)]
Barometric pressure, *pB in kPa*	Vaisala PTB 101B barometer (periodic)
Air temperature at engine intake, *Ta in deg K*	Testo 600 thermometer (periodic)
Rel. Humidity at engine intake, *Ra in %*	Testo 600 hygrometer (periodic)
Engine load, *P in kW*	From ship's instrumentation (fuel pump index) (continual if possible)
Fuel carbon content, *BET in wt-%*	Default value of 86,7 %
Fuel heating value, *LHV in MJ/kg*	Ship fuel analysis certificate; 40,44 (*Manon*) and 41,7 (*Stena Jutlandica*)
Charge air temperature, *TSC in deg K*	Ship instrumentation (periodical); 313 (*Manon*), 321 (ME2 *Stena Jutlandica*), 323 (ME4 *Stena Jutlandica*)
Ref. charge air temperature, *TSCref in deg K*	From engine manufacturers;); 308 (*Manon*) and 314 (*Stena Jutlandica*)

[1)] Uses an extractive measurement system (stainless steel multi-hole probe, 10 m heated line, gas conditioning system) where concentrations were analysed in the dry sample gas.

Unfortunately, on *MV Manon* a continual measurement of the engine load could not be arranged in time for the measurements. An installation of the IVL 0-20 mA logger in series with the display panel showing the fuel pump indicator was judged as a safety risk as this may have interfered with the adjacent digital governor unit using the same signal. Since time was not available to check this installation with the appropriate personnel from NORControl A/S, IVL in discussion with the electrical engineer on board (Lars Johanisson) decided to opt for a manual approach. Thus, the engine load was read off at the panel display as often as possible (every minute during load changes). Although this proved time-consuming the overall results were very satisfactory. By comparing values of other engine parameters (turbocharger speed, engine speed, charge air pressure etc.) to the fuel pump values and discussing these with the chief engineer and MAN B&W (Jensen and Pedersen, 2003), the fuel pump values were adjusted as best as possible to correspond to the engine load.

Engine load measurements from the fuel pump index in the engine room on *Stena Jutlandica* were however logged simultaneously and synchronised with the exhaust measurements without difficulties.

As indicated in the Phase 1 draft report (Hansén *et al.*, 2003), the measurements were carried out following the standard procedures set out in ISO 8178, 1996 and IMO Technical NO_x Code, 1997 (6.3 "Simplified Measurement Method"). Measurement equipment performance fulfilled the requirements of IMO Technical NO_x Code, 1997 and forms part of IVL's accreditation status routinely assessed by SWEDAC (Swedish Board for Accreditation and Conformity assessment)[2]. The equipment and calibration standards used are presented in Table III. The fuel analysis certificates (used for obtaining LHV) were obtained from the chief engineers on board each ship and the reference charge air temperatures from the engine manufacturers (Glensvig, 2000; Gallersdörfer, 2003).

[2] Enquiries concerning accreditation procedure, certification documents, inspection routines etc. can be directed to SWEDAC, Box 878, 501 15 Borås (Tel. 033-177700). IVL Swedish Environmental Research Institute has been given accreditation number 1213.

Table III. Measurement equipment (as required in IMO Technical NO_x Code, 1997).

Instrument	Manufacturer/model	Range used	Calibration standard
NO_x gas analyser	Ecophysics CLD700EL	0 – 1000 ppm	894 ppm ± 2 rel-% tolerance AGA Gas OTM-5 20600 00633
CO_2 gas analyser	Maihak Multor 610	0 – 20 vol-%	14,7 vol-% ± 2 rel-% tolerance AGA Gas OTM-5 38400 21086
Intake air temp. instrument	Nordtec Testo 600	-20 – 80 ^oC	SP/SWEDAC traceable calib. Certificate F1 06477
Intake air humidity instrument	Nordtec Testo 600	0 – 100 Rel. %	SP/SWEDAC traceable calib. Certificate F1 06477
Atmos. pressure barometer	Vaisala PTB 101B	60 – 106 kPa	SP/SWEDAC traceable calib. Certificate MTmF 113308

Gas concentration and ME effect measurement signals were recorded every 15 seconds and 1 minute averages stored using PC driven Intab AAC-2 and Tiny Tag loggers. The time was synchronised to Central European Time. As indicated in the draft Phase 1 report, a record of ship position, in addition to the measured emission reductions, will be required for the future trading system. The possibilities available for logging ship position will however be dealt with later in Phase 2b of the project. During this work, the ships position was manually noted on *Manon* (voyage left EU waters) where time allowed. *Stena Jutlandica* operated entirely within EU waters.

Emission calculations were based on the so-called "universal" mass balance in IMO Technical NO_x Code, 1997 and as described in detail in the Phase 1 draft report (Hansén *et al.*, 2003).

The gas analysers were calibrated at four (*Manon*) and seven (*Stena Jutlandica*) separate intervals during the voyages and the measurement signals compensated for signal drift. It is conceivable that for a future, permanent measurement system installed in a temperature-controlled housing, the number of necessary calibrations required would most probably be less than that in these measurement campaigns.

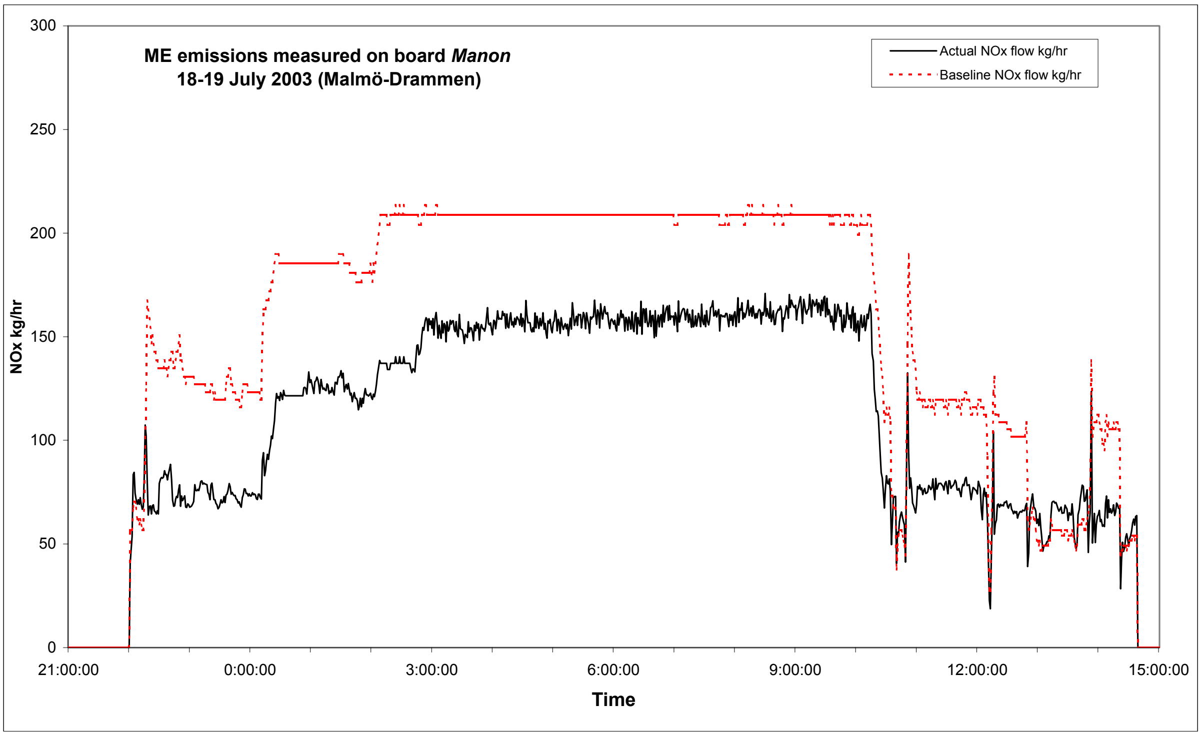
3 Results

The evaluated NO_x emissions (baseline and actual) and marketable reductions measured during the voyages are presented in Figures 3, 4 and 5. The corresponding emission reports showing the hourly reductions are shown in Tables IV and V. Other raw data including concentration, engine load and exhaust flow profiles and ship position are included in Appendix 1 (*Manon*) and Appendix *2 (Stena Jutlandica*). Note that *Manon* left EU waters at precisely 10:35 and entered Norwegian sea territory, i.e. the emissions after 10:35 have not been included in the emission reduction report[3].

[3] In the Phase 1 Draft report it assumed that a future market based system for reducing emissions from sea going ships will have a boundary at a certain distance from shore. In order to demonstrate that it is possible to monitor the emission reductions within (and outside) the system boundary, the future boundary was assumed to be the EU territory waters in this case.

It is important to bear in mind that for *Manon* the general baseline methodology following the IMO NO_x emission limit curve (i.e. NO_x baseline set at 17,0 g/kWh_{corr}) was adopted[4]. A ship specific baseline was not available. Thus the *Manon* emission reduction credits are based on this theoretical and "politically assigned" baseline, with an uncertainty from this rigid baseline of ± 16% (95% confidence level). For *Stena Jutlandica* however, baseline emissions were measured separately (at 75% engine load) just prior to the test voyages by switching off the urea flow to the SCRs. Thus for *Stena Jutlandica* a ship specific baseline methodology was used in calculating a "real" marketable reduction (i.e. NO_x baseline set at 15,4 g/kWh_{corr} for ME2 and 15,0 g/kWh_{corr} for ME4). The uncertainty in this case has been estimated to ± 20% (95% confidence level).

During the measurements no abnormalities were reported and the engines and abatements systems were considered to be running as normal.



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[4] Several baseline methodologies are possible for a future trading system. Different methodologies are presented and discussed in the Phase 1 Draft report.

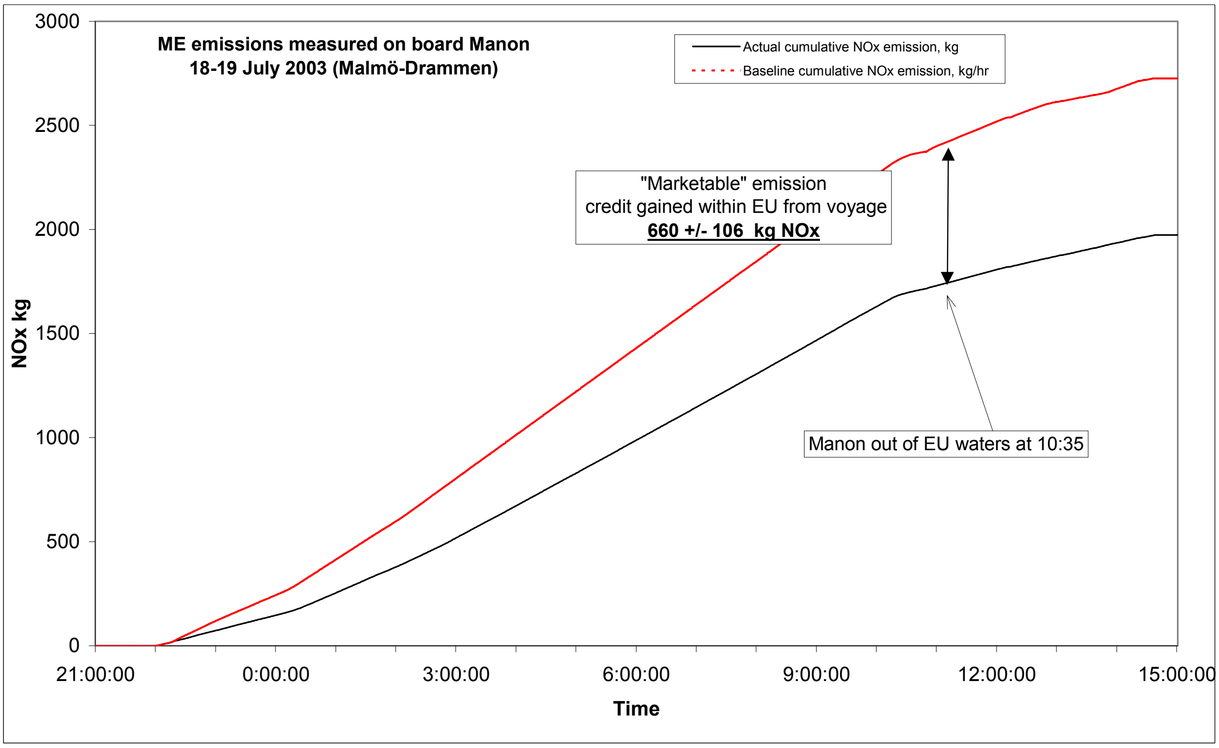
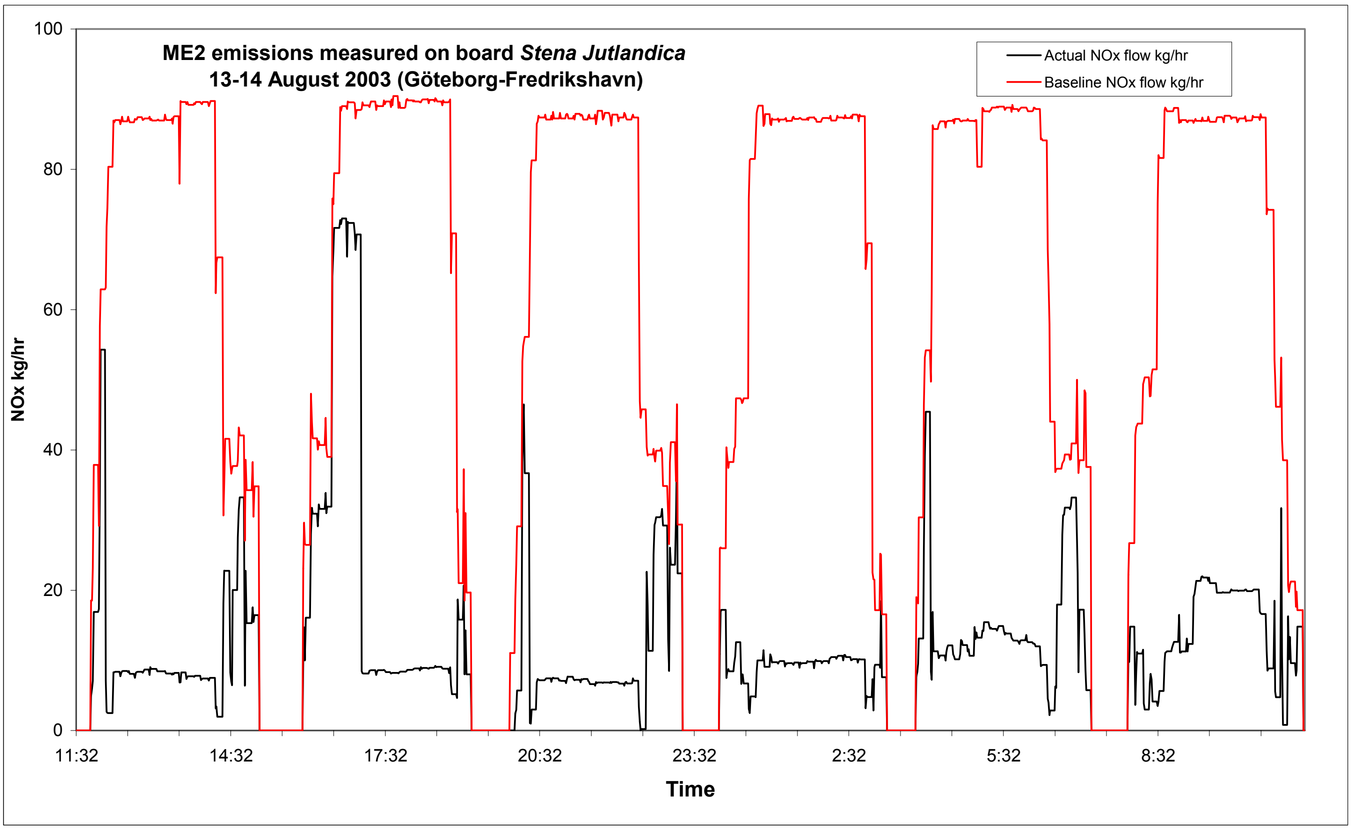


Figure 3. Measured NO_x emissions on board *Manon*.



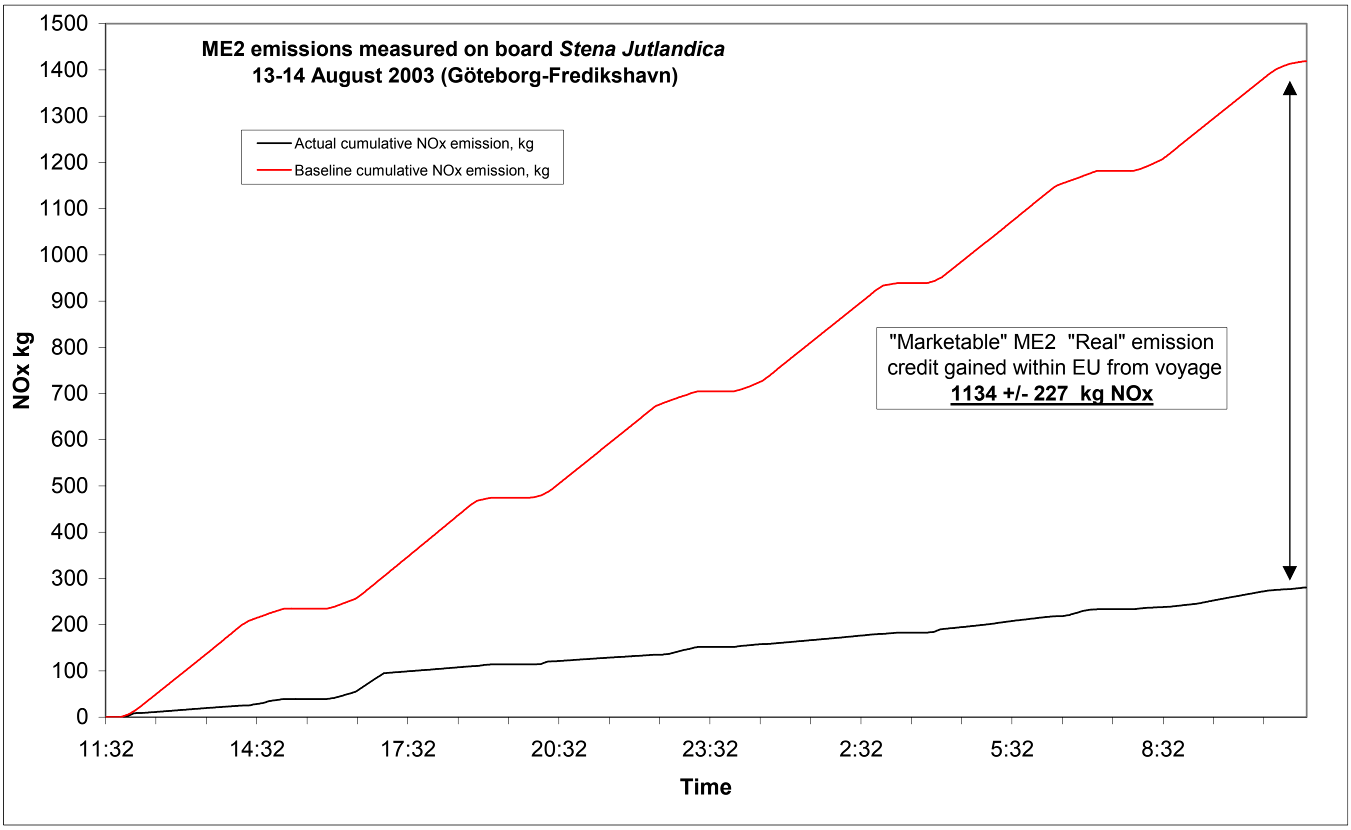
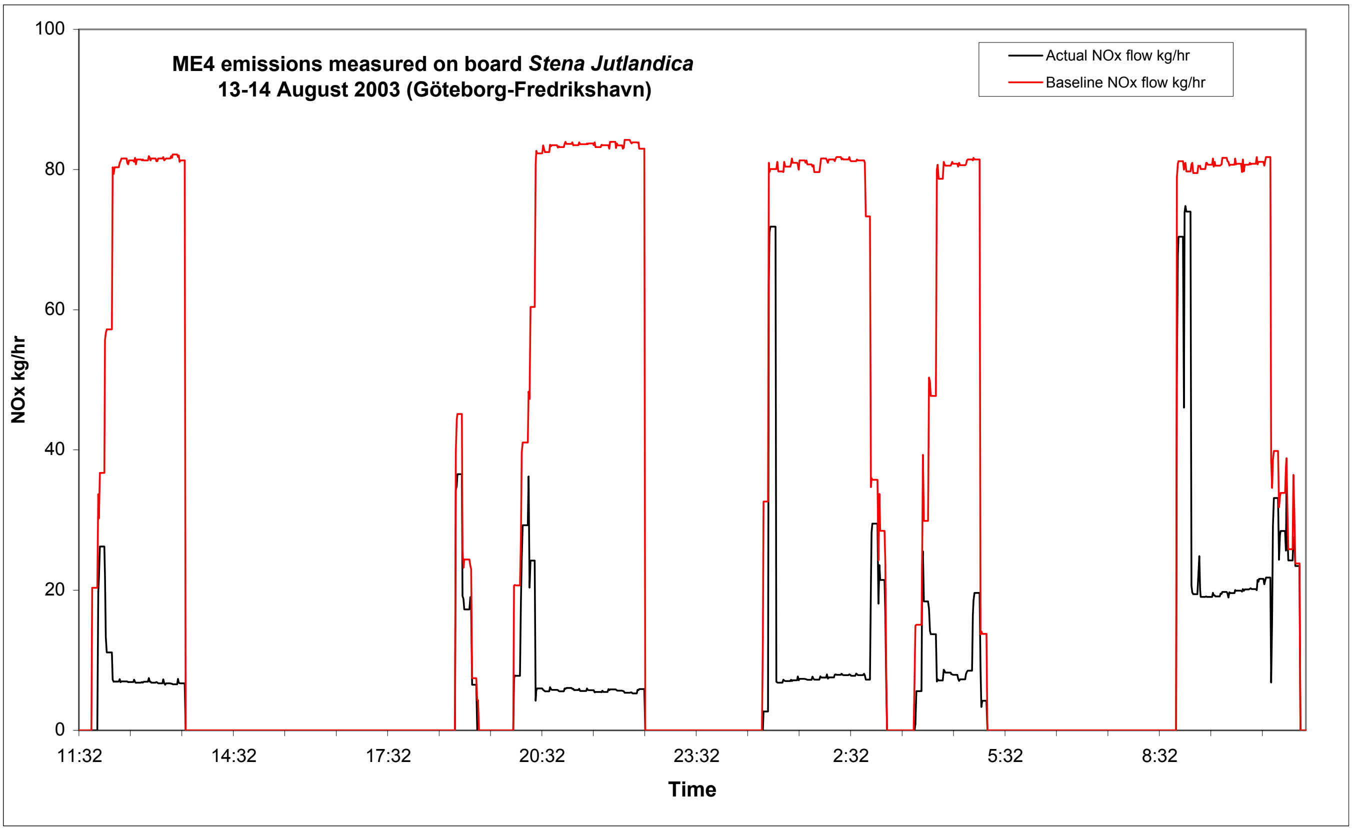


Figure 4. Measured NO_x emissions from ME2 on board *Stena Jutlandica*.



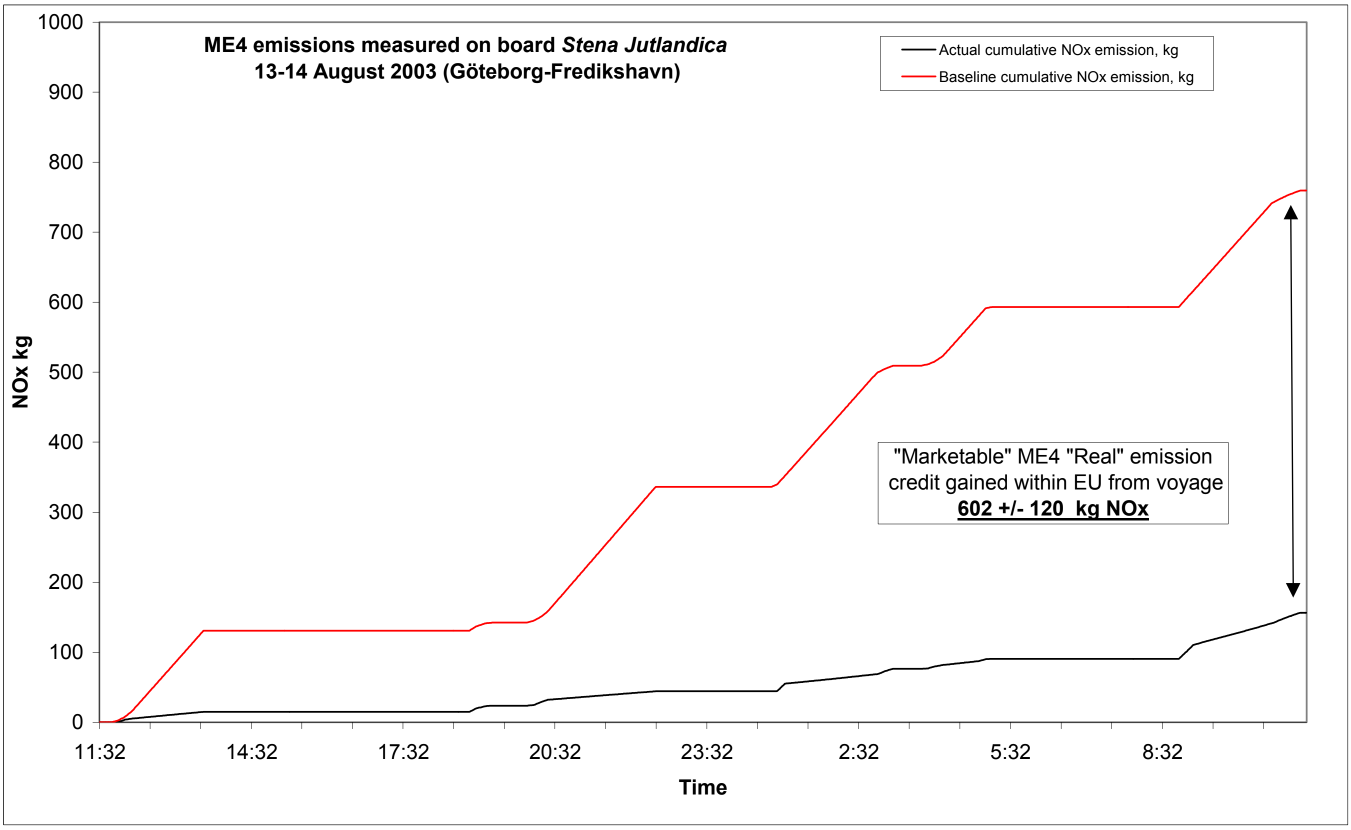


Figure 5. Measured NO_x emissions from ME4 on board *Stena Jutlandica*.

Table IV. An example of the emission reduction report for *Manon*.

ME Emission Reduction report for Manon 18-19 July (Malmö-Drammen)	
time	EU NOx emission reduction (kg)
2003-07-18 18:00	0
2003-07-18 19:00	0
2003-07-18 20:00	0
2003-07-18 21:00	0
2003-07-18 22:00	45
2003-07-18 23:00	51
2003-07-19 00:00	63
2003-07-19 01:00	59
2003-07-19 02:00	67
2003-07-19 03:00	55
2003-07-19 04:00	52
2003-07-19 05:00	50
2003-07-19 06:00	50
2003-07-19 07:00	48
2003-07-19 08:00	47
2003-07-19 09:00	46
2003-07-19 10:00	27
2003-07-19 11:00	0
2003-07-19 12:00	0
2003-07-19 13:00	0
2003-07-19 14:00	0
SUM--->	**660**
(emissions at 18:00 refer to emissions from 18:00 up to 18:59 etc.)	

Table IV. An example of the emission reduction report for *Stena Jutlandica*.

ME2 and ME4 Emission Reduction report for Stena Jutlandica 13-14 August (Göteborg-Fredrikshavn)			
time	ME2 NOx emission reduction (kg)	ME4 NOx emission reduction (kg)	SUM
2003-08-13 11:00	4	4	8
2003-08-13 12:00	71	69	140
2003-08-13 13:00	80	40	120
2003-08-13 14:00	38	0	38
2003-08-13 15:00	3	0	3
2003-08-13 16:00	13	0	13
2003-08-13 17:00	77	0	77
2003-08-13 18:00	71	4	75
2003-08-13 19:00	3	2	5
2003-08-13 20:00	61	55	116
2003-08-13 21:00	81	78	158
2003-08-13 22:00	48	36	84
2003-08-13 23:00	4	0	4
2003-08-14 00:00	51	7	58
2003-08-14 01:00	77	68	145
2003-08-14 02:00	71	66	137
2003-08-14 03:00	6	4	11
2003-08-14 04:00	67	65	131
2003-08-14 05:00	74	3	77
2003-08-14 06:00	42	0	42
2003-08-14 07:00	7	0	7
2003-08-14 08:00	57	3	60
2003-08-14 09:00	68	53	122
2003-08-14 10:00	57	44	102
2003-08-14 11:00	4	1	4
SUM--->	**1134**	**602**	1737
(emissions at 18:00 refer to emissions from 18:00 up to 18:59 etc.)			

4 Discussion

In conclusion, the marketable emission reductions were determined as ca. 753 ± 120 kg NO_x for the ME during a Malmö-Drammen 17-hr voyage on board *Manon* and ca. 1736 ± 347 kg NO_x for ME2 and ME4 during six Göteborg-Fredrikshavn crossings over 24 hrs on board *Stena Jutlandica.* The emission reduction for *Manon* was based on a theoretical baseline whereas for *Stena Jutlandica* the emission reduction was a "real" reduction (measured baseline).

The measurement methodology as outlined in the Phase 1 draft report (Hansén *et al.*, 2003) has been demonstrated as suitable thus far. Procedure for recording engine effect (lacking on *Manon*) can however be improved given a greater time period for planning prior to the measurements. Regarding recording ship position this will be addressed together with emission measurements on other ships in the following Phase 2b study.

To our knowledge continual NO_x emission monitoring studies covering complete voyages using similar methodology as to that described here has now been demonstrated on 10 different ships (Cooper, 1996; Cooper and Andreasson, 1998; Cooper 2001; Cooper and Ekström, 2003; Ahlbom and Duus, 2003).

In general the portable exhaust monitoring equipment has been proven satisfactory despite excessive ambient temperatures in some cases (e.g. on board *Stena Jutlandica* in this study). The studies have however not been performed on voyages with significant tilting and jolting (i.e. small ships during heavy seas) nor for extended periods (i.e. most cases < 5 days). Measurement uncertainty and eventual erroneous data (e.g. in exhaust flow) can arise for periods with rapid engine load changes where calculated fuel consumption (from engine effect) and measured CO_2 values are not fully concerted. By introducing conditional calculation steps these can however most likely be minimised.

An interesting follow-up project to this work would be to conduct a more, long-term demonstration (6 – 12 months) of a measurement system that is operated and calibrated entirely by the ship's crew.

5 References

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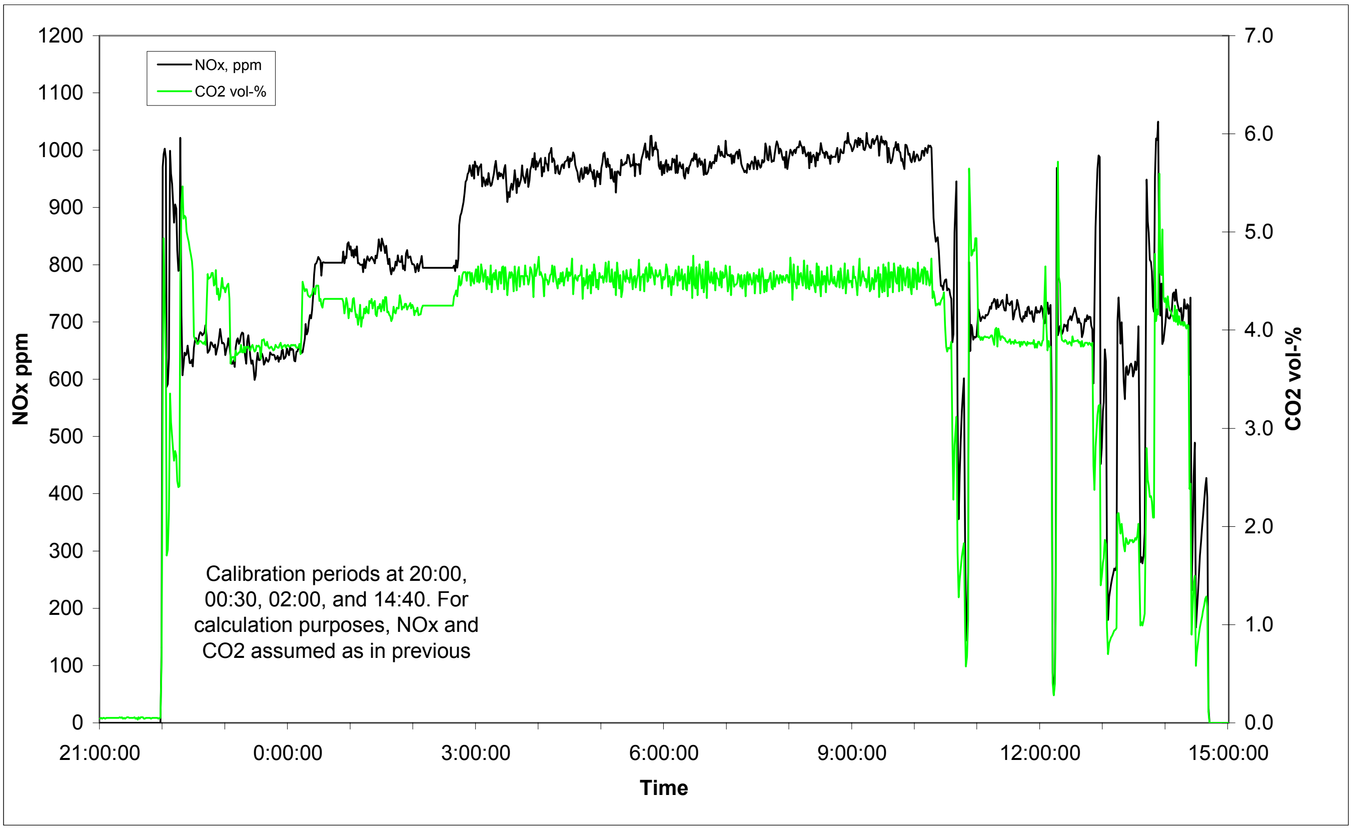
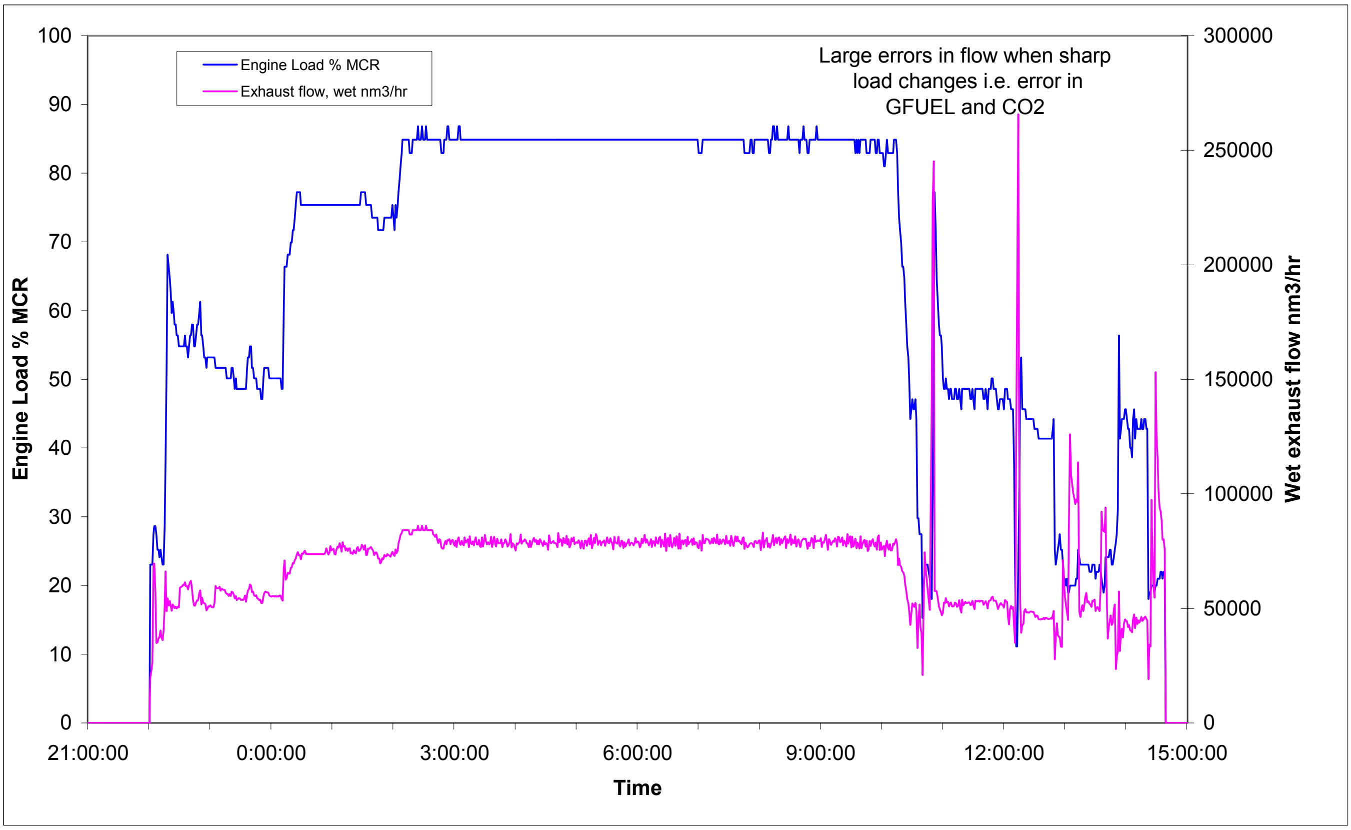
Appendix 1

Raw data from measurements onboard *Manon* 18-19 July 2003





Noted ship positions during voyage on board *Manon* 18-19th July 2003.
(Manon left EU waters at 10:35)

time	latitude position	longitude position
22:15	55 38.132 N	012 58.229 E
23:30	55 53.735 N	012 44.786 E
23:57	55 59.739 N	012 41.296 E
01:07	56 14.216 N	012 41.296 E
08:15	58 18.951 N	010 58.404 E
09:56	58 51.149 N	010 40.762 E
11:16	59 09.628 N	010 39.548 E
13:10	59 32.996 N	010 24.469 E

Appendix 2

Raw data from measurements onboard *Stena Jutlandica* 13-14 August 2003