FAST-TIME SIMULATION FOR PREDICTION OF FUEL CONSUMPTION AND EMISSIONS DURING SHIP MANOEUVRES

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ABSTRACT

Low carbon shipping can be achieved in various ways, e.g. by applying constructive measures, using low carbon fuels or alternative propulsion systems. Another approach will be discussed in this paper: By means of Fast-Time-Simulation (FTS) Technology the ship's motion can be calculated for more than 20 minutes within only one second. This prediction is based on a highly non-linear system of equations of motion as used in Ship Handling Simulators. Within the project ISTTES (Integrated Application of Simulation regarding Trim and Draught for an effective Ship's Control and Improvement of Risk Handling) a method to adapt the ship's model to different trim and draught conditions is being developed in order to facilitate the application in the daily shipping business.

An online FTS-Monitoring module provides path and status predictions that show the immediate reaction of the vessel on any ordered control (i.e. engine, rudder or thrusters). In the offline FTS-Planning module various manoeuvring strategies can be tried out and discussed beforehand. The navigational officer is enabled to take into account manoeuvre technique, safety and economic aspects as well as time consumption.

The propulsion units of the ship models calculate the engine torque and thus propeller revolutions and thrust. Presently, in order to enhance this simplified engine model and to meet the challenge of considering the combustion process as detailed as possible keeping the ability of the FTS likewise, an enhanced model is under development to predict also fuel consumption and emissions. Studies had been carried out to estimate the benefit of a detailed, but therefore more time-consuming process-calculation for transient engine operation. Several data coming from laboratory test bed as well as from engines installed on a real RoPax-ferry form the basis of the on-going research work.

Such a comprehensive prediction covering also engine processes will give an additional and more profound basis for decision-making to the navigational officer and supports better involvement of the officer on watch (OOW) in energy efficient ship operation.

Keywords: role of human on energy efficient ship operation, monitoring, recording, data utilisation, simulation, prediction, trim and draught

NOMENCLATURE

Fast-Time Simulation (FTS) is a technology which allows for predictions of ship's behaviour up to 24 minutes. This prediction calculates the future ship's behaviour for the actual input of commanded steering values and is renewed with the frequency of 1 Hz. It is based on a highly non-linear system of equations of motion.

Simulation Augmented Manoeuvring Design and Monitoring (SAMMON) is a toolbox which allows for a new type of design of a manoeuvring plan as enhancement of the common pure way point planning and an unmatched monitoring of ship handling processes with multiple prediction of the future ship's motion to follow the underlying manoeuvring plan.

1. INTRODUCTION

Actions and measures to reduce emissions can be classified according to several aspects. For instance, legal frameworks can be seen as indirect and rather global and generic measures contributing to more environmentally-friendly maritime transportation by developing and establishing rules and regulations. Those indirect measures also may include training and education in sustainable shipping by learning how to apply procedures, methods and technologies in a smooth and optimized manner.

Direct measures are usually those actions and measures that are directly related to the transportation and concrete navigation processes and are mainly technical and operational. Technical measures are those that contribute to sustainable shipping and reduction of greenhouse gas (GHG) emissions and are related to ship design, development and installation of technical systems as e.g. for propulsion, engines and using alternative fuels or cleaning exhaust gases etc. Operational measures are related to the processes of planning and executing voyages time- and energy-efficiently and taking into account the reduction of GHG emissions through sophisticated operation of the ship under the different environmental conditions and ship status.

In principle, there are two ways to achieve lower emissions in shipping: on the one hand to reduce the energy impact by renouncing to parts of the world wide sea trade or by making sea trade more efficient. The former can be realized by producing and consuming more regionally, as well as by making the cargo logistics (e.g. shipping of empty containers) more efficient. The latter often focuses on constructive improvements for more energy efficiency in engine combustion and ship’s propulsion as well as alternatives fuels. Another approach is to give the vessel a favourable trim and draught in order to decrease the ship’s resistance.

This paper describes investigations and studies into a way combining ideas of these approaches, taking especially into account the role of the human operator in energy efficient ship operation. The authors are specifically focussing on the aspect of manoeuvring a ship in different sea areas and under different circumstances. The aim is to enable ship’s operators to plan manoeuvres and provide an immediate feedback on consequences of manoeuvring actions. Even when executing manoeuvres experienced navigators (captains, pilots and navigating officers) shall always be informed about the consequences of an intended action by the assistance of the FTS prediction technology. The operator gets an understanding which manoeuvres should be avoided and which are favourable. Furthermore, this approach can lead to even compare the impact of constructive innovations on the environment.

For these purposes FTS technology has been integrated in an enhanced ECDIS-based user interface and can be used for briefing, monitoring and debriefing of ship manoeuvres (see nomenclature SAMMON).This interface visualizes the ship’s hydrodynamic behaviour and is to improve the ship operation regarding time consumption, economical and safety aspects as well as environmental impacts. The propulsion units of the actually used ship models calculate the engine torque and thus propeller revolutions and thrust. Presently, there is not yet a detailed calculation of the combustion process which is needed to predict fuel consumption and emissions.

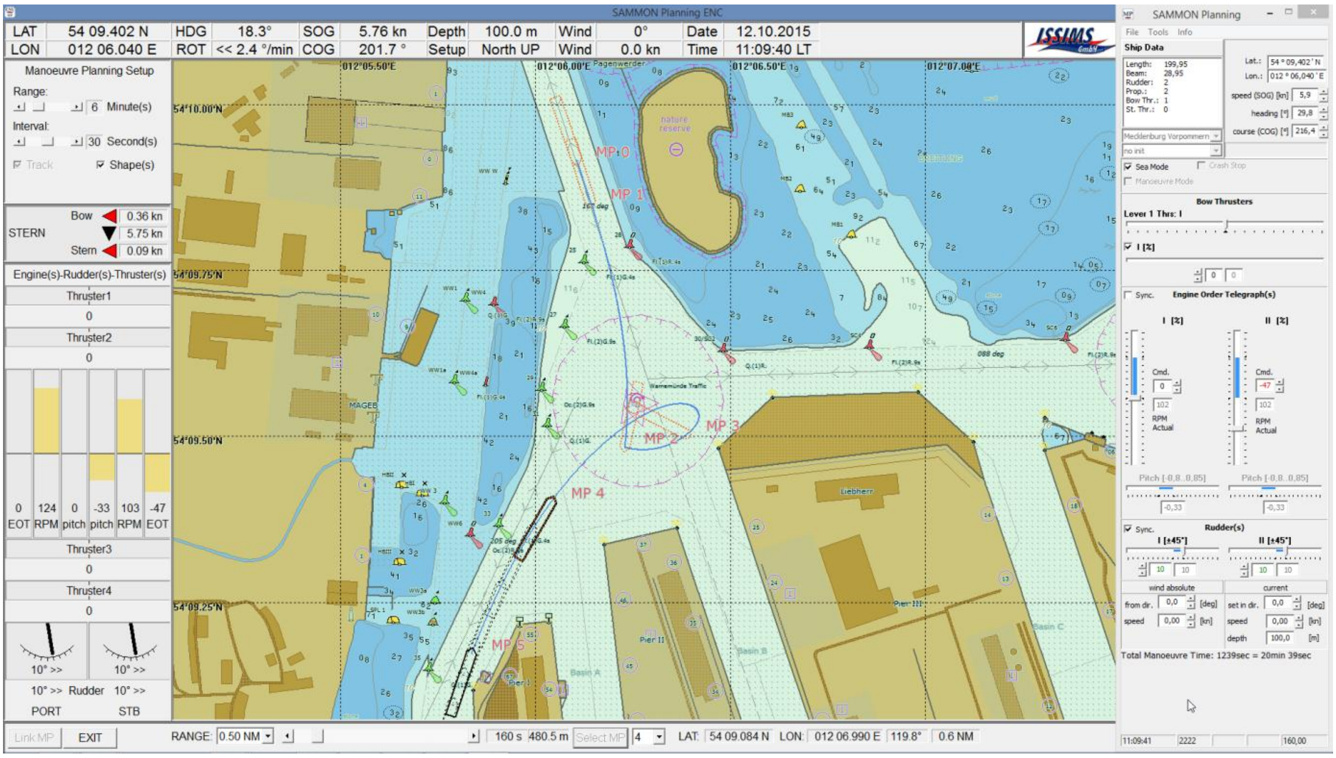
The trial vessel for these studies is the ferry “Mecklenburg-Vorpommern”. The advantage to take a ferry ship for this kind of investigation is that there is almost no change in trim and draught. For the time being, each change in trim and/or draught would lead to newly tune the ship’s model. Each ship model is tuned in a way to replicate the hydrodynamic behaviour as exact and close to reality as possible. This means, e.g., for each trim and draught condition a new set of ship parameters is necessary to reproduce the ship’s real behaviour under the respective conditions. The research project ISTTES (Integrated Application of Simulation regarding trim and draught for an effective Ship’s Control and Improvement of Risk Handling) focusses on a method to determine correlations between the actual ship condition and the relevant parameters in order to make the model adaptive to any trim and draught.

2. SAFETY, TIME AND ECONOMICAL ASPECTS OF MANOEUVRING

There are a great number of possible manoeuvres and manoeuvring strategies to enter or to leave a port. Ship operators are liable for time- and energy-efficient as well as for save manoeuvring. Sometimes the optimization criteria for save and time-efficient manoeuvring are fulfilled with one and the same manoeuvring strategy, sometimes very different strategies are necessary to reach the one or the another objective. Setting priorities and taking decisions is the task of the shipping company, the captain and/or the navigator in charge. However, for decision-making profound knowledge and reliable information about the consequences of any action is essential.

2.1 SAFETY ASPECTS

Save manoeuvring is e.g. not necessarily related to slow speeds, but on the other hand requires a safety reserve for each propulsion and steering unit. The example in Figure 1 shows the planned manoeuvre for a RoPax ferry in the port of Rostock. The vessel stops in the turning basin, turns about 160° and goes astern towards the pier.


SAMMON Planning ENC

LAT	54 09.402 N	HDG	18.3°	SOG	5.76 kn	Depth	100.0 m	Wind	0°	Date	12.10.2015
LON	012 06.040 E	ROT	<< 2.4 °/min	COG	201.7 °	Setup	North UP	Wind	0.0 kn	Time	11:09:40 LT

Manoeuvre Planning Setup
Range: 6 Minute(s)
Interval: 30 Second(s)
☑ Track ☑ Shape(s)

STERN
Bow 0.36 kn
5.75 kn
Stem 0.09 kn

Engine(s)-Rudder(s)-Thruster(s)
Thruster1: 0
Thruster2: 0

0	124	0	-33	103	-47
EOT	RPM	pitch	pitch	RPM	EOT

Thruster3: 0
Thruster4: 0
10° >> Rudder 10° >>
PORT STB

RANGE: 0.50 NM | 160 s 480.5 m | 4 | LAT 54 09.084 N LON: 012 06.990 E 119.8° 0.6 NM

SAMMON Planning

Ship Data
Length: 199,95
Beam: 28,95
Rudder: 2
Prop.: 2
Bow Thr.: 1
St. Thr.: 0
Mecklenburg Vorpommern
no init

Lat.: 54 ° 09,402 ' N
Lon.: 012 ° 06,040 ' E
speed (SOG) [kn] 5,9
heading [°] 29,8
course (COG) [°] 216,4

☑ Sea Mode ☐ Crash Stop
☐ Manoeuvre Mode

Bow Thrusters
Lever 1 Thrs: I
☑ I [%] 0 0

☐ Sync. Engine Order Telegraph(s)
I [%] Cmd. 0, 102 RPM Actual
II [%] Cmd. -47, 102 RPM Actual
Pitch [-0,8..0,85] -0,33
Pitch [-0,8..0,85] -0,33

☑ Sync. Rudder(s)
I [±45°] 10 10
II [±45°] 10 10

wind absolute: from dir. 0,0 [deg], speed 0,00 [kn]
current: set in dir. 0,0 [deg], speed 0,00 [kn], depth 100,0 [m]

Total Manoeuvre Time: 1239sec = 20min 39sec

11:09:41 | 2222 | 160,00

Figure 1: SAMMON Planning user interface displaying a manoeuvring plan for a save manoeuvre with a ferry entering the port of Rostock/Germany.

Figure 2 shows the time history of the speed over ground (SOG) and the engine order telegraph (EOT) of a planned manoeuvre as depicted in Figure 1 during that manoeuvre. The ship reduces its speed up to 0 kts before turning by means of the thrusters. Then it takes up speed in order to run astern. For steering the propulsion units on port and starboard side are applied. The time to execute these manoeuvre sequences is around 20 min 40 sec. There is always sufficiently reserve to manoeuvre the ship differently if any incident happens as e.g. the occurrence of a strong wind gust, other traffic ships or a sudden failure of a manoeuvring unit. The thruster’s thrust for turning the ship does not exceed 60 % of its nominal power. The maximum thrust when accelerating the ship after the turning is not more than 50 %.

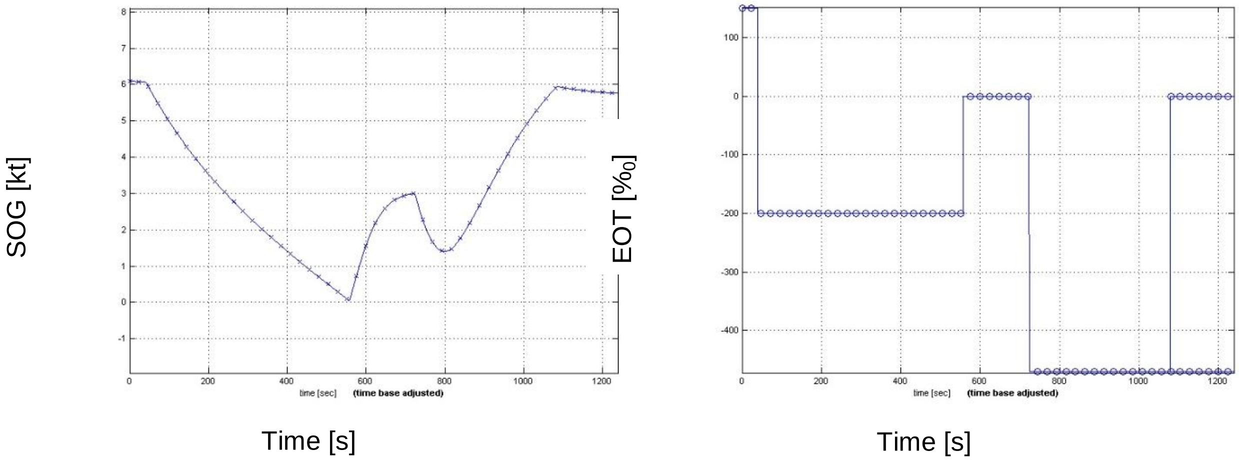
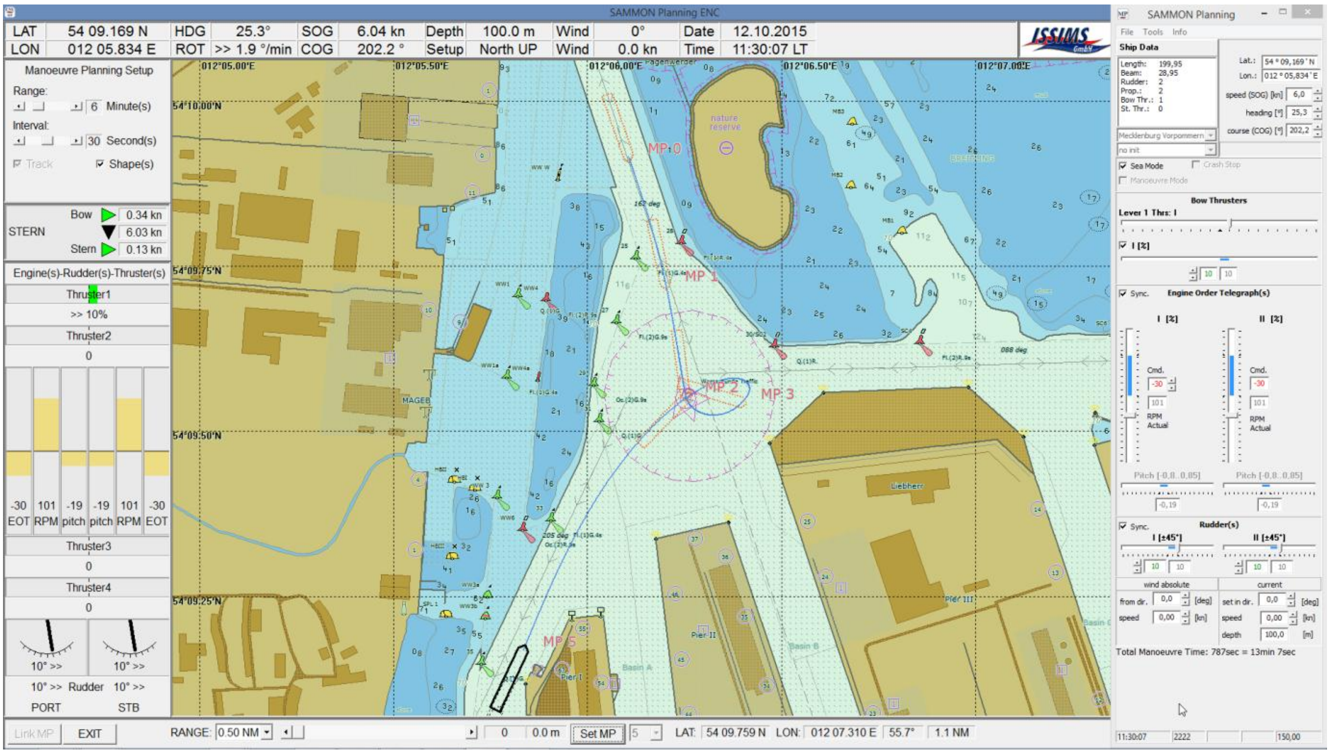


Figure 2: Time history of Speed over Ground (left) and Engine Order Telegraph (right) during the manoeuvring of the ferry.

2.2 TIME ASPECTS

The same manoeuvre objective can be achieved in a very different way and in shorter time than shown in Figure 1. The path displayed in Figure 3 looks almost the same, but the time-consumption is only around 13 min 10 sec which means a time-saving of around 7 minutes!



LAT	54 09.169 N	HDG	25.3°	SOG	6.04 kn	Depth	100.0 m	Wind	0°	Date	12.10.2015
LON	012 05.834 E	ROT	>> 1.9 °/min	COG	202.2 °	Setup	North UP	Wind	0.0 kn	Time	11:30:07 LT

Manoeuvre Planning Setup
Range: 6 Minute(s)
Interval: 30 Second(s)
☑ Track ☑ Shape(s)

Bow 0.34 kn
STERN 6.03 kn
Stern 0.13 kn

Engine(s)-Rudder(s)-Thruster(s)
Thruster1
>> 10%
Thruster2
0

-30	101	-19	-19	101	-30
EOT	RPM	pitch	pitch	RPM	EOT

Thruster3
0
Thruster4
0
10° >> 10° >>
10° >> Rudder 10° >>
PORT STB

Link MP EXIT RANGE: 0.50 NM 0 0.0 m Set MP 5 LAT: 54 09.759 N LON: 012 07.310 E 55.7° 1.1 NM

Ship Data
Length: 199,95
Beam: 28,95
Rudder: 2
Prop.: 2
Bow Thr.: 1
St. Thr.: 0

Lat.: 54 ° 09,169 ' N
Lon.: 012 ° 05,834 ' E
speed (SOG) [kn] 6,0
heading [°] 25,3
course (COG) [°] 202,2

Mecklenburg Vorpommern
no init
☑ Sea Mode ☐ Crash Stop
☐ Manoeuvre Mode

Bow Thrusters
Lever 1 Thrs: I
☑ I [%] 10 10

☑ Sync. Engine Order Telegraph(s)
I [%]: Cmd. -30, 101 RPM Actual, Pitch [-0,8..0,85] -0,19
II [%]: Cmd. -30, 101 RPM Actual, Pitch [-0,8..0,85] -0,19

☑ Sync. Rudder(s)
I [±45°] 10 10
II [±45°] 10 10

wind absolute: from dir. 0,0 [deg], speed 0,00 [kn]
current: set in dir. 0,0 [deg], speed 0,00 [kn], depth 100,0 [m]

Total Manoeuvre Time: 787sec = 13min 7sec

11:30:07 2222 150,00

Figure 3: SAMMON Planning user interface displaying a manoeuvring plan for a time-saving manoeuvre with a ferry entering the port of Rostock/Germany.

Figure 4 illustrates the comparison between the two manoeuvre strategies. The propulsion units (propeller and thrusters are used up to 100 % of their nominal power during the time-saving manoeuvring strategy. A slight tendency towards this behaviour could be observed on board the real RoPax ferry trading in this area.

Both strategies – the time-saving and the save one – are economical in their own ways. If nothing happens, the time-saving strategy might be on an economic point of view more efficient. But if suddenly an unforeseen accident happens a lot of money can get lost. The remaining question is: which of the two strategies is more fuel-efficient or even less harmful to the environment. One possible answer is that the slower, “non-aggressive” manoeuvre is the better due to lower fuel consumption per hour. Another opinion is that due to higher time-consumption the slower strategy consumes more fuel in total. An answer to this question can be found only in measuring the real consumption of fuel and the emissions, and furthermore: to build up models in order to simulate the engine behaviour, the fuel consumption and exhaust gases in order to get fuel consumption and emissions as a third objective criteria besides the time and safety aspect as basis for decision-making.

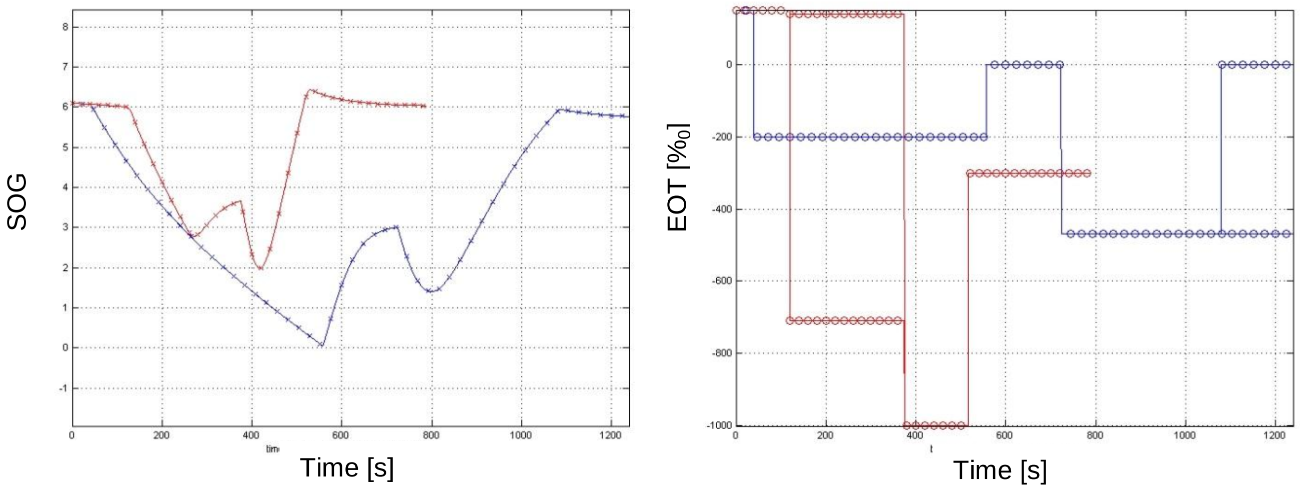


Figure 4: Time history of Speed over Ground (left) and Engine Order Telegraph (right) during the manoeuvring of the ferry for a save strategy (blue) and a time-saving strategy (red).

3. ENGINE IN TRANSIENT OPERATION

During manoeuvres the propulsion engine does not work at the level of its optimized nominal operating point. Furthermore, varied propulsion performances are required which lead to transient engine operations.

Investigations have been performed on this topic: In a first step different bench test studies were required to identify the characteristics which describe the transient condition, and existing simulation models must be developed and validated for the use of simulating the transient condition. In parallel, the real ship behaviour has been analysed and a transfer of some characteristic engine manoeuvres to the test bed experiments was done. Prospectively, in a second step, the focus will be led on the real ship for model validation, in order to implement those models in a third step into the FTS applications as presented above.

3.1 IMPACT OF TRANSIENT CONDITION

Depending on the ratio of sea voyage and the navigation in coastal sea areas including fairways, rivers and harbour basins the importance of the transient operation during manoeuvring can differ quite a lot. The test vessel for these studies, the RoPax ferry ship “Mecklenburg-Vorpommern” is trading between the port of Rostock/Germany and Trelleborg/Sweden.

50 voyages (i.e. 321 hours of sailing, 4242 nm total distance) had been analyzed. Thereof, 29 voyages headed from Trelleborg to Rostock. For this voyage direction it can be stated:

11.8 % of the whole voyage distance is conducted in manoeuvring mode (standard deviation: 0.6 %)

18.2 % of the voyage duration is conducted in manoeuvring mode (standard deviation: 3.3 %)

17.4 % of the whole fuel consumption is used during manoeuvring mode (standard deviation: 1.8 %)

Over the total 50 voyages the stationary operation points had been logged and analyzed separately. Thereof, a cubic regression formula was established, where the fuel consumption depends on the ship's speed (Figure 5, green plot). Furthermore, all voyages were recalculated with this regression formula taking the SOG measurements from each second and calculating the corresponding (stationary) fuel consumption.

On average, about 8% are calculated too less fuel consumption. This corresponds to 1000 kg fuel for this example. The reasons for this deviation are:

The transient condition, especially during manoeuvres, but also due to environmental influences increasing the ship's resistance during sea voyages,

The fact that the stationary calculation only calculates according to the consumption of the main engines and ignores the fuel consumption of the auxiliaries which are mainly needed during manoeuvring mode for thruster actions.

This investigation demonstrates the importance of these on-going studies on transient engine operation.

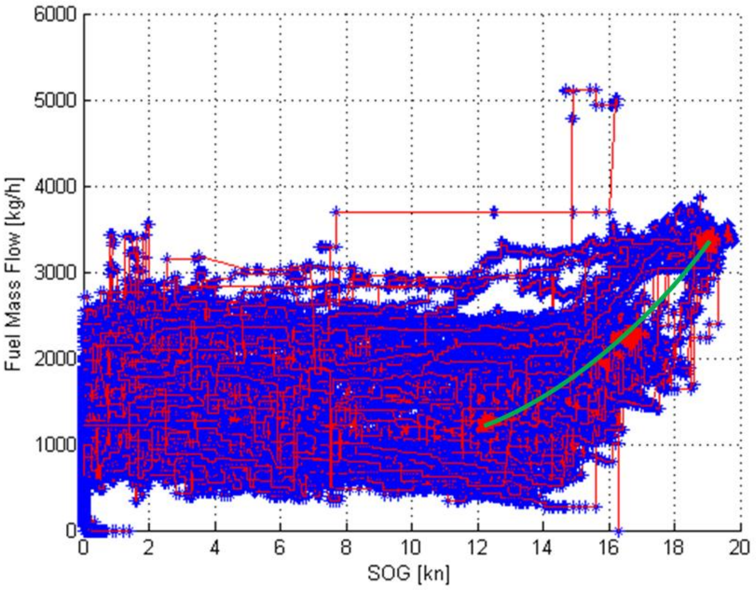


Figure 5: Range of fuel consumption for a sample of 50 voyages (321 h sailing-time over 4242 nm) of a RoPax ferry (blue dots/red line) and its approximated stationary operating points (green plot); measurements form ferry "Mecklenburg-Vorpommern"

The 17.4 % fuel consumption during manoeuvring mode corresponds nearly to 2000 kg. This outcome shows that by simulating none-steady state operation with stationary models might result in differences up to 50 %!

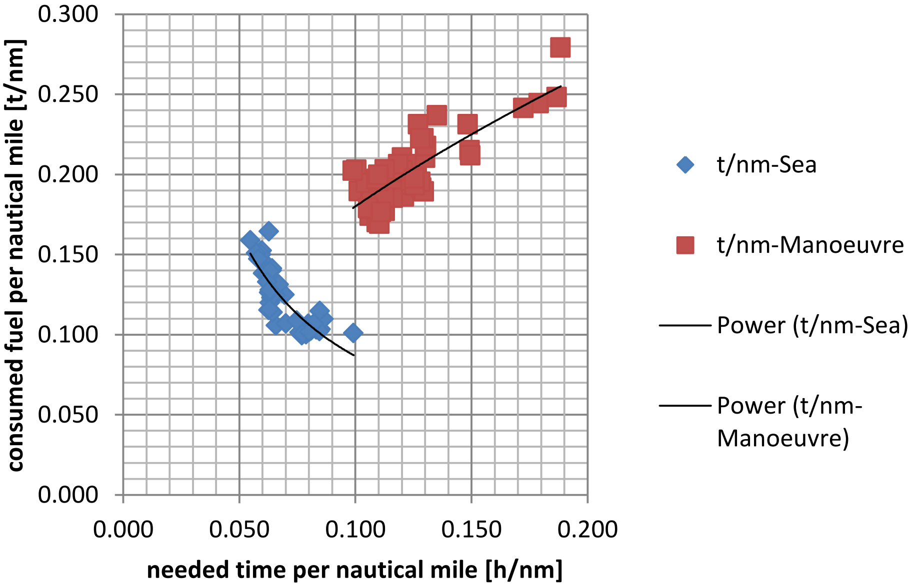


Figure 6: Fuel consumption per nautical mile in relation to the time availability per nautical mile: the more time is needed (due to manoeuvres), the more fuel is consumed; measurements from ferry "Mecklenburg-Vorpommern"

Figure 6 visualizes the difference of fuel consumptions when operating in sea and manoeuvring mode regarding the fuel needed per nautical mile depending on the time needed for the same distance. During manoeuvring the relation "the slower the ship, the less fuel consumption" is wrong as shows the following figure. This is due to turning, crabbing and acceleration.

3.2 BENCH TESTS

The test bed engine is a MaK 6M20 4-stroke ship diesel engine with a nominal, constant turning speed of 1000 rpm and a nominal power of 1000 kW.

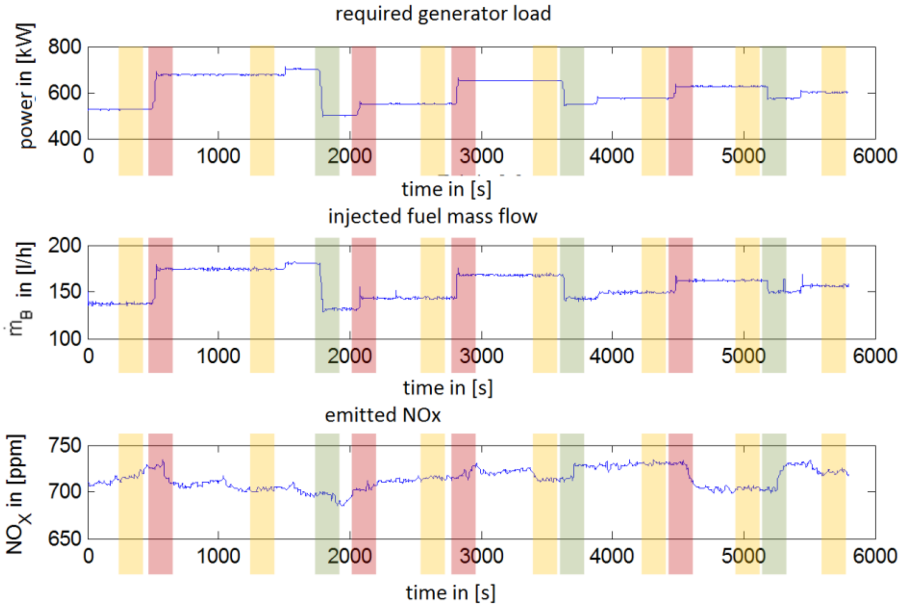


Figure 7: test sequences for analysing different stationary and transient load conditions (yellow: stationary operation, red: load increases, green: load decreases) showing the required power, the therefore injected fuel mass flow and the resulting nitric oxides (NOX) emissions.

According to the observed changes in operating points on the 4-stroke diesel engines installed on the RoPax ferry, equivalent scenarios were executed on the test bed engine between around 200 and 800 kW (Figure 7). Whilst the reaction of the injected fuel mass flow depends on the installed automation system and control parameters of the specific engine, the resulting emissions depend also on the thermodynamic condition in the combustion chamber. Figure 7 shows that the injected fuel reacts immediately onto a change of the required generator load. On a ship this behaviour corresponds to the reaction on change in load e.g. due to variation of the propeller pitch. The reaction of nitric oxides (NOX) does not seem to be obvious in the graphs.

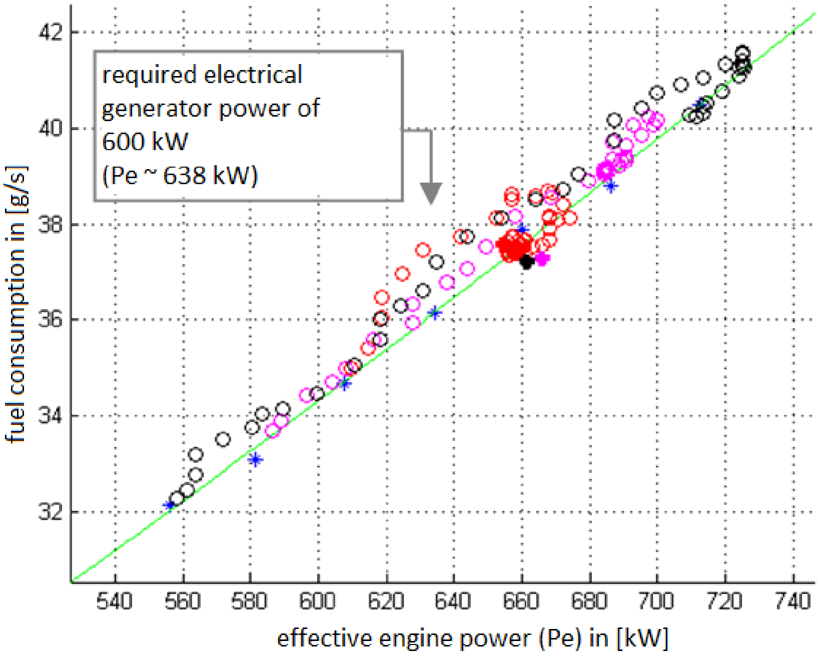


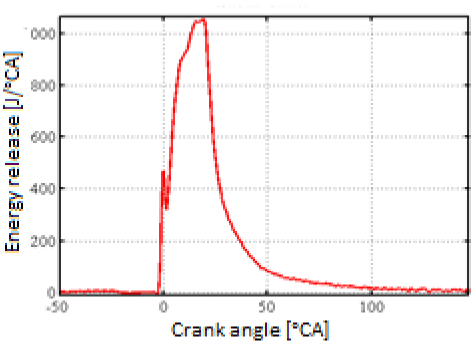
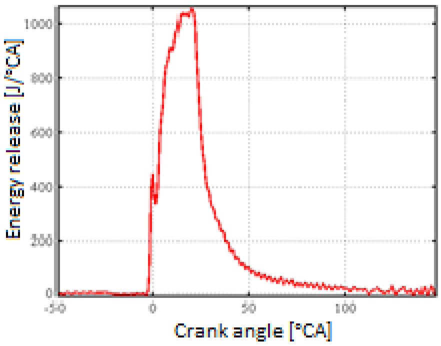
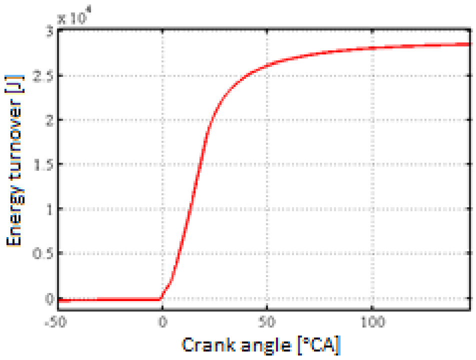
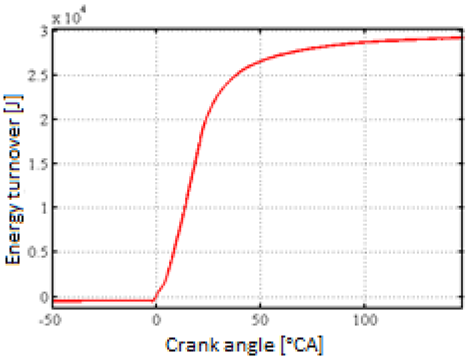
Figure 8: Comparison of stationary engine power and three different cases of load increase passing the effective engine power of 638 kW. Black, red, pink dots: measurements of different load increases; Blue dots: measurements of stationary operating points; Green line: regression curve through stationary operating points.

Fuel mass flows in transient conditions are not corresponding to the fuel consumption during stationary operation, even if the same engine power is performed. Figure 8 shows three cases of load increase passing the effective engine power of 638 kW. All three transient experiments require a higher fuel mass flow than is required for the operation in stationary condition at the same engine operating point. Also the charge air mass flow is not the same and therefore different thermodynamic reactions happen within the combustion chamber.

Table 1 illustrates the combustion process (energy release, upper graphics) and the corresponding integrated combustion process (energy turnover, lower graphics). The column at the left side concerns the operation point at 638 kW effective engine power whereas at the right side the same effective engine power is shown during transient operation.

Not only fuel mass flow and specific fuel consumption increases when engine load increases, but also exhaust gas emissions change in their quantity and proportion.

Table 1: Energy release [J/°CA] and the energy turnover [J] depending on crank angle during combustion process at stationary and transient engine operation with same effective engine power

Pe ≈ 638 kW: stationary	Pe ≈ 638 kW: transient
	
	

Exhaust gas emissions are measured partly (χ in [ppm]) after the exhaust gas turbo charger. The time delay thereby is considered and corrected for these studies. Afterwards, the emission mass flow in [g/s] is calculated according to Resolution MEPC.177(58). The following example shows the calculation of nitric oxide (NO) mass flow:

$$\dot{m}_{NO} = u_{NO} \cdot \chi_{NO,h} \cdot (\dot{m}_A + \dot{m}_F) \cdot k_{f,corr} \tag{eq. 1}$$

With,

$\dot{m}_{NO}$ = mass flow of NO

$\dot{m}_{A}$ = air mass flow

$\dot{m}_{F}$ = fuel mass flow

$\chi_{NO,h}$ = ppm of NO in humid exhaust gas

u_{NO} = specific smoke gas factor

$k_{f,corr}$ = correction factor for humid exhaust gas

Considering not only the relative part of the emission (in [ppm]), but the absolute (in [g/s]), the results change their character, as shown in the next figure (Figure 9).

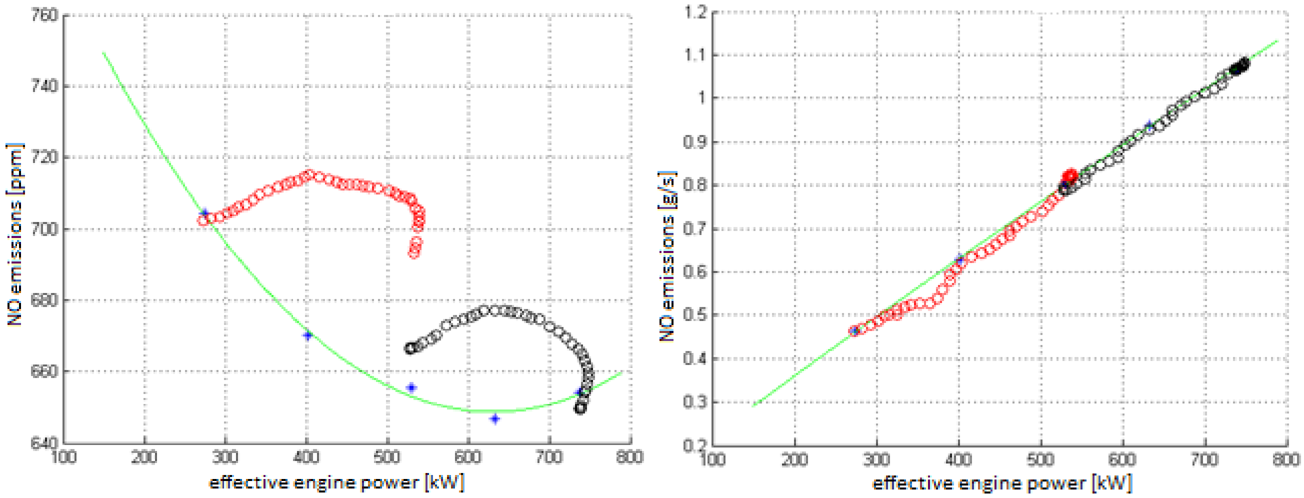


Figure 9: NO emissions due to changes in generator load from 270 to 520 kW (red), resp. from 520 to 735 kW (black) in [ppm] (left) and in [g/s] (right). Blue dots: measurements of stationary operating points; Green line: regression curve through stationary operating points.

The graph on the left hand side in Figure 9 shows that NO emissions even decrease when engine power increases. But due to the indication of the relative amount of NO within the exhaust gas, the result might be confusing. As the exhaust gas flow augments even more than the NO emissions, it seems like a decrease of those emissions. But in absolute numbers (graphic on the right) an increase of power means also an increase of NO emission building rate. This example of two load increases shows a quite good relation between stationary and transient engine conditions for that engine and fuel type.

For other types of emission the emission building rate is very different in transient condition compared with stationary operation. Figure 10 shows the history of carbon monoxide (CO) during increase of engine power. For each change of load two runs have been executed.

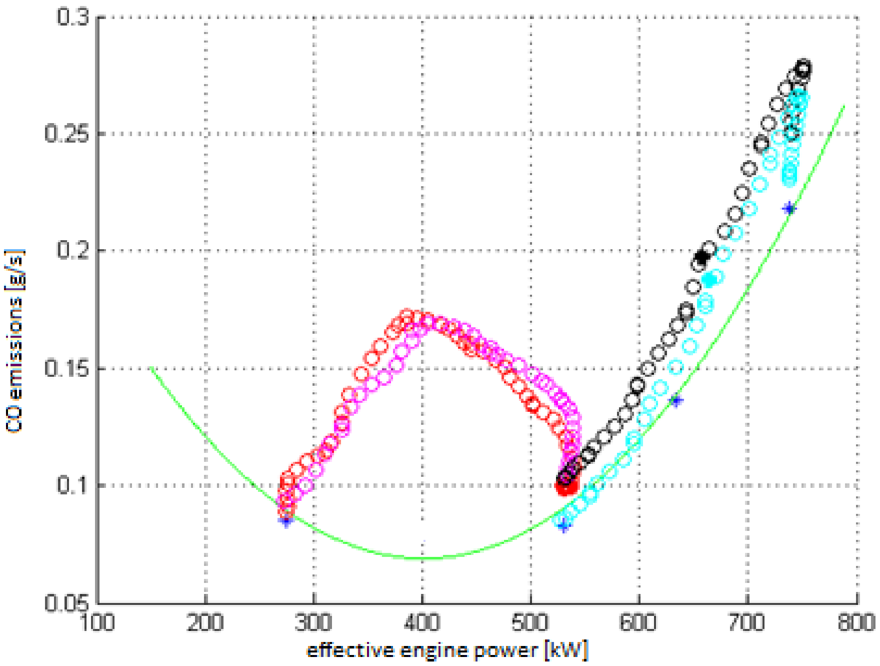


Figure 10: Dark blue dots: CO measurements at stationary engine condition; Green line: regression curve for stationary condition; Changes in load from 270 to 520 kW (reddish) and from 520 to 735 kW (cyan/black), absolute CO mass flow in [g/s]

3.3 VALIDATION OF EMISSION MODELS

There are different emission building models for stationary condition. In a first approach these models have been validated for the test bed engine for various exhaust gas components (O_2, CO_2, NO, soot, SO_X).

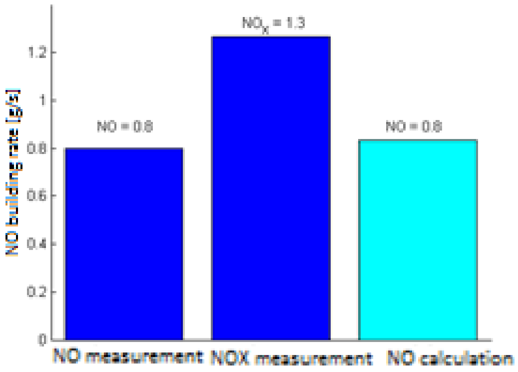


Figure 11: NO emission building rate: measurements of NO and NOX (blue) and calculation of NO emissions (cyan)

The model parameters have been adapted for achieving useful results for any operating point of the test bed engine. Figure 11 gives an example for the measurement and calculation of the NO emission building rate. For further information the total amount of measured NO and NO_2 (= NO_X) is illustrated as well. Once these models had been parametrised and considered valid for stationary operation, they were applied in transient engine operation.

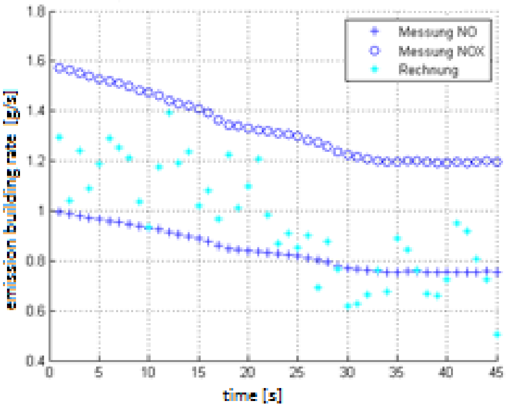


Figure 12: NO emission building rate: measurements of NO (blue stars) and NO_X (blue circles) as well as calculation of NO emissions (cyan)

Figure 12 shows the result of NO calculation and the comparison with measurements during load decrease. This example emphasizes the statement shown in Figure 9: during transient operation the NO building rate does not differ a lot from stationary condition. Moreover, it can be seen that a decrease of engine load leads to an absoltue decrease of NO emissions.

For carbon monoxide emissions (CO) the emission composition in transient operation will be very different (see Figure 10). The same can be stated for carbon dioxides (CO_2), particles and soot. Whilst for CO_2 and for soot (Filter Smoke Number, FSN) mathematical models exist at least for stationary condition, such models are not yet easily established for other emissions as e.g. CO and HC. There is still a lot of need for resarch, first for models at stationary and further at none-steady state condition.

4. SUMMARY, CONCLUSIONS AND OUTLOOK

The performed preliminary studies using comprehensive measurements on a real RoPax ferry as well as test bed trials in an engine laboratory have clearly demonstrated the importance of taking especially into account the transient operation of the vessel's engine during ship manoeuvring periods. Moreover, evidence has been produced that there is an urgent need for specific adjustment of each engine (e.g. on fuel injection times) and needs especially to be considered when for predictions of fuel consumption and emissions. Even a small adjustment in fuel injection time by a technical engineer may lead to either fuel saving or NO_X-reduced operation and therefore has to be sufficiently integrated into simulation models.

Valuable results have been gained and are also of specific interest for improvement of existing training regimes and courses. Training modules developed and tested in earlier research i.a. see Baldauf, M.; Pourzanjani, M. & Brooks, B. et al (2012) and Baumler, R. , Ölçer, A. , Pazaver, A. et. al. (2014) can substantially be improved by taking into account the aspects of engine operations as studied in this paper. Integration of validated and proven simulation models contributes to much more realistic training and support the smooth introduction of sophisticated tools into practice.

The objective of the next step of this on-going research project is to investigate the needed level of detail for sufficient modelling of the engine and combustion processes and to what amount of engine data is needed. The ultimate goal of this R&D is to provide end-users (navigators, captains and pilots on a ships navigational bridge) information to assess and influence the actual level of "green ship operation".

For that purpose enhanced engine simulation models shall be integrated into the existing FTS-Software modules. Integrated simulation modules addressing the ecological impact of current and planned manoeuvres will enable bridge teams providing them with a profound basis for decision making. Furthermore, enhanced engine simulation models will allow future research projects focussing on optimization strategies and considering time-wise aspects, safety, economics and ecological matters.

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Furthermore, the bench tests had been executed during a master thesis at the University of Rostock (Schaub, 2014). These studies are being elaborated more in depth during an ongoing doctoral thesis in collaboration with the University of Rostock (Chair of Technical Thermodynamics) and Wismar University (Maritime Department).

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