Proceedings
ISBN 978–952-5183-54-2

Kai Zenger* and Nguyen Khac Hoang

Optimal control maps for fuel efficiency and emissions reduction in maritime diesel engines

Abstract: The paper introduces an advanced modelling method and optimisation algorithm, by which ship diesel engines control parameters can be effectively designed. The fuel consumtion is minimised while at the same time fulfilling the NO_x emission constraints. The problem is non-trivial: the methodology introduced proves efficient, is fair and fulfils the regulations set by the International Maritime Organisation.

Keywords: diesel engine, NOx emissions, fuel efficiency, control map, optimisation, optimal design

***Corresponding Author: Kai Zenger:** Aalto University, School of Electrical Engineering, E-mail: kai.zenger@aalto.fi
Nguyen Khac Hoang: Aalto University, School of Electrical Engineering, E-mail: hoang.kh.nguyen@aalto.fi

1 Introduction

Oceangoing ships are the largest single cause of nitrogen oxides (NOx) emissions globally, and NOx is generally a major air pollutant in the atmosphere. Most of these emissions are released near the land, which causes a major pollutation problem and health risk to the people. It has been reported that outdoor air pollutation caused about three million premature deaths globally in 2010. Since ship transportation is constantly increasing, it is easy to understand that the International Maritime Organization (IMO) is setting more and more stringent restrictions to ship emissions [1]. Large tankers are major pollutants driven by diesel engines. Even if the number of diesel engines in automobile industry is foreseen to decrease fast in the future, such a trend cannot be foreseen for maritime engines, because replacement of large diesel engines as power source in maritime applications seems to be a hopeless task for several decennia to come.

The engine manufacturers are interested in developing more and more efficient engines with increasing efficiency, reduced fuel consumption and redured emissions. Unfortunately, considerable efficiency increase is already hard to establish, and reducing fuel consumption generally implies higher NOx emissions and vice versa. Because of this, IMO has set regulations (Tier II and Tier III) that set limits to NOx emissions in some operation points (speed and load) of the ship. However, only a few operation points have been set, which means that it is unclear how the ship emissions should be controlled over the whole operation range. Even worse, the current regulations give a possibility to “cheat” by setting the emissions low at the given operation points (high fuel consumption) but use all effort to save fuel in other operation points (high NOx emissions). The paper presents a method, where the Design of Experiments (DOE) method is used to model the fuel consumption and NOx emission at any given operation point. It then becomes possible to construct smooth functions to cover all operation points of the ship engine. At any operation point an optimization problem can be set and solved, where the fuel consumption is minimized under a given constraint of maximum NOx emission. The solution gives certain control parameters of the ship (common rail pressure, charge air pressure, start of ignition timing), which are to be used in the operation point in question for optimal performance. It now becomes possible to compare the fuel consumption and emission level under standard routes travelled by the ship. In addition to that it becomes possible to construct optimal operation parameters and allowed NOx levels under a large number of operation points, thus giving advice to IMO how te future regulations could be stated, in order to cover all operational areas and to avoid all possibility to cheat. The results of the paper have been obtained and confirmed using real diesel engine data from large engine manufacturers.

2 Research objectives

The fuel consumption and emissions of a diesel engine can be affected by a set of input parameters, which can be set and controlled before and sometimes even during a cruise. In this section key parameters are presented and their influence on the break specific fuel consumption (BSFC) and nitrogen-oxide (NOx) emissions are studied. Specifications by the International Maritime Organisation are shortly presented and later in Section 3 the Design of Experiments method is described as a means to model the BSFC and NOx in a given operation point as a function of key operation parameters.

2.1 Key parameters of the engine

The intake pressure P_I, the common rail pressure P_{CR} and the start of injection SoI are considered to have a major effect on BSFC and NOx. Their effect is highly dependent on the operation point of the engine (speed and load), [2], [3]. The fuel consumption, here BSFC is defined by the fuel flow per the produced work [kWh]. The emissions, here specifically NO_x emissions are measured by the amount per produced work [g/kWh].

High intake pressure (boost pressure) has a major effect on engine performance. It leads to efficient combustion of the air/fuel mixture with reduced exhaust emissions of unburned fuel. At the same time however the amount of CO_2 and NO_x emissions can increase [4].

Common rail pressure affects the fuel spray into the cylinders and therefore has an impact on the ignition quality. High pressure reduces the amount of smoke but at the same time increases NO_x emissions. Moreover, there is a big relationship between high common rail pressure and engine load: under heavy load high pressure is beneficial, but the NO_x emission is increased. Under light load the fuel consumption ($BSFC$) increases.

The start of ignition (SOI) means the time at which fuel is injected into the cylinder to start the combustion process. It is measured as the crankshaft angle reaching the top dead center. Nowadays the heat release process is a major concept in the development of combustion engines in order to optimise fuel saving and emission reductions. Therefore the ignition process and specifically the (SOI) is particularly important.

Static maps are used to determine the control variables of the engine. The operation point (speed, load) pay a key role, because the optimal parameters are a nonlinear function of them. In Fig. 1 it is shown how the setpoints in engine control are set by the maps.

2.2 Emission reduction targets

The International Maritime Organisation (IMO) sets regulations for the allowed emissions of ships [5]. An example is given in Fig. 2.

According to Tier II conditions at the operation speed 1000 rpm the NO_x emission can be at most 9 g/kWh calculated over the whole trip. For practical use

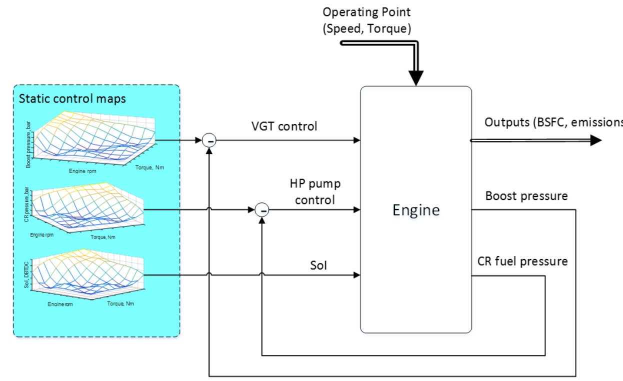

Fig. 1. Static maps to determine the control setpoints for intake (Boost) pressure, common rail pressure and (indirectly) fuel consumption. VGT=variable geometry turbocharger, HP=high pressure pump

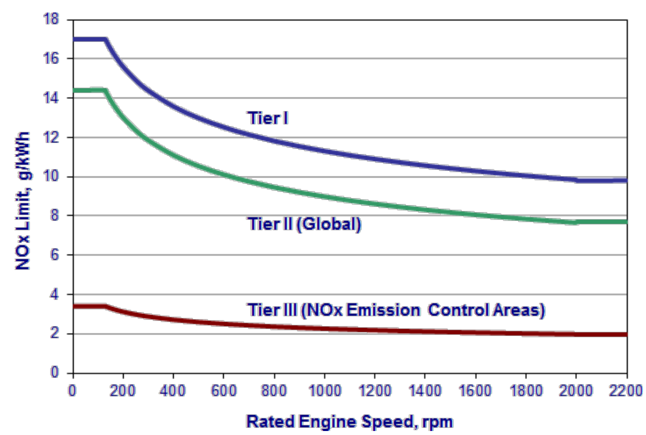

Fig. 2. NO_x emission limits under TierI, II and III

the requirement can be extended by defining the operation point as (speed, load) and by giving weights related to the time that a ship travels at a given load. For example, consider Fig. 3 where the ship is assumed to travel at a constant speed but with varying loads. The weights represent the assumed time fraction of the total trip that the ship travels under the load given in the table.

E2: Constant-speed main propulsion application including diesel-electric drive and all controllable-pitch propeller installations	Speed (%)	100	100	100	100
	Power (%)	100	75	50	25
	Weighting factor	0.2	0.5	0.15	0.15

Fig. 3. Setpoints with different weights

If the NO_x emissions corresponding to the operation points in the table are $n4$, $n3$, $n2$ and $n1$, respectively, the hard constraint for the emissions during the cruise is

$$(0.15 * n1 + 0.15 * n2 + 0.5 * n3 + 0.2 * n4) < 9 \text{ g/ kWh} \quad (1)$$

It is important to realize that the IMO regulations are fulfilled as long as (1) is fulfilled. In other words there is no maximum value of NO_x emissions at any specific load. Under the contemporary regulations this gives a possibility to "cheat" by allowing high emissions on loads, under which the ship is normally not run. Also, minimizing the emissions at the load points 25%, 50%, 75%, 100% gives clearly an acceptable running policy, which unfortunately gives the possibility to high emissions (with good savings in fuel use) in "intermediate" loads.

It is clear that the design of optimal engine parameters to be used during a cruise of a ship must be designed such that both fuel use and emissions are set to minimal values, however such that the constraints on emissions at all loads are fair (no "cheating").

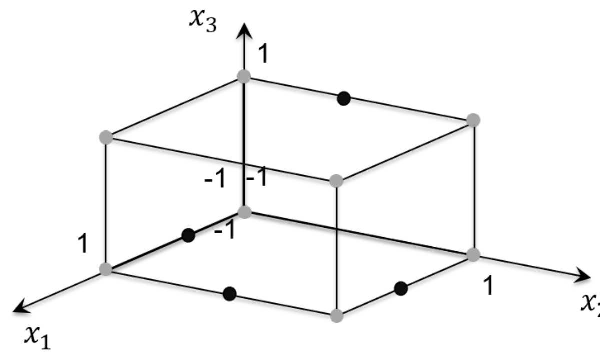

Fig. 4. Choosing the coded factors in the design of experiments

Factor	(-)	(0)	(+)
Boost, bar	1.1	1.5	1.9
CR pressure, bar	1100	1250	1400
SoI, DbTDC	-4	4,5	13

Fig. 5. Factor intervals (example data only)

3 Modelling by the design of experiments

In order to design the optimal control policy as function of the operation point of the ship the model for fuel usage (BSFC, break specific fuel consumption) and NO_x emissions is needed. To construct these models with as small number of measurements the method (*Design of Experiments, DOE*) was used. For the theory of *DOE* see e.g. [6]. The coded response variables are $BSFC$ and NO_x and the coded factors boost (intake) pressure x_1, common rail (CR) fuel pressure x_2 and start of ignition (SoI) x_3. The experiments are typically run at 500 rpm speed intervals at 8-16 load points. The idea is to use statistically relevant experiments to construct the relationship ot the output function with the input variables by using as small number as experiments as possible. In the current case the Box-Behnken design method with 15 experiments at each setpoint was used [4]. See Figs. 4 and 5. Each variable has been given three values denored as -1, 0 and +1 and experimental runs are done according to the Box-Behnken table.

The maps of the coded variables are obtained as a function of setpoint, see Figs. 6, 7, 8.

After the test runs have been done, least squares method is used at each setpoint to determine the coefficients in

$$\begin{aligned} BSFC = a_0 + a_1 P_1 + a_2 P_{CR} + a_3 SoI \\ + a_{12} P_1 P_{CR} + a_{13} P_1 SoI + a_{23} P_{CR} SoI \\ + a_{11} P_1^2 + a_{22} P_{CR}^2 + a_{33} SoI^2 \end{aligned} \quad (2)$$

$$\begin{aligned} NOx = b_0 + b_1 P_1 + b_2 P_{CR} + b_3 SoI \\ [\quad + b_{12} P_1 P_{CR} + b_{13} P_1 SoI + b_{23} P_{CR} SoI \\ + b_{11} P_1^2 + b_{22} P_{CR}^2 + b_{33} SoI^2 \end{aligned} \quad (3)$$

where the values for $BSFC$ and NO_x were obtained by measurements from a real engine.

Note that the models with one set of parameters a_i, b_i are valid in one operation point only. Also note that the variables P_1, P_{CR} and SoI are always restricted by lower and upper limits

$$\begin{aligned} P_{1l} \le P_1 \le P_{1u} \\ P_{CRl} \le P_{CR} \le P_{CRu} \\ SoI_l \le SoI \le SoI_u \end{aligned}$$

It would now be possible to consider the table E2 of IMO regulations, Fig. 3, and take the 4 operation points N_1 (100, 25), N_2 (100, 50), N_3 (100, 75), N_4 (100, 25) to

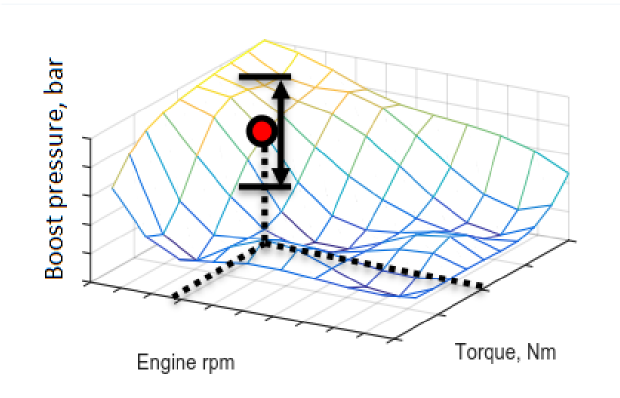

Fig. 6. Intake pressure variation and limits

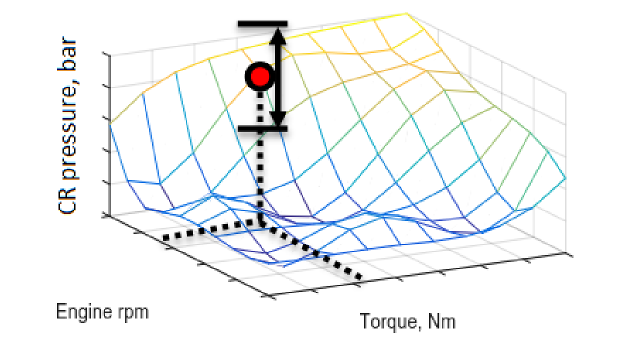

Fig. 7. Common rail variation and limits

calculate the optimal operational parameters by solving for all i

$$\begin{aligned} &\min BSFC(i) \\ &\text{s.t} \quad NO_x(i) < \alpha \\ &\quad P_{1l} \leq P_1(i) \leq P_{1u} \\ &\quad P_{CRl} \leq P_{CR}(i) \leq P_{CRu} \\ &\quad SoI_l \leq SoI(i) \leq SoI_u \end{aligned} \tag{4}$$

where α is the limit 9 g/kWh. However, acting like this would probably lead to a result that NO_x levels would be exremely high for other operation points than those four ones selected in the E2 table (to minimise BSFC). That would not be fair and it would be "cheating", although it would formally satisfy the IMO regulations. To solve this problem, more advanced algorithms are needed.

Optimization problems like in (4) can be solved numerically by e.g. the Sequential Quadratic Programming (SQP) algorithm. There the nonlinear problem is at each iteration embedded into a Quadratic Programming subproblem in order to form the new iteration of the solution vector [7].

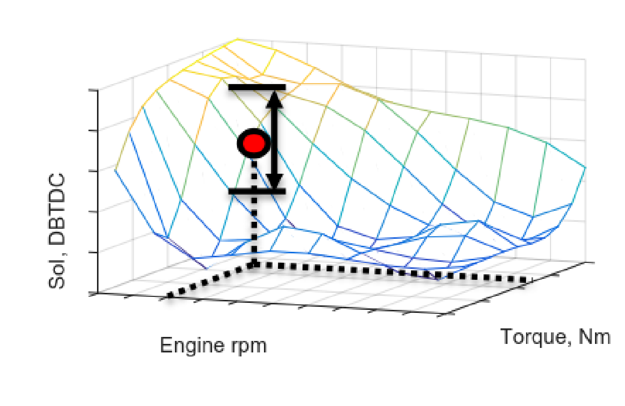

Fig. 8. Start of Ignition variation and limits

4 Optimisation by including weights and the cruise profile

Consider Fig. 9 which gives a load distribution over a whole cruise of a ship. It is possible to minimize the fuel consumption during the whole cruise while fulfilling the NO_x constraints as follows.

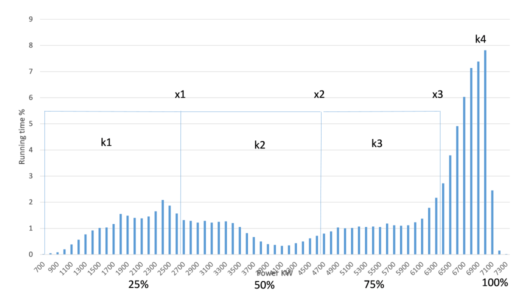

Fig. 9. Cruise characteristics (invented data)

– Choose 4 random points n_1, n_2, n_3, n_4 for admissible values in (3)
– Set the points as a candidate for the NO_x curve as in Fig. 10.
– Check that the constraint (1) is fulfilled. If not, pick new values for $n1$, $n2$, $n3$ and $n4$.
– Interpolate by piecewise approximation for all load vs. NO_x data α_i available from measurements, as in Fig. 11.

– Minimise the fuel consumtion by

$$\min BSFC(i)$$
$$NO_x(i) < \alpha(i)$$

where $\alpha(i)$ is obtained from the piecewise linear NO_x curve.

– Pick new values for $n1$, $n2$, $n3$ and $n4$ and start again from the first step. After a desired number of trials the NO_x curve is chosen, which gives the minimum fuel consumption.

Note that the amount of iterations can be quite large. If three values for the intake pressure, three values for the common rail pressure and three values for the ignition time are chosen, each n_i:s has 27 possible values, and the whole grid of n_i has 27^4 possible values. Some of these are not admissible in that they do not fulfil the IMO E2 constraint, but anyway the search space is large.

The algorithm calculates 12 optimal engine parameters (intake pressure, common rail pressure and ignition time at 4 operation points). The E2 weighting quarantees that the IMO regulation is fulfilled (hard constraint).

The figure 10 shows the resulting NO_x curve. The 'circled' points correspond to the loads 25%, 50%, 75% and 100%. The curve fulfills the IMO regulations by construction (optimisation constraint) and by a piecewise linear interpolation it gives a reasonable target for allowable emissions at each load. See Fig. 11 for an example.

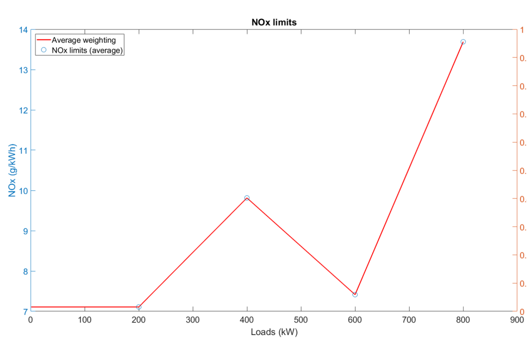

Fig. 10. NOx limits

The final objective function is the estimated fuel consumption over the whole cruise (e.g. Fig. 9) under assumption of a load profile and a fixed NO_x curve. The parameters obtained by searching over different load profiles are then used to apply over a real cruise, and total fuel savings can be evaluated. In Fig. 12 an

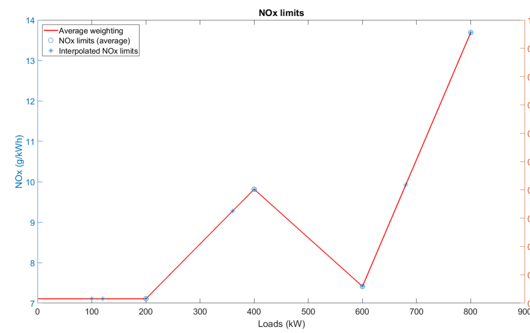

Fig. 11. NOx limits at interpolated load points

interpolated curve has been presented, where 8 operation points have been used during a given cruise. The corresponding estimated engine fuel use in a year was to be 576 tons, when nominal operation leads were 607 tons of fuel usage. The saving is approximately 5%.

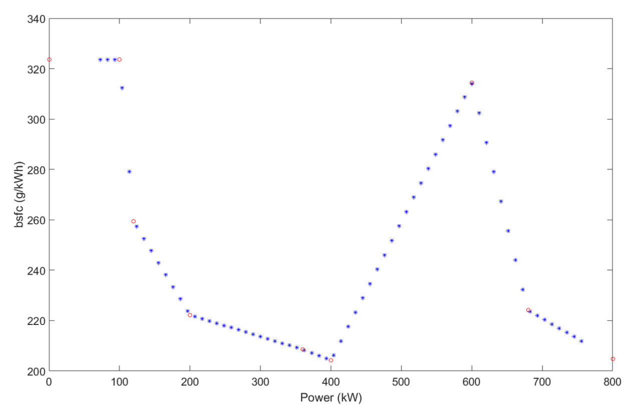

Fig. 12. Interpolated optimal bsfc values at based on eight operation points

5 Conclusion

The paper has discussed a systematic method to optimise engine control parameters of a ship diesel engine, with the goal to minimise fuel consumption but fulfilling the NO_x constraints set by the IMO. These regulations have so far been given in a way that gives room to interpretations and even possibility to unfair design, where NO_x emissions are only minimised where absolutely necessary. The paper introduces an advanced algorithm, which actually sets a NO_x curve that can be used in minimising the fuel consumption with constraint on any operation point. It is believed that the method can be used for general greenhouse gas emissions also (not only NOx). Also, the design gives valuable information on the Tier regulations as such, specifically on how they should be considered over a whole cruise of a ship. It goes without saying that the optimization approach presented in the paper can lead to extremely useful improvements technically, economically and from the environmental viewpoint.

In spite of the fact that the results are promising, the method and algorithms are still under investigation.

ACKNOWLEDGMENT

The EU project Hercules 2 funded by the European Commions and the Intens project funded by Business Finland are greatly acknowledged.

References

[1] R. M. A. VI. Regulations for the prevention of air pollution from ships and nox technical guide 2008. *International Maritime Organisation*, 2009.
[2] L. Guzzella and A. Amstutz. Control of diesel engines. *IEEE Control Systems*, 18(5):53–71, 1998.
[3] J. B. Heywood. *Internal Combustion Engine Fundamentals*. Mc-Graw-Hill, 1988.
[4] N. K. Hoang and K. Zenger. Designing optimal control maps for diesel engines for high efficiency and emission reduction. European Control Association, 2019. (to appear).
[5] Imo marine engine regulations. *Emission Standards*. URL https://www.dieselnet.com/standards/inter/imo.php.
[6] P. G. Mathews. *Design of Experiments with MINITAB*. ASQ Quality Press, 2005.
[7] P. T. Boggs and J. W Tolle. Sequential quadratic programming. *Acta numerica*, 4:1–51, 1995.