CLINSH

SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR

Deliverable B3.2

Develop NOx emission factors through data from CLINSH measurements

CLEAN INLAND SHIPPING

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Project:	CLINSH – Clean Inland Shipping
Goal:	The objective of LIFE CLINSH is to improve air quality in urban areas situated close to ports and inland waterways, by accelerating IWT emission reductions.
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1 Introduction

CLINSH is a European consortium promoting clean waterway transportation. The main objective of this project is to improve air quality in urban areas by accelerating emission reductions in inland waterway transport.

Within the CLINSH, 42 selected inland vessels were monitored under 12 emission abatement technologies, among them, 15 were retrofitted with 8 emission reduction technologies, the measured emission data of these 15 vessels have two sets, before and after refitting mitigating technologies or measures. The comparison of these two conditions would reveal the performance of each selected abatement technology in real life. In addition, the overall analysed data would reflect the general emission conditions in inland waterway transport which would be beneficial to policy maker, stakeholders, and ship owners.

This project started from 2016, after the initial investigation and research work, the continuously onboard monitoring emission data were measured and uploaded to database month by month from June 2018 till the end of August 2020. The data was provided by MULTRONIC, an environmental monitoring company with nearly 40 years of experience in air emissions measurement. The measurements contained 40 variables and two "day and time" series, which mainly focus on the NOx, PM and CO_2 emissions, the objective of this section in the project was to generate the generic NOx emission factors through analysing the measured data for each vessel.

2 Measurements

42 selected vessels were separated into 4 groups according to the engine classification, which were CCNR0, CCNR1, CCNR2 and EURO VI.

CCNR, Central Commission for the Navigation of the Rhine, is the oldest international organisation dating back to the Congress of Vienna (1815). The main objective is to prosper and ensure a high safety standard Rhine and European inland navigation and its environment. In order to control the harmful constituent compounds which related to the combustion of diesel fuels for inland navigation propulsion. A type approval is designed and required by the Central Commission for new engines installed on board inland vessels, which are CCNR0 before 2003, CCNR1 since 2003 and CCNR2 since 2007.

Based on the previous European emission standards, EURO VI is a vehicle emission standard originating from the European regulatory pathway aiming at tightening limits on air pollutant emissions. It specially noted that considerable reduction in NOx emission is very essential to improve the air quality. Compared with the Stage V requirement, overall NOx emissions is 4.5 times lower. Stage V emission requirements is set by the European Union for Non-Road Mobile Machinery (NRMM), which requires all the new engines for inland waterway vessels must comply with it since 2019.

Within the CLINSH, the number of vessels separated into each group with the engine classification of CCNR 0, CCNR 1, CCNR 2 and EURO VI were 13, 9, 18 and 2.

Including the traditional diesel engines, vessels with 13 emission reduction technologies were selected to be monitored in CLINSH. These technologies covered the most air emission reduction technologies in marine industry, some were after treatment, some were alternative fuels. They were Biodiesel, Change TL (one kind of alternative fuel), Diesel-electric, Diesel-electric + SCR-DPF, Diesel-hydrogen injection, EURO VI, FWE (Fuel Water Emulsion), GTL (Gas to Liquid), SCR (Selected Catalytic Reduction), SCR-DPF (Selected Catalytic Reduction – Diesel Particulate Filter), GTL+FWE, LNG (Liquified Natural Gas).

In addition, 15 vessels were measured under “before refit” and “after refit” conditions, which means they were retrofitted with several reduction technologies during the project. This action could reveal the performance of the selected technologies more accurately in real life. The NOx emissions under “before refit” condition could be treated as a base line, the difference between the base line and the “after refit” condition was the real performance of the selected reduction technology. The selected air emission reduction technologies were Biodiesel, Diesel–electric, Diesel–hydrogen injection, Euro VI, FWE, FEW + GTL, GTL and SCR–DPF. Beyond this scope, the vessels under the “before refit” condition were treated as measured samples of diesel engines.

The distribution of measured vessels under engine classification and emission reduction technologies was shown in Table 2.1.

Table 2.1 Distribution of measured vessels

Technology	CCNR 0	CCNR 1	CCNR 2	Euro VI
Biodiesel	1			
Change TL	1			
Diesel	7	7	4	
Diesel-electric			4	
Diesel-electric + SCR-DPF			1	
Diesel-hydrogen injection			1	
Euro VI				2
FWE	3	1		
FWE+GTL	1			
GTL	4	1	1	
LNG			2	
SCR	2		2	
SCR-DPF	1	4	4	

3 Methodology

The monitoring system captured data samples every four seconds, it measured 40 onboard variables and two “day and time” series. The measurements contained location information, speed, revolution per minute, engine load, NOx emission, CO_2 emission, fuel rate etc. The detailed measurements were depicted in Fig 3.1.

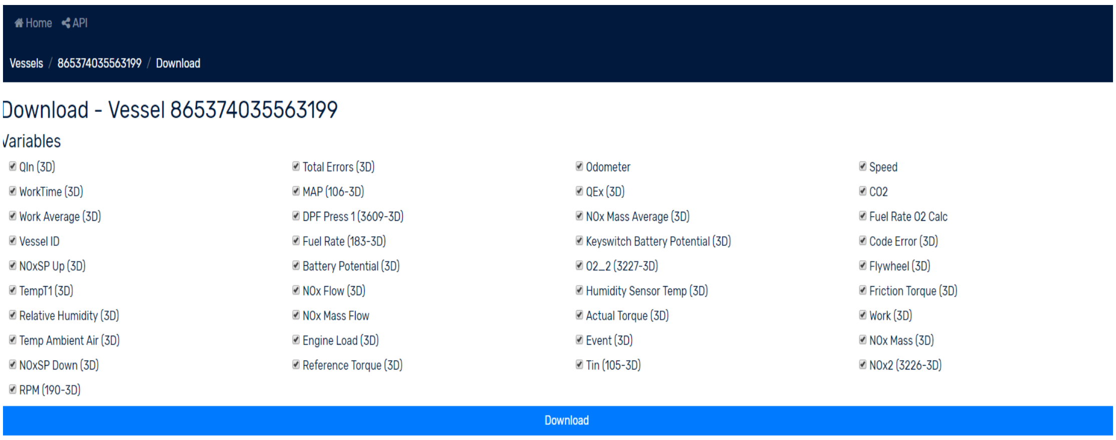


Fig 3.1 Detailed onboard measurements.

As the main objective was to generate NOx emission factors, the NOx emission, Engine load, RPM, Speed and Fuel Rate would be the key parameters to be analysed in this case.

Each data sample were gathered as a large data set in a month scale and uploaded to the database, how to extract information from these monthly data sets had the highest priority in data analysing. In this case, clustering data sets into each voyage, detailing each power and RPM range was utilised for further analysing.

3.1 Voyage unit data

Even though the data sets were uploaded month by month, it still recorded and reflected the engine and emission performance in real daily life. Looking into each vessel, it completed assigned working tasks by accomplishing each voyage. Meanwhile, the NOx emission is highly related to the internal combustion of the engine, thus from the engine and emission aspects, the vessels performed repeatedly from the state of “Engine Stand by” to “Finish with Engine” by voyages. Although the measured data under each voyage would vary significantly according to different working and environmental conditions, it was significant to extract the NOx emission condition from analysing the voyage data sets.

The initial filter was utilized to screen out the outliers, when either the RPM or the engine power equals zero. Figures 3.2 and 3.3 show before and after filtration of raw data respectively.

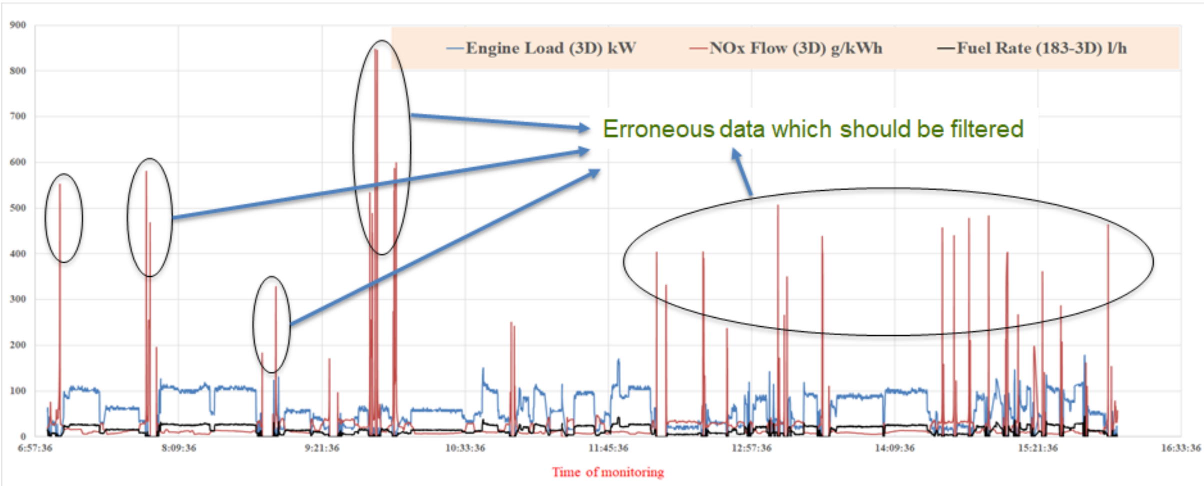


Fig 3.2 Continuous monitoring on ships – Raw data before filtering

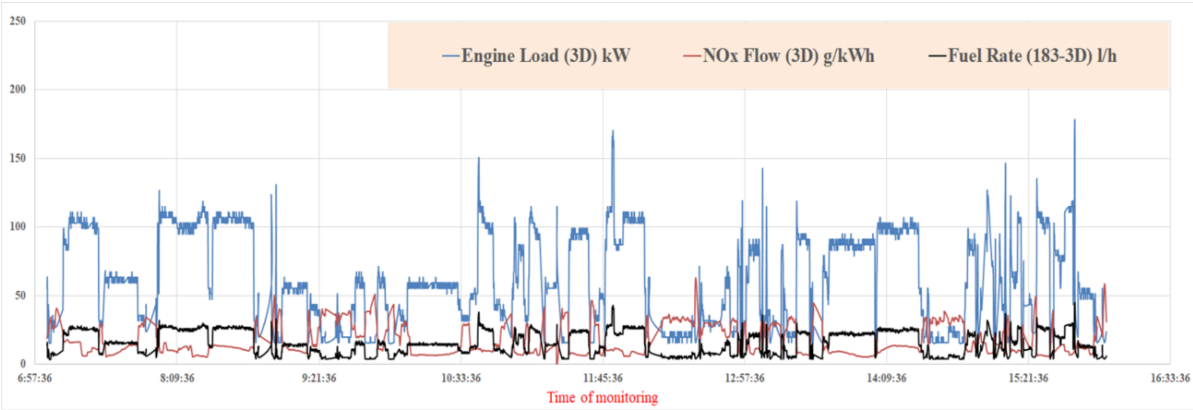


Fig 3.3 Continuous monitoring on ships – Raw data after filtering

After looking into the raw data, eight measurements were selected as the key parameters to be analysed in this case, which were RPM (r/min), Engine load (kW), Speed (km/h), Fuel Rate (l/h), NOx (ppm), NOx Mass Flow (g/h), NOx Flow (g/kWh) and CO_2 emission (kg/h).

As the measurements data would vary significantly according to various conditions, average was more accurate to express the mean or typical value in a set of data when the data sets in each voyage was analysed. The average value of 8 key parameters were calculated based on power range and RPM range for each voyage.

After separating the monthly raw data into voyage, the second process was segregating the voyage data into power range of 25kW and RPM range of 100 r/min. One voyage data set was then separated into various data pools according to these two ranges. The average values of all the measured data within the same range for eight key parameters were calculated. The standard deviations of key parameters were also calculated for each range.

In addition, the distributions, "number and percentage" of data samples in each range, were also calculated to reveal the number of data samples in each range for analysis. Details could be seen in Fig 3.4.

RPM Range		Number of data	Likelihood of the case (%)	RPM 1/min		Engine Load kW		Speed km/h		Fuel Rate l/h		NOx ppm		NOx Mass Flow g/h		NOx Flow g/kWh		CO2 kg/h	
				Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std
1400	1500	4	✖ 0.24	1493.50	4.50	150.55	38.31	4.75	2.28	38.00	9.67	379.50	60.94	662.02	183.12	4.17	0.10	100.32	25.53
1500	1600	1639	✔ 99.76	1528.68	6.04	131.86	104.29	3.53	3.99	33.28	26.32	324.45	118.87	602.13	456.57	4.85	0.98	87.87	69.49

Power Range		Number of data	Likelihood of the case (%)	RPM 1/min		Engine Load kW		Speed km/h		Fuel Rate l/h		NOx ppm		NOx Mass Flow g/h		NOx Flow g/kWh		CO2 kg/h	
				Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std
0	25	6	✖ 0.37	1529.83	1.77	23.77	0.00	2.33	4.76	6.00	0.00	166.17	24.71	213.95	32.65	7.91	1.22	15.84	0.00
25	50	220	! 13.39	1527.70	4.46	35.95	6.49	1.26	2.67	9.07	1.64	210.61	15.22	277.18	25.59	6.49	1.44	23.95	4.33
50	75	372	✔ 22.64	1527.91	4.56	60.49	5.78	1.25	2.38	15.27	1.46	235.96	13.06	317.43	24.37	5.20	0.52	40.31	3.85
75	100	253	✔ 15.40	1528.49	6.30	91.86	7.62	1.37	2.24	23.19	1.92	266.30	20.41	380.89	40.66	4.30	0.34	61.21	5.08
100	125	240	! 14.61	1528.46	6.95	111.48	7.78	2.98	2.71	28.14	1.96	303.03	28.83	460.98	66.45	4.25	0.26	74.28	5.18
125	150	116	! 7.06	1527.72	7.79	133.41	6.94	4.48	2.83	33.67	1.75	346.50	33.64	559.93	85.85	4.29	0.16	88.90	4.62
150	175	58	! 3.53	1530.26	8.30	159.16	5.94	4.64	3.55	40.17	1.50	399.14	41.12	684.80	105.68	4.43	0.17	106.06	3.96
175	200	98	! 5.96	1529.61	6.22	184.43	5.25	6.15	3.35	46.55	1.33	444.13	30.89	812.53	90.76	4.46	0.14	122.89	3.50
200	225	45	! 2.74	1528.69	8.75	210.42	6.32	3.73	2.21	53.11	1.59	463.84	19.77	907.25	84.55	4.32	0.10	140.21	4.21
225	250	32	! 1.95	1532.03	10.11	235.24	7.72	1.63	0.88	59.38	1.95	481.75	17.59	1015.88	87.11	4.33	0.09	156.75	5.14
250	275	9	✖ 0.55	1534.56	17.80	260.61	7.18	3.33	4.11	65.78	1.81	483.00	25.04	1069.69	193.47	4.32	0.12	173.65	4.78
275	300	2	✖ 0.12	1530.50	1.50	295.16	1.98	6.00	1.00	74.50	0.50	501.00	23.00	1072.85	54.59	4.24	0.08	196.68	1.32
300	325	10	✖ 0.61	1522.90	4.44	316.56	5.45	4.50	1.02	79.90	1.37	507.30	12.34	1319.16	42.23	4.21	0.05	210.94	3.63
325	350	1	✖ 0.06	1530.00	0.00	340.72	0.00	6.00	0.00	86.00	0.00	545.00	0.00	1486.34	0.00	4.25	0.00	227.04	0.00
350	375	5	✖ 0.30	1534.80	18.45	366.87	7.76	9.80	4.96	92.60	1.96	551.40	34.49	1643.92	93.15	4.40	0.20	244.46	5.17
375	400	158	! 9.62	1529.95	3.68	384.76	5.37	13.51	2.36	97.11	1.35	579.83	18.71	1771.98	48.97	4.60	0.14	256.38	3.58
400	425	17	! 1.03	1531.47	3.68	405.98	4.53	5.59	1.85	102.47	1.14	533.41	7.96	1661.64	47.06	4.16	0.03	270.52	3.02
425	450	1	✖ 0.06	1532.00	0.00	431.85	0.00	6.00	0.00	109.00	0.00	518.00	0.00	1662.37	0.00	4.14	0.00	287.76	0.00

Fig 3.4 Averages in RPM and Power Range.

3.2 Power and RPM accumulation

The accumulation of all the measured voyages data sets in power and RPM range reflected the real performance of the selected key parameters. The average values and standard deviations in each range for the 8 key parameters, which were RPM (1/min), Engine load (kW), Speed (km/h), Fuel Rate (l/h), NOx (ppm), NOx Mass Flow (g/h), NOx Flow (g/kWh) and CO_2 (kg/h) were calculated.

3.2.1 Power accumulation

The number of data and its likelihood were calculated to evaluate whether the data pool had enough data for analysis. The likelihood of the data pools less than 0.15% was ignored and more than 2% was considered as a good pool, which had enough number of data for analysis.

One example of power accumulation for vessel Amulet is presented in Fig 3.5.

Ship name	Amulet	
Installed power per engine	500	kW
Abatement Technology	Diesel	

NO. of Voyages	Sailing time [hh:mm]	Sailed distance [mile]	Fuel consumption [litre]	NO_x Generation [kg]	CO_2 Generation [tonne]
262					
All voyages	731:47:00	2744.98	45671.4	817.398	120.573
Per voyage (average)	2:47	10.48	174.3	3.120	0.460

Power Range		% MCR		Number of data	Likelihood of the case (%)	RPM 1/min		Speed km/h		Fuel Rate l/h		NOx ppm		NOx Mass Flow g/h		NOx Flow g/kWh		CO2 kg/h	
		Av.	Std			Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std
0	25	0.1	0.4	6371	! 0.97	1505.11	149.34	0.40	1.69	5.72	0.44	25.83	186.57	210.96	53.12	8.34	2.31	15.11	1.17
25	50	7.7	1.2	31421	✓ 4.81	1531.48	23.62	1.12	2.33	9.69	1.51	18.06	236.72	277.06	40.95	6.66	1.18	25.59	4.00
50	75	12.3	1.4	52500	✓ 8.03	1528.94	15.34	1.18	2.38	15.49	1.82	19.78	256.28	312.80	47.19	4.98	0.75	40.89	4.80
75	100	17.9	1.5	41466	✓ 6.34	1527.71	9.04	1.56	2.82	22.65	1.90	23.53	312.76	374.79	57.80	4.27	0.44	59.80	5.03
100	125	22.6	1.4	44209	✓ 6.76	1528.17	7.62	1.31	2.55	28.58	1.74	28.41	364.75	470.96	81.71	4.20	0.42	75.45	4.60
125	150	27.0	1.4	31032	✓ 4.75	1528.02	7.12	1.07	2.48	34.08	1.81	30.11	418.76	595.12	93.94	4.43	0.47	89.96	4.77
150	175	32.1	1.4	25475	✓ 3.90	1525.46	8.48	1.59	3.12	40.53	1.79	28.45	448.37	730.31	107.67	4.56	0.45	107.00	4.72
175	200	37.6	1.5	21056	✓ 3.22	1526.06	15.31	2.62	4.04	47.44	1.84	27.04	474.61	831.10	104.76	4.46	0.36	125.25	4.85
200	225	42.5	1.3	23253	✓ 3.56	1524.73	8.37	3.56	4.73	53.59	1.69	24.98	510.46	956.82	131.14	4.53	0.46	141.47	4.46
225	250	47.8	1.7	33225	✓ 5.08	1524.18	8.34	5.42	5.89	60.32	2.11	17.15	529.09	1117.17	123.73	4.68	0.44	159.23	5.58
250	275	52.6	1.5	17387	✓ 2.66	1523.98	9.29	4.82	5.63	66.33	1.95	18.59	528.90	1217.56	142.79	4.65	0.46	175.10	5.15
275	300	57.8	1.4	28236	✓ 4.32	1522.90	11.72	8.71	6.20	72.98	1.82	15.68	529.30	1273.65	228.15	4.41	0.77	192.68	4.81
300	325	62.4	1.5	60024	✓ 9.18	1526.12	6.89	11.61	5.39	78.79	1.89	16.19	534.35	1352.58	291.91	4.34	0.93	208.00	4.99
325	350	68.2	1.4	25555	✓ 3.91	1526.86	6.12	11.30	4.98	86.02	1.74	16.33	566.93	1560.69	233.29	4.57	0.65	227.08	4.59
350	375	72.9	1.5	46500	✓ 7.11	1524.47	8.29	9.54	6.18	91.98	1.86	16.06	600.61	1709.52	151.04	4.69	0.39	242.83	4.92
375	400	77.5	1.4	83304	✓ 12.74	1527.04	5.98	12.69	4.73	97.76	1.83	17.59	583.60	1778.05	128.47	4.59	0.35	258.08	4.82
400	425	81.8	1.6	68310	✓ 10.45	1527.28	6.12	13.43	4.48	103.23	1.96	20.94	569.26	1793.68	142.99	4.39	0.33	272.53	5.17
425	450	87.5	1.1	12923	! 1.98	1526.93	7.49	14.13	4.64	110.39	1.33	21.37	587.88	1892.72	147.85	4.35	0.33	291.43	3.52
450	475	91.2	1.1	1398	! 0.21	1524.98	10.98	11.89	6.24	115.13	1.38	14.63	443.84	2024.43	179.25	4.46	0.32	303.94	3.65
475	500			48	✗ 0.01														
500	525			0	✗ 0.00														
525	550			2	✗ 0.00														

Fig 3.5 Power accumulation of vessel Amulet

In Fig 3.5, the average value of Engine Load (kW) was transferred into percentage of MCR (Maximum Continuous Rated power). This was a better way to construct the relationship between the NOx emissions and the engine load. The averages of measured Engine Load (kW) for different vessels varied significantly under a scale of their MCR, from 0 to their maximum rated power, which was difficult to evaluate their NOx emissions as they had different MCR. Percentage MCR was more stable as it varied between 0% to 100% MCR for all the vessels. As the main objective was to generate NOx emission factors, the NOx Flow (g/kWh) was selected to develop the generic emission factor formula. Figure 3.6 shows the averaged emitted NOx (g/kWh) against %MCR for each power range for vessel Amulet. The vertical error bar showed the standard deviation of each average NOx Flow.

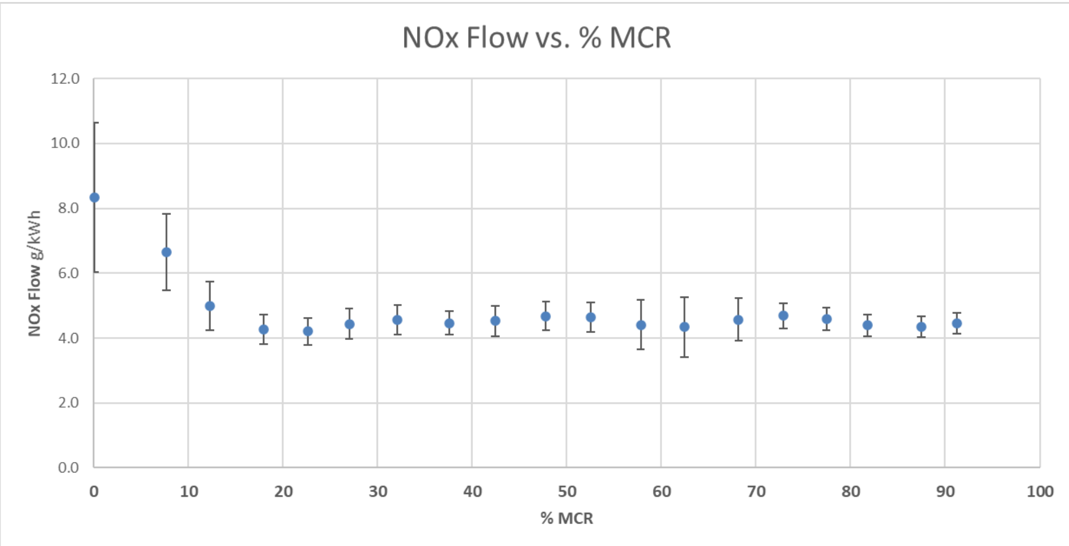


Fig 3.6 Scatter of NOx Flow and % MCR for vessel Amulet

From the generated graph for the CLINSH vessels, relating NOx to % MCR, a power curve in the form of $NOx\ emission = m(\%MCR)^n$ was chosen to generate the best fit curve. Further analysis will determine "m & n" for each vessel based on the engine type and technology used to give the specific emission factor for NOx.

The Journey information were also accumulated which would be benefit for further research in operational performance. It provides the sum and the average per voyages of Voyage time, Distance travelled (mile), Fuel consumption (litre), NOx generation (kg) and CO_2 (tonne) as shown in Figure 3.7.

3.2.2 RPM accumulation

The difference between RPM and Power accumulation was the criteria of the likelihood of data range pool. The likelihood of RPM range below 0.5% was ignored in calculation as it did not have enough data for analysis and above 10% was considered as a good data range pool for analysis. Figure 3.7 shows the RPM accumulation of vessel Amulet.

Liklihood below	0.5	% is not considered in calculation because it does not have enough number of data in.
Liklihood above	10	% is considered in calculation as a good case with well enough numbers of data

RPM Range		Number of data	Likelihood of the case (%)	RPM 1/min		Engine Load kW		Speed km/h		Fuel Rate l/h		NOx ppm		NOx Mass Flow g/h		NOx Flow g/kWh		CO2 kg/h	
				Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std	Av.	Std
0	100	3	✗ 0.00																
100	200	8	✗ 0.00																
200	300	12	✗ 0.00																
300	400	8	✗ 0.00																
400	500	22	✗ 0.00																
500	600	26	✗ 0.00																
600	700	39	✗ 0.01																
700	800	32	✗ 0.00																
800	900	33	✗ 0.01																
900	1000	23	✗ 0.00																
1000	1100	23	✗ 0.00																
1100	1200	18	✗ 0.00																
1200	1300	11	✗ 0.00																
1300	1400	8	✗ 0.00																
1400	1500	5999	! 0.92	1491.79	5.49	285.67	63.88	0.14	0.86	72.11	16.12	580.34	77.79	1437.20	315.19	5.02	0.56	190.36	42.57
1500	1600	647430	✓ 99.04	1527.16	7.12	247.65	131.06	7.02	6.02	62.51	33.08	461.56	148.79	1118.05	599.55	4.65	0.88	165.02	87.33
1600	1700	2	✗ 0.00																
1700	1800	0	✗ 0.00																
1800	1900	0	✗ 0.00																
1900	2000	0	✗ 0.00																

Fig 3.7 RPM accumulation of vessel Amulet

The data samples were concentrated in 1500-1600 rpm range, this was because the main engine of vessel Amulet was running under a E2 cycle, in a constant speed.

Since there was not variety in RPM, for the generic NOx emission factor % MCR was used.

3.3 Regression of NOx emission factors

UNEW developed an optimisation Solver in Excel, which then was utilised to generate the NOx emission factors, "m & n". Solver is a Microsoft Excel add-in program which is used to analyse what-if questions.

In this case, the changing values were emission factors “m & n”, the objective cell was a set value “P”, which meant utilising Solver to find the maximum value of P by changing the cells, “m & n”. If the set value P reached the maximum, the related “m & n” were the NOx emission factors of this calculated vessel.

Set value: $P = \frac{A}{|B| * C}$

A: Percentage of the measured NOx Flow (g/kWh) within the scale of estimated value ± standard deviation of the residue.

B: The average of the residue of the average value in the accumulation power range.

C: The residual standard deviation.

The maximum value of P could be obtained when “A” value is high, meaning the maximum coverage of all data within standard deviation is achieved and/or B*C is minimum, which means the deviation from average is minimum.

“A & C” were calculated by considering all the observed NOx Flow (g/kWh) measurements for each data sample.

The measured Engine Power (kW) and its related NOx Flow were taken into consideration. Each Engine Power (kW) measurements was transferred into percentage of MCR by dividing the rated engine power of the vessel, and the related NOx Flow (g/kWh) measurements were treated as the observed values of the NOx emissions. By setting the initial emission factors “m & n”, the predicted NOx emission for each data point was calculated through the formula, $NOx\ emission = m(\%MCR)^n$, which was treated as predicted value. The residue equalled the difference between the predicted and observed values. And the standard deviation of this residue was the value of “C”.

$$C = Standard\ deviation\ (Predicted\ NOx\ emission - Observed\ NOx\ emisson)$$

This residual standard deviation “C” calculated how much the data points spread around the regression line. The less the value of “C”, the observed data points were more concentrated around the regression line, meaning the regression was more accurate.

In addition, the observed value of measured NOx Flow (g/kWh) was checked whether within the range of residual standard deviation. The scale of the range was the predicted NOx emission (g/kWh) ± “C” calculating from the related observed “% MCR”. The number of data points within the range of residual standard deviation was collected and divided by the overall observed data samples was the percentage of the data within “C”, which was the value of “A”. The higher the value of “A”, the more percentage of observed data were coped with the range of residual standard deviation, which meant the regression line were more reasonable.

$$A = \frac{Number\ of\ Observed\ NOx\ within\ (Predicted\ NOx\ \pm "C")}{Number\ of\ overall\ data\ points}$$

In NOx emission regression, “A & C” had the different optimization directions. The optimization of “A” was higher, the regression can cope with more percentage of the observed data points, and the “C” was lower, the observed data spread more concentratedly around the regression line. From the formula of “A”, one better way was to optimize NOx emission factors “m & n” to make the predicted NOx emission more accurate to the observed value. Thus, “B” was proposed to accurate the predicted NOx emission.

$$B = Average\ of\ residual\ standard\ deviation$$

The dots in Figure 3.6 is the power accumulation averages, however, the regression only considered the averages between 5 to 100% MCR, as the NOx emissions varied significantly under 5% MCR.

B represented the average distance between each power accumulation NOx average dot to the regressed fit curve. To maximize objective value P, B was optimized to be infinitely close to zero. The regressed fit curve went through the centre of the red dots, in other words, the total regressed NOx emissions under the measured %MCR equals to the measured emissions. The sum of the regressed NOx emissions calculating from the accumulation %MCR was infinitely close to the sum of accumulation NOx Flow. This was a key criterion to evaluate the accuracy of the regressed emission factors.

In addition, some constrains were added in the calculation. The scale of emission factor “m” displaced between 0.01 to 100, and for “n”, -0.99 to -0.01. For value B, the constrains was between -0.1 to 0.1. Figures 3.8 & 3.9 present the details in calculation and the results of vessel Amulet.

Objective Cell (Max)

Cell	Name	Original Value	Final Value
P2	Value: P	335.6815737	60528102.91

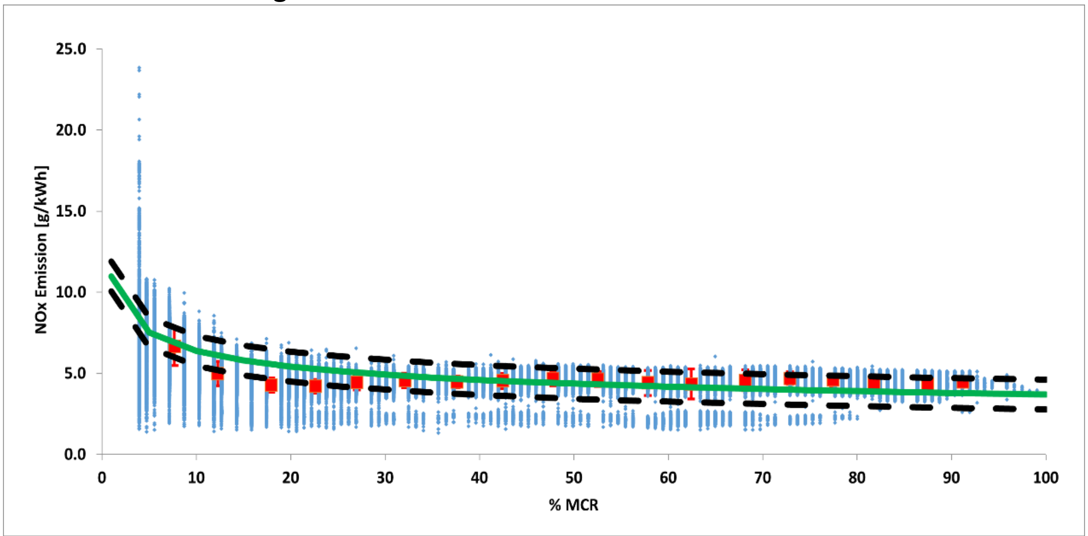
Variable Cells

Cell	Name	Original Value	Final Value	Integer
I1	Emission factor: m	10.16	10.97	Contin
I2	Emission factor: n	-0.20	-0.24	Contin

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
N2	Average of Red residue	0.0000	N2<=0.1	Not Binding	0.099998749
N2	Average of Red residue	0.0000	N2>=-0.1	Not Binding	0.1000
I1	Emission factor: m	10.97	I1<=100	Not Binding	89.02529187
I1	Emission factor: m	10.97	I1>=0.01	Not Binding	10.96
I2	Emission factor: n	-0.24	I2<=-0.01	Not Binding	0.226109512
I2	Emission factor: n	-0.24	I2>=-0.99	Not Binding	0.75

Fig 3.8 Details in Calculation of vessel Amulet



Trend as NOx=a(MCR)^b	a (var.)	10.97	RESULT	total NO. of data	NO. of data in band ±S	% data placed in ±S	Average of Red residue	S: StDev of residue	Value: P
	b (var.)	-0.24		639128	445741	70	0.0000	0.92	60528102.91

Fig 3.9 Regression of NOx emission factors of vessel Amulet

In Fig 3.9, the green line was the regressed fit curve which represented the emission factors. The blue dots were the measured data points, the number of them was 639,128. The residual standard deviation was 0.92 showing as the black broken lines in the figure. Value A was 70%, 445,741 observed data points placed within the band of Residual standard deviation, between the upper and lower black broken lines. The average of residual standard deviation was zero, which meant the average distance between each dot to the green fit curve equalled to zero. The objective value P reached to its maximum value.

The detailed NOx emission factors for all the vessels in each engine classification could be checked in Table 3.1 – Table 3.4.

Table 3.1 NOx emission factors for CCNR0 vessels

Vessel	Technology	M	N	Classification
Leidsegracht	SCR-DPF	11.62	-0.17	CCNR0
	Diesel	12.61	-0.12	
Mon Desir	GTL	21.5	-0.32	CCNR0
Melvin	GTL	22.52	-0.13	CCNR0
	ChangeTL	19.82	-0.08	
Ora_etLabora	GTL	6.79	-0.01	CCNR0
Watna	GTL	29.1	-0.32	CCNR0
Factotum	SCR	21.94	-0.55	CCNR0
Salute	SCR	25.57	-0.49	CCNR0
Triton	Diesel	31.47	-0.24	CCNR0
La Coruna	Diesel	21.42	-0.01	CCNR0
Sulmaro	Diesel	35.8	-0.31	CCNR0
	FWE+GTL	16.19	-0.21	
	FWE	25.82	-0.21	
Endeavour	FWE	18.74	-0.09	CCNR0
	Diesel	30.67	-0.16	
Cornelis Sr	FWE	30.94	-0.36	CCNR0
	Diesel	16.64	-0.11	
Westropa	Biodiesel	22.65	-0.35	CCNR0
	Diesel	22.91	-0.35	

Table 3.2 NOx emission factors for CCNR1 vessels

Vessel	Technology	M	N	Classification
RyGo	Diesel	16.02	-0.20	CCNR1
	SCR-DPF	9.45	-0.39	
Philipskercke	SCR-DPF	28.45	-0.52	CCNR1
Seba	SCR-DPF	9.50	-0.35	CCNR1
Mejana	Diesel	12.01	-0.37	CCNR1
	SCR-DPF	5.04	-0.19	
Vantage	GTL	10.23	-0.18	CCNR1
	Diesel	17.36	-0.26	
Keraanvogel	Diesel	24.44	-0.17	CCNR1
Invontes	Diesel	29.19	-0.32	CCNR1
	FWE	38.32	-0.41	
Lotus	Diesel	44.41	-0.43	CCNR1
Deja	Diesel	54.12	-0.35	CCNR1

Table 3.3 NOx emission factors for CCNR2 vessels

Vessel	Technology	M	N	Classification
Vera Pax	SCR-DPF	23.93	-0.35	CCNR2
Maranta	SCR-DPF	10.44	-0.45	CCNR2
Amulet	Diesel	10.97	-0.24	CCNR2
	SCR-DPF	4.48	-0.10	
MS Xander	SCR-DPF	4.12	-0.26	CCNR2
	Diesel	9.74	-0.16	
Osar	GTL	9.17	-0.08	CCNR2
MS Delta	SCR	15.04	-0.15	CCNR2
Comienzo	SCR	8.71	-0.15	CCNR2
Tharsis	Diesel-electric	9.77	-0.17	CCNR2
Keraanvogel	Diesel-electric	7.78	-0.06	CCNR2
Poolster	Diesel-electric	7.14	-0.06	CCNR2
Copenhagen	Diesel-electric	13.05	-0.25	CCNR2
Essex	Diesel-electric + SCRDPF	14.09	-0.29	CCNR2
Deseo	Diesel	13.15	-0.24	CCNR2
	Diesel-hydrogen Injection	20.73	-0.31	
Heerenschip	Diesel	12.34	-0.08	CCNR2
Ecotanker II	LNG	46.10	-0.36	CCNR2
Ecotanker III	LNG	40.69	-0.55	CCNR2

Table 4.4 NOx emission factors for EURO VI vessels

Vessel	Technology	M	N	Classification
Liane	Euro VI	3.76	-0.35	Euro VI
La Coruna	Euro VI	0.80	-0.41	Euro VI

4 Averaged NOx emission factors for the CLINSH fleet

After regressed NOx emission factors for all the measured vessels under different conditions, the emission factors for the CLINSH fleet were calculated as the averages of the regressed emission factors in the same group. The detailed results could be found in Table 4.1.

Table 4.1 Averaged NOx emission factors

Technology	CCNR0		CCNR1		CCNR2		Euro VI	
	m	n	m	n	m	n	m	n
Biodiesel	22.65	-0.35						
Change TL	19.82	-0.08						
Diesel	24.50	-0.19	28.22	-0.30	11.55	-0.18		
Diesel-electric					9.44	-0.13		
Diesel-electric + SCRDPF					14.09	-0.29		
Diesel-hydrogen Injection					20.73	-0.31		
Euro VI							2.28	-0.38
FWE	25.17	-0.22	38.32	-0.41				
FWE+GTL	16.19	-0.21						
GTL	19.98	-0.19	10.23	-0.18	9.17	-0.08		
LNG					43.39	-0.46		
SCR	23.76	-0.52			11.88	-0.15		
SCR-DPF	11.62	-0.17	13.11	-0.36	10.74	-0.29		

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