ASSESSMENT OF SHIP'S ENGINE EFFECTIVE POWER FUEL CONSUMPTION AND EMISSION USING THE VESSEL SPEED

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Abstract

Currently, the Baltic Sea States suggests a proposal to designate the Baltic Sea as an Emission Control Area for nitrogen oxides, in accordance with Annex VI of MARPOL73/78. The emission would be estimated on the data produced by the AIS (Automatic Identification System) system that is compulsory for ships. Therefore, exhaust emission of the ships' can be computed using the actual speed and main propulsion shaft power. Mostly, main propulsion engines' exhaust emission is dependent to realistic performance and can be determined. The research plan has been prepared, aimed an evaluating the main propulsion engine performance and emissions. In cooperation with the ship owner, the experimental program onboard the container vessel, equipped with latest large bore, two-stroke, and slow speed MAN B&W electronic controlled engine was carried out. The records set of vessel speed and related engine shaft power, fuel consumption and exhaust emission for container vessel is formed. Taking into account; main engine performance, types of fuel and other input data, the emission factors were determined for ship sea service state. Main engine shaft power estimation and measurement setup, examples of main engine shaft power, the shaft power equation coefficients density, example of main engine service operation, fuel oil consumption group, the ship speed estimated form, example of main engine area operation influenced by weather conditions are presented in the paper.

Keywords**:** *ships, main propulsion, marine diesel engine, exhaust emission*

1. Introduction

The fundamental requirement of a ships' main propulsion engine is to meet the torque requirements and it must do within the constraints appropriate to the application. Universally, the ship propulsor is a screw propeller; therefore torque characteristic of the engine must coordinate with that of a propeller. This implies that torque–revolutions propeller characteristic determines the acceptability of the torque–revolutions characteristic of the engine and this conveys equivalent of delivered power. Power–revolutions relation is used in the subsequent paper discussion. Since the engine developed power exceeds the required propeller power at given revolutions, the engine is able to accelerate the propeller to the rated condition. The set of propeller curves indicate a range within the characteristic of a particular propeller may fall. The change from one curve to another occurs because of a change in CPP propeller pitch, or if the FP propeller is used, within the class of the vessel resistance characteristic [1]. The usual shift of propeller curve to the left (increase in pitch or increase in resistance) is compensated with shift upward of the engine load. In some cases it may not be possible without overloading the engine [2, 4, 5]. The load profile in marine propulsion system depends on the type and service of the ship. A dominated profile is characterized by long periods of continuous engine operation at service engine rating, with occasional periods of low power operation. This is representative commercial ship service in long trade routes. The main propulsion engine is expected to run without the interruption for about 500-600 hrs [3]. Best efficiency resulting in low fuel consumption is likely desired.

2. The shipmain propulsion performance and data

Many variables affect the performance of a ship's propulsion at sea, so the acceptance sea trial gives practical basis to create a propulsion specification. The margin between the sea trial trip power and sea service requirements of speed and loading must ensure that the main propulsion engine has sufficient capacity. However, the ship trials results represent uncertainties due to uncontrollable environmental conditions in addition to the measurement errors [6]. Speed trials are conducted at the end of ship construction usually at a limited time scale. It is rarely possible to conduct the trials at contract conditions. Therefore, measured ship speed and shaft power must be corrected for the differences between trial conditions and the contract conditions. Hence, ship trials have uncertainties mainly due to following sources:

- trial measurements: engine torque and shaft revolutions, and ship speed,
- trial analysis: necessary corrections applied to trial results.

Important parameters for a marine main diesel engine are the rating figures, usually stated as: continuous service rating (CSR) and maximum continuous rating (MCR). The rating which is commonly concerns is the maximum output at which the engine will operate continuously to maintain the desired ship service speed - fully loaded. Basically, ship operators insist that the main engines be capable of maintaining such speed, developed at approximately 80% of rated brake power. Normally a ship will run sea trials to meet the contract trial ship speed and the engine continuous service rating should be applied when the vessel is in service. For each type of engine, there is a maximum power limit outside which the engine should not be run continuously. An option available to reduce the fuel consumption of diesel engines is so called economy ratings. This means operation of an engine at standard maximum cylinder pressure for continuous service rating, but at lower mean effective pressure and shaft speed. This can be achieved by altering the fuel injection timing. The similar effect for NO_x emission is used and lower emission level is available. Controls to limit exhaust gas emissions which is tightening nationally, regionally and globally led to complicated engine system control optimization, readily available for latest electronically controlled engine.

3. Experimental program details and methodology

The experimental plan, aimed an evaluating the ships' main propulsion engine performance. In cooperation with the ship operator, sea service trials carried out on board the container vessel driven, by a large bore and slow speed diesel engine (see Tab. 1).

Tab. 1. The vessel and main engine specifications

Vessel		Container carrier	
Length - LOA		m	180
Breadth - BOA		m	28
Deadweight		T	22300
Main propulsion		Direct, fixed pitch propeller	
Engine		MAN B&W 6L70ME-C	
MCR	Power	kW	16980
	Speed	r/min	98.3
Bore		mm	700
Stroke		mm	2360
IMO NO_x (economy)		g/kWh	15.22
IMO NO_x (low emission)		g/kWh	12.35

There are some uncertainties related to engine performance during the service operation, and emission factors as well. The combination of internal engine measures, such as: retard injection, higher compression ratio, increased turbo efficiency, common rail injection, higher cylinder pressure and low intake temperature were used in main engine to lower NO_x emission. The experimental results research will involve an analysis of individual main propulsion engine performance in order to investigate feasible measures of emission reduction, taking into account ship speed and related aspects. During the sea trial several important characteristics were investigated, supported by the main engine rotational speed and torque, which has been measured – $P_{eff.measur}$ (propeller shaft) in order to obtain realistic engine developed power - P_{eff}, in accordance to the ISO 3046 standard (see Fig. 1).

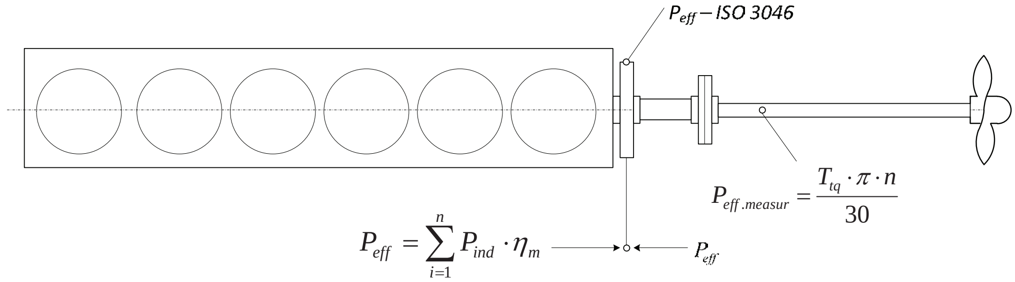

Fig. 1. Main engine shaft power estimation

Engine effective (developed) power (P_{eff}) estimation was attained through two alternative methods:
1. Speed and torque measurement – using the propulsion shaft arrangement,
2. Engine mean indicated pressure measurement – using the in cylinder pressure transducer.

The first solution is efficient and accurate when power prediction is made for direct propulsion unit engines. Otherwise, where non-direct propulsion unit is present (i.e. gearbox is installed) the power estimation accuracy based on the torque measurement is insufficient and additional power measurement is advised – the second method.

3.1. Main propulsion shaft torque and speed measurement

The propulsion shaft torque measurement telemetry system, presented in Fig. 2, with specification given in Tab. 2, offers wireless transmission of strain gauge signals from rotating shafts. Strain gauge sensor (>350 Ohm) in full bridge configuration is directly connected to a radio transmitter allowing transfer of data. The encoder is mounted on the rotating shaft. The data transfer between transmitter and receiver is digital. The transmitter provides a pulse code modulated signal (PCM) to an induction winding around the shaft. The magnetic field of this winding enables the inductive transmission of the signal from the coil to the pickup probe. From there the signal is transferred to the receiver. The receiver unit offers analog and digital outputs for PCM interface.

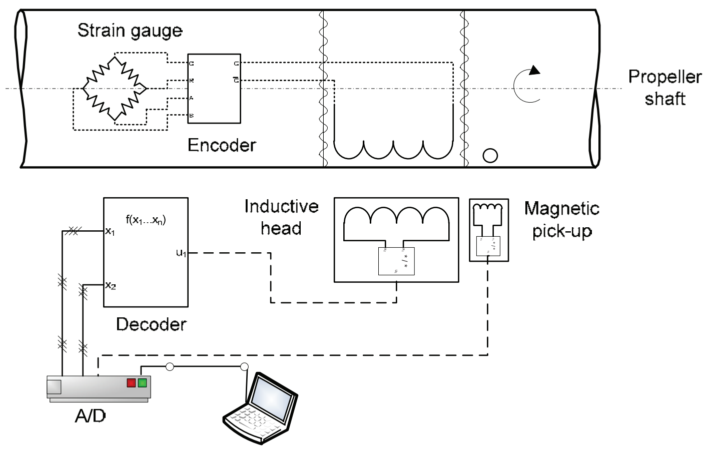

Fig. 2. The main engine shaft power measurement setup

Shaft speed measurement is made with magnetic sensor, built in combined inductive head and a frequency-voltage converter. The number of pulses are counted for a predetermined time and divided into number pulses per revolution to find shaft rate of revolution.

Tab. 2. Shaft power measurement setup characteristic

	Component	Specification
1	Strain gauge	350 Ω
2	Encoder	7.5kHz/12bit
3	Decoder	Analog output: ±10V Digital output: PCM IF16

The recorded average torque and shaft speed data are used for engine effective power estimation in accordance to the formula:

$$P_{eff.measur} = \frac{T_{tq} \cdot \pi \cdot n}{30} \text{ [kW]}, \tag{1}$$

where:
T_{tq} - mean measured torque [kNm],
n - mean engine-propeller rotational speed [rpm].

3.2. Engine Mean Indicating Pressure

In order to simplify the engine data acquisition process the ship's genuine pre-installed PMI cylinder combustion pressure system was employed and the related description is presented in Tab. 3. The electronic MIP calculator with TDC (Top Dead Centre) sensor enables cylinder direct combustion pressure measurement. With the TDC sensor connected, the course of pressure with relation to the crank shaft angle is measured thus enabling calculation of indicated power and extensive combustion analysis. Analysis software allows the computation of power for each engine cylinder.

Tab. 3. MIP electronic indicator specification

Type	Maker	Measured parameter	Range
Off Line PMI System	MAN B&W Diesel	Combustion pressure	1-200 bar

Additionally, to increase power output estimation precision engine effective power is estimated through a sum of individual cylinder indicated power in accordance to formula:

$$P_{eff} = \sum_{i=1}^{n} P_{ind} \cdot \eta_m , \tag{2}$$

where:
P_{ind} - engine cylinder indicated power [kW],
η_m - engine mechanical efficiency [-].

3.3. Fuel consumption estimation

The volumetric method of fuel consumption measurement was employed for fuel mass flow estimation according to the formula:

$$B = \frac{V_p \cdot \rho_p}{t} , \tag{3}$$

where:
B - fuel mass flow [kg/s],
V_p - fuel volume consumed during the measurement time [m^3],
ρ_p - fuel gravity in measurement condition [kg/m^3],
t - time of measurement [s].

For the purpose of fuel mass flow estimation the engine fuel oil system standard instruments was used - main engine fuel oil flow meter equipped with temperature gauge. Fuel oil analysis receipt will be utilized as the source of fuel oil basic data for further calculations. The fuel oil gravity temperature correction factor will be calculated accordingly. The specific fuel oil consumption of main engines calculated, based on the formula:

$$b = \frac{B}{P_{eff}}, \tag{4}$$

where:
b - specific fuel consumption [kg/kW·h],
B - fuel mass flow [kg/hr],
P_{eff} - engine effective power [kW].

Recalculation for standard ISO condition will be provided according with the accepted standards.

4. Results an discussion

When considering emissions caused by shipping a differentiation must be made between a ship at move as the emissions depend on the main engine operational state. The type and amount of pollutants emitted depend directly on the engine management system, technical condition of the engines and the fuel used. The experimental data set which contains over 130sea service trials records, in different weather conditions and vessel loads were analyzed. Subsequently, a subset of 20 records for diverse weather conditions was chosen for further investigation. The characteristic subsets signify main propulsion data recorded during the relatively short vessel ocean voyage period (usually two or three days) under stable weather condition and vessel load. Extracted record sets of main engine load are shown in scatter plot form – Fig. 3.

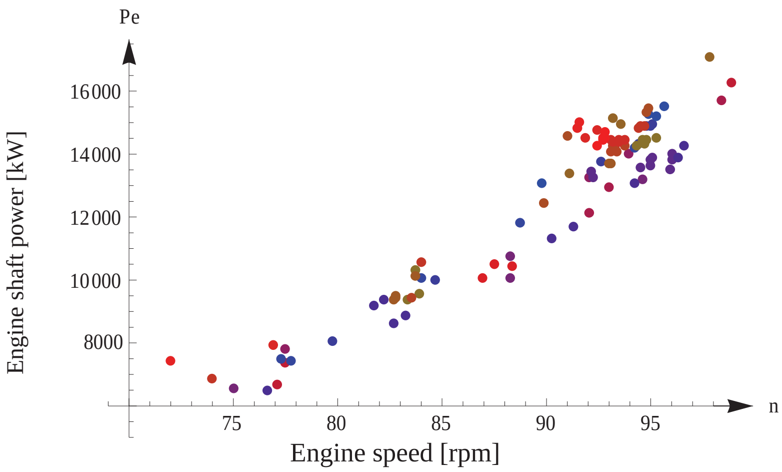

Fig. 3. Examples of main engine shaft power in different conditions

Each analyzed engine and vessel record is provided with several engine power, caused by vessel speed control system, In response, combined effect of engine speed and shaft power achieved. Assuming a functional dependence of the propulsion system shaft power and vessel speed using the formula:

$$P_{eff}(n) = a_1(wc, V, sr) \cdot n^{b_1(sr,wc,V)}, \tag{5}$$

where:

P_s - main propulsion system shaft power,

a - coefficient dependent to: weather conditions (*wc*), vessel speed (*V*) and ship resistance (*sr*),

b - coefficient dependent to ship resistance, weather conditions and vessel speed.

If vessel is driven by means of direct propulsion system and fixed pitch propeller, then the main engine effective power could be expressed as follows:

$$P_{eff}(n) = a_1(wc, V, sr) \cdot n^{b_1(sr,wc,V)}. \tag{6}$$

Effectively, the extracted and arranged data sets fitted with power function, using the method of least squares. The result effects in twenty type functions class. Two of them discarded as clearly diverged from the others and they were not taken into account. The remaining 18 functions are characterized by coefficients; a_1 ranged from 0.000844 to 1.966 and coefficients b_1 in range 1.91 to 3.667.The average value of a_1 coefficient is 0.175within 95% confidence interval which is (-0.0737236, 0.424136) for all 18 sets. As the two sets and their coefficients have come off to far from average level they were removed. Alternatively, the average value of a_1 is 0.0137 within 95% confidence interval which is (0.00416403, 0.0232059) for the 16 sets, after eliminating two outliers. The average value of coefficient b_1 is 3.058 within 95% confidence interval which is (2.83232, 3.28394) for all 18 sets and for 16 sets the average value of b_1 is 3.188 within 95% confidence interval which is (3.0467, 3.32931). Consequently, two of them were removed as they were clearly outliers. The histogram of the prevalence factors value a_1 and b_1 shows Fig. 4.

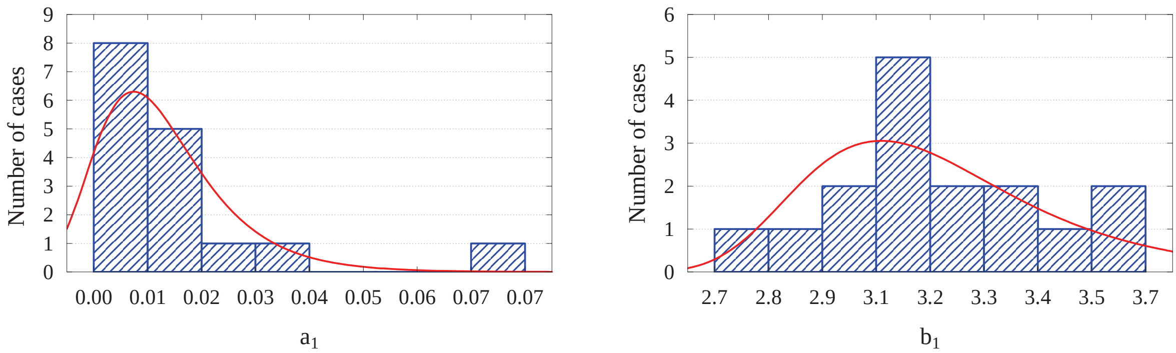

Fig. 4. The shaft power equation coefficients density

The determined set of a_1 and b_1 coefficients was used for main propulsion service area designation and comparison with nominal engine performance that was made during the acceptance shop trial and acceptance sea trial, after the ship construction completion. The applicable real-valued functions comparison is presented in Fig. 5.

Mostly, propulsion service operation area was denoted by established sets of characteristics which fall between the curve of ship sea trial – light condition and the engine nominal curve. However, some service operation cases go beyond the nominal curve, hence presented an engine light overload. The average ship and propulsion characteristic defined by a_1– 0.0113 and b_1– 3.0996 coefficients, fall between the curve for sea trials, and the nominal curve. At this stage it was not to conclusively determine the average curve of ship propulsion load. More important was designating the entire range of a service operation area, expressed by coefficients a_1 and b_1 matrix. An additional aspect of the main propulsion performance operational testing was determined by fuel oil consumption.

In contrast to engine effective power measurements the mass fuel oil consumption was estimated through the daily engine system readings. Due to the technical circumstances estimated fuel oil consumption readings were not exactly synchronized in time with the actual engine loads, but were based on fixed time intervals (12hours -a property of the system).The analyzed data set (shown in Fig. 6) comprises over600 cases, which were used to designate the averaged interrelation of fuel oil consumption for the typical voyage condition of the ship.

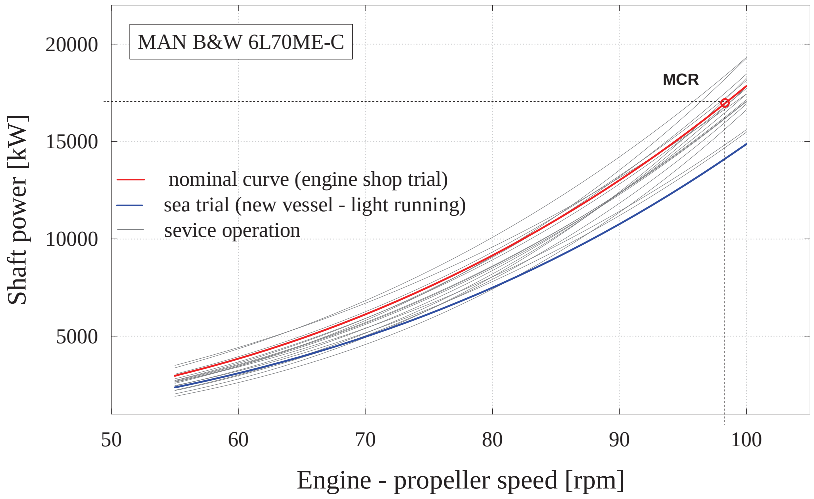

Fig. 5. Example of main engine service operation influenced by weather conditions

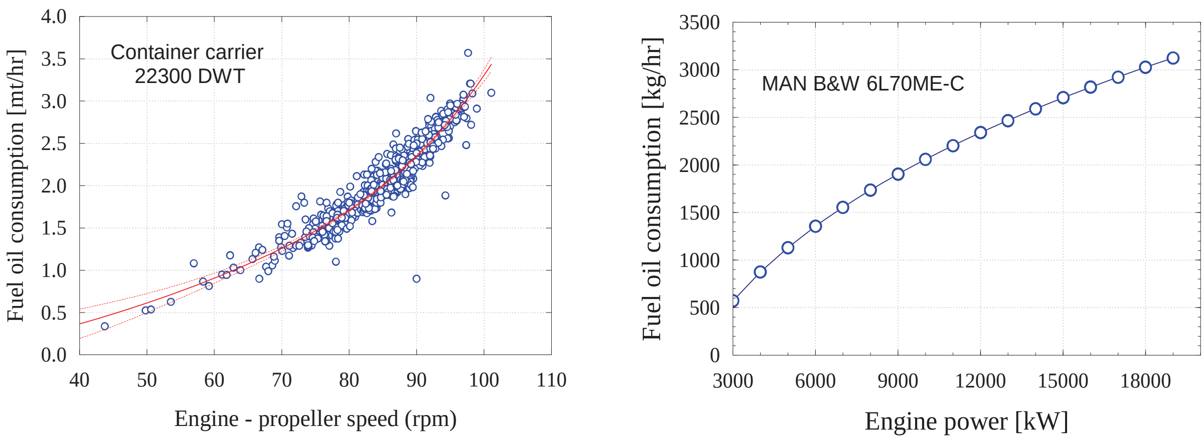

Fig. 6. Fuel oil consumption group and averaged curve for propulsion unit in moderate weather conditions

When dealing with ships, there are several different speeds to consider. They are interconnected together with the apparent and real slip. The measured ship's speed will contain a component of the tidal and current effects. This component will change with time and so will be different for each sea passage. Some method must be used to separate these effects and so obtain the true speed of the ship. During the sea passage a certain amount of data are measured and recorded, namely: speed of the ship over the ground, log of the ship (speed relative to the water), propeller - engine rotating speed and shaft power, corresponding to these speeds, wind force and direction, tide speed, condition of the sea, water depth and water density. Comparison of both type of ship's speeds estimation is shown in Fig. 7.

5. Conclusions

The implemented sea trial program, performed during the normal service ship operation in various weather and ship’s load conditions and different climatic zones allowed to collect representative set of main propulsion system performance data. As assumed, the new vessel that is characterized by a satisfactory hull state is able to achieve contractual speed, while maintaining the structurally established engine load and associated important performance factors, which demonstrates Fig. 8.

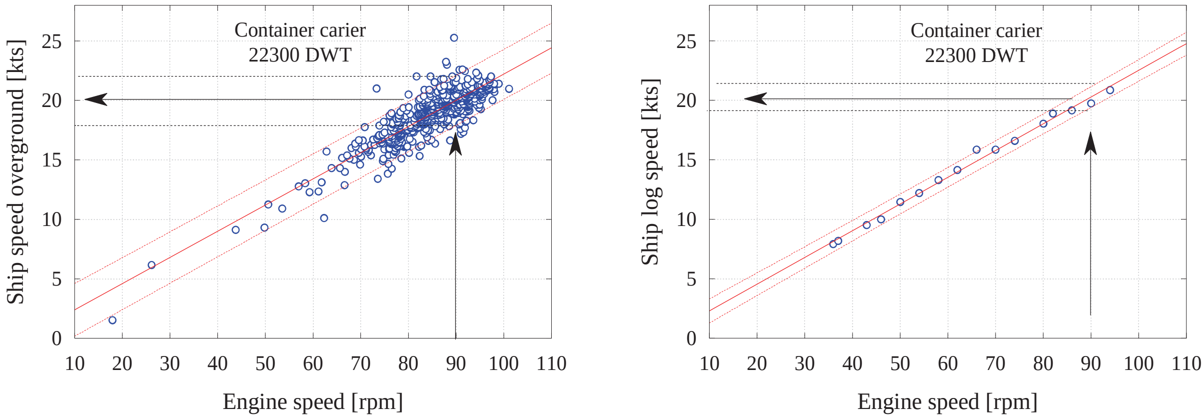

Fig. 7. The ship speed estimated form measured engine – propeller rotational speed

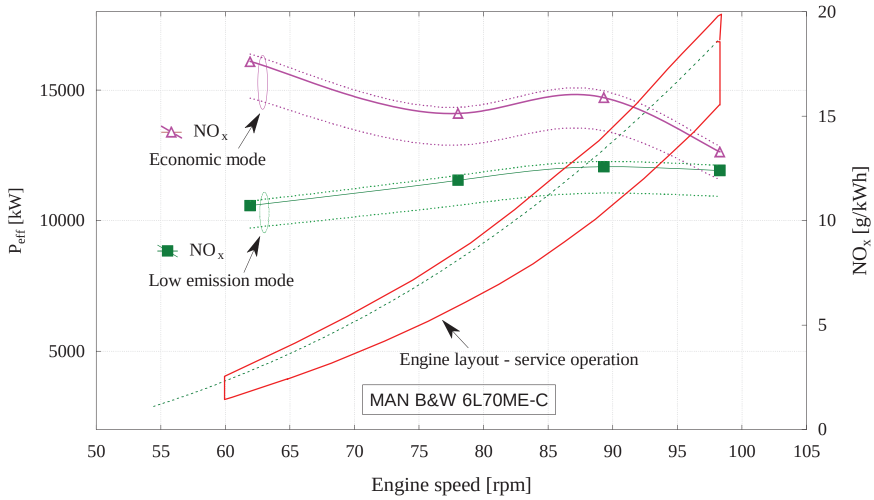

Fig. 8. Example of main engine area operation influenced by weather conditions

The weather condition influence can significantly alter the power demand in the main propulsion system. Thus, exhaust emission will follow these demands in both modes of engine operation, economic and low emission, accordingly. The main engine performance estimation possibility, based on observed ship speed is not equally accurate, if different methods are engaged. Remarkably, engine - propeller rotational speed evaluation using the ship's over ground speed encounters ~20%error. By contrast, when estimation is based on a ship log speed - relative to the water, this error is ~8%. Therefore, determined main engine load conditions will affect the prediction of fuel consumption and emissions as well. There is a need to enhance the quality of estimating the propeller speed of the ship propulsion system by introducing the weather effect.

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