Quantifying Fuel Consumption & Emission in Ship Handling Simulation for Sustainable and Safe Ship Operation in Harbour Areas

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Keywords: Fast manoeuvring prediction, Voyage planning, Simulator & On-board training, Emissions & fuel reduction.

Abstract:

There is a unique approach at ISSIMS-Institute called "Rapid Advanced Prediction & Interface Technology" (RAPIT): It provides instant visualization of the ship's track for the intended rudder, thruster or engine manoeuvres, additionally the ship can be steered by a smart interface to allow for the involvement of the professionalism of a human operator for complex manoeuvres. This technology allows for a new method of manoeuvring support which is called "Simulation-Augmented Manoeuvring Design, Monitoring & Conning" – SAMMON. A unique software system was developed together with a small company to apply this method. A novel approach is the concept for the future integration of advanced engine process models, specifically for the transient engine behaviour to predict fuel consumption and emissions during non-steady operation during ships manoeuvres. Interfaced into the SAMMON Software it will enable the user to optimize ship manoeuvring actions e.g. with respect to effective measures for safe distances, shortest time or most effective and least environmental effect.

1. INTRODUCTION – CURRENT STATE

Digital models of maritime systems (nowadays also called „digital twins") have been widely used in ship design for a long time, but now they become also important for the operation of systems, e.g. for manoeuvring ships – And not only for the well-known training in bridge simulators, but in future also for the real ship operation on-board, e.g. as assistance systems for decision support. In earlier papers we introduced specifically the use of mathematical models for Fast Time Simulation (FTS) of ships manoeuvring motion to support in planning and executing ship manoeuvres. The need of such a method, the operational concept of the innovative software and potential benefits were shown e.g. in [1] - [7] .

In contrast to conventional FTS concepts with autopilot control ([11] [12] which are already known for simple manoeuvres only, there is now a unique approach at ISSIMS which is called "Rapid Advanced Prediction & Interface Technology" (RAPIT): With this innovative simulation technology, based on complex dynamic models for ships manoeuvring motion, the ship can be steered by a smart interface to allow for the involvement of the professionalism of a human operator for complex manoeuvres.

This allows to operate the software manually by both:

- Students / young nautical officers for improving training skills and mental model of ship dynamic and
- Experts / professional ship handlers to make better use of their professional knowledge and skills and improve their performance for complex manoeuvres.

This innovative RAPIT technology allows for a new method of manoeuvring support which is called “Simulation-Augmented Manoeuvring Design, Monitoring & Conning” – SAMMON. A unique software system was developed together with a small company (ISSIMS GmbH [3]) to apply this method which consists of various modules. Fig. 1 shows the elements of manoeuvring and ship handling operation - and the potential of SAMMON: on the left side the great potential is shown for the support both for Lecturing & Simulator Training, and on the and right side the elements which could support the application on-board ships.

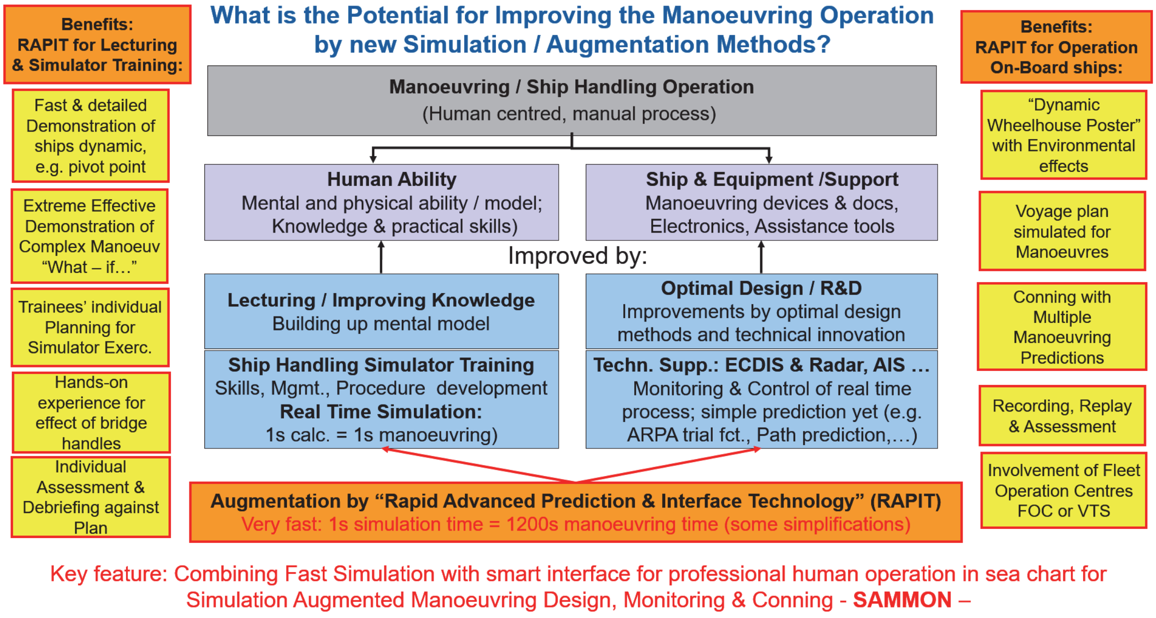
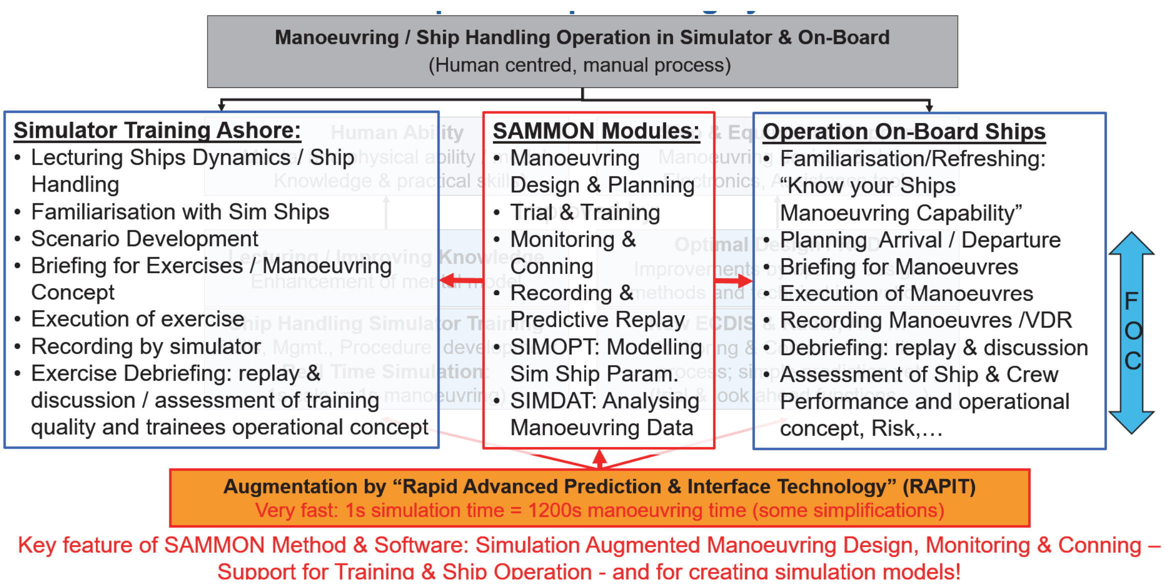


Fig. 1 Process elements of manoeuvring operation and advantages by using Fast Time Simulation FTS in Lecturing & Simulator training as well as support on-board ships.

In Fig. 2 a list is given of the different SAMMON modules (centre) and the elements of using the tools in simulator training ashore (left) and for operation on-board ships (right). It should be highlighted that this software is unique also for training on-board supporting continuous learning. Now the modules of the system have matured and in this paper we will shortly describe some successful applications to show the benefits of the existing software but also to describe the future prospects. The main focus is on future improvements to extend the scope of application - from increasing safety and improving performance to also reduce fuel consumption and emissions during manoeuvres in future.

In Fig. 3 a sample is shown for successful application of the new software at Carnival Cruises Training Centre CSMART at Almere/NL: Two large Touch Screens are used for parallel Presentation & SAMMON application, complete manoeuvring plans can be made as concepts for full mission simulator exercises, not only by the instructor but also by the students which are using Laptops with mouse for operation of the Planning software.



Manoeuvring / Ship Handling Operation in Simulator & On-Board
(Human centred, manual process)

Simulator Training Ashore:
- Lecturing Ships Dynamics / Ship Handling
- Familiarisation with Sim Ships
- Scenario Development
- Briefing for Exercises / Manoeuvring Concept
- Execution of exercise
- Recording by simulator
- Exercise Debriefing: replay & discussion / assessment of training quality and trainees operational concept

SAMMON Modules:
- Manoeuvring Design & Planning
- Trial & Training
- Monitoring & Conning
- Recording & Predictive Replay
- SIMOPT: Modelling Sim Ship Param.
- SIMDAT: Analysing Manoeuvring Data

Operation On-Board Ships
- Familiarisation/Refreshing: "Know your Ships Manoeuvring Capability"
- Planning Arrival / Departure
- Briefing for Manoeuvres
- Execution of Manoeuvres
- Recording Manoeuvres /VDR
- Debriefing: replay & discussion
- Assessment of Ship & Crew Performance and operational concept, Risk,…

Augmentation by "Rapid Advanced Prediction & Interface Technology" (RAPIT)
Very fast: 1s simulation time = 1200s manoeuvring time (some simplifications)

Key feature of SAMMON Method & Software: Simulation Augmented Manoeuvring Design, Monitoring & Conning – Support for Training & Ship Operation - and for creating simulation models!

Fig. 2 Elements of Manoeuvring Training & ship operation and new SAMMON Modules/Tools to improve ship handling by innovative RAPIT

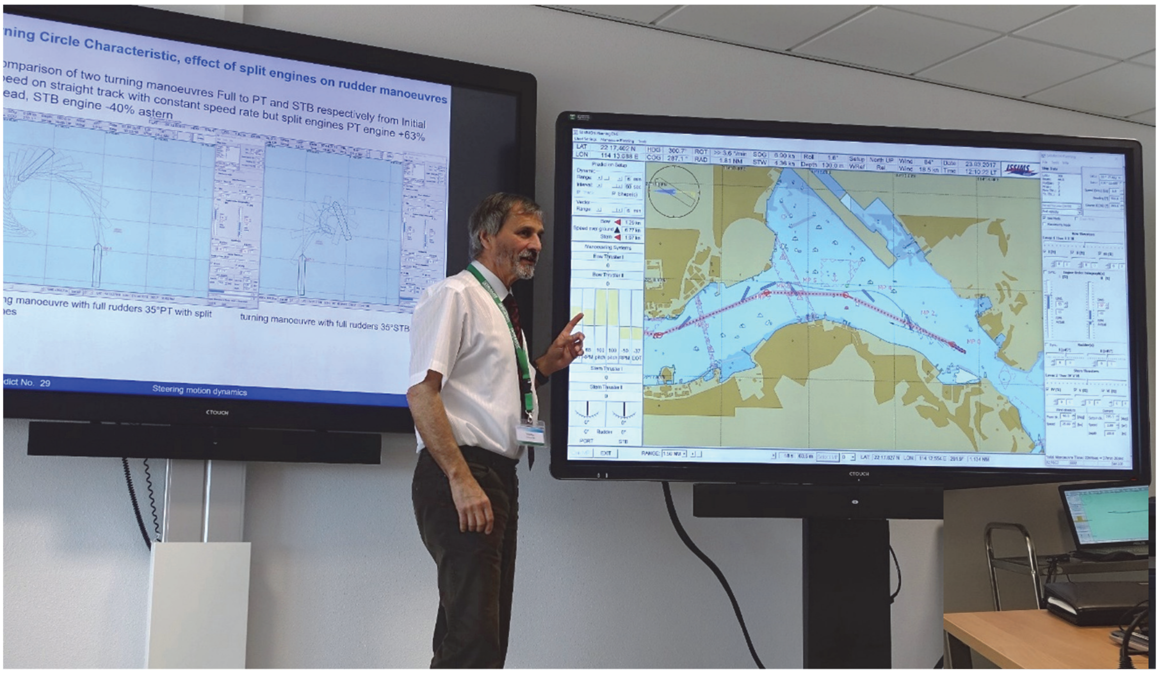


Fig. 3 Carnival Cruises Training Centre CSMART: Lecturing & Training at Touch screen - "Rapid Advanced Prediction & Interface Technology" (RAPIT) is used in the SAMMON Planning for Lecturing effective turning of Cruise ships & wind impact in a Hong Kong arrival exercise

Now the new software is transforming from successful training tool to future use on-board for pre planning as new element in voyage planning for the final part for manoeuvres in ports. In Fig. 4 a sample is shown for planning a manoeuvre for a cruise vessel arrival. The ship manoeuvre is steered by the virtual handle panel on the right side, the resulting ships manoeuvring motion is immediately shown on the central ENC for up to 24 min ahead. Then the new manoeuvring point has to be chosen on that track to add the next manoeuvring segment with new control settings. The full procedure of planning takes about 10 min, this manoeuvre planning was explained in detail e.g. at INSLC 2018 [7] .

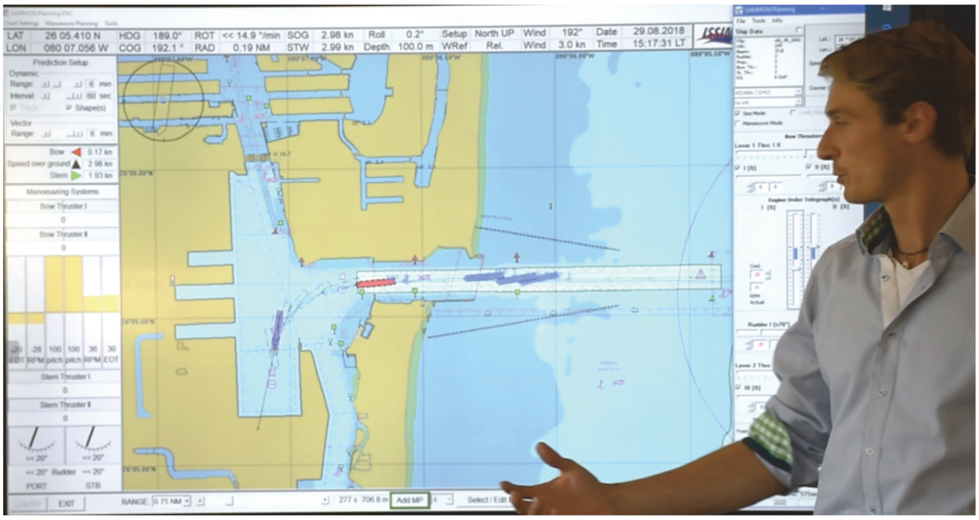


Fig. 4 Manoeuvring Design & Planning Tool Demonstration: Planning of manoeuvring sequence for a cruise vessel for arrival at Ft. Lauderdale by Nautical Officer of AIDA Cruises on touch screen.

Fig. 5 is a demonstration of the Monitoring and conning tool where the FTS is used to display the result of the steering or engine control changes during the ship motion and using the bridge handles. For practical application in training and research the new FTS-features were interfaced to the new Full-Mission and Desktop ship handling simulator Systems, configured by benntec (MarineSoft) Systemtechnik GmbH, based on Rheinmetall Electronics GmbH bridge simulator software ANS 6000 [6] .

Fig. 5 Manoeuvring Monitoring & Conning Module – Demo of using bridge handles in to train "Touch and Feel" for Controls with Multiple Dynamic Prediction showing the effect of any control change immediately as future ship shape on ENC (SAMMON Demo on Bridge Simulator at benntec / Marinsoft Office at Rostock-Warnemünde Germany)

For the time being the SAMMON software is used to design manoeuvres with respect to safety (e.g. to ensure safe distances to limit lines and buoys) and feasibility of a concept (e.g. to make sure that the concept is also possible for high wind forces). In the following chapters will be shown how the software will be used to also allow for efficient manoeuvring procedures, i.e. to also compute the power consumption and analyse the use of controls. Moreover, sustainable aspects of manoeuvring come into view: the software will be extended by modules to predict the fuel consumption and emissions will be added to the core system.

2. IDENTIFYING THE POTENTIAL FOR IMPROVEMENTS AND BENEFITS OF MANOEUVRING PERFORMANCE

2.1 Results from Test trials for Manoeuvres with SAMMON in simulators

In order to expect the possible range of consumptions different Test Trials in a Full Mission simulator had been carried out. The main task for a group of experienced nautical officers was to reach a certain destination, e.g. an anchorage, crossing a TSS and avoiding other ship on anchor. Every test candidate had to carry out different scenarios in order to eliminate bias due to the learning effect,. The first attempt had to be carried out without prediction, a second one with prediction and the third one with prediction and manoeuvre planning. Every candidate had to make his own manoeuvre plan ahead, so that he can carry out his own individual concept. Fig. 6 shows a sample of the manoeuvring track generated by a candidate during the simulator trial. The blue line represents the track crossing the TSS to sail to the assigned anchorage position at the end of the track avoiding other ships at anchor.

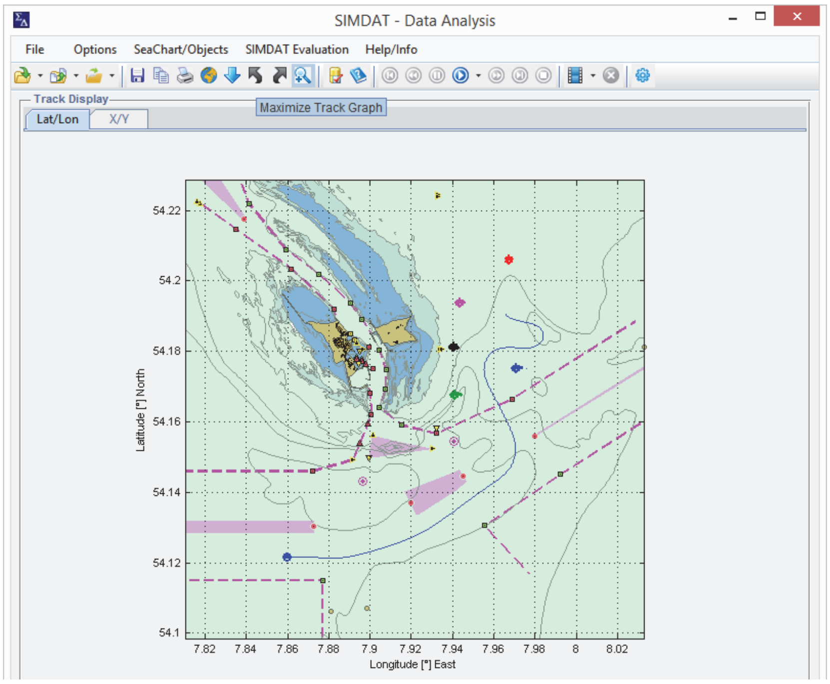


Fig. 6 Sample for manoeuvring track generated by candidate during the simulator test run

Fig. 5 shows the result of these test trials. The power consumption is dropping in average down to 80% with the sole use of prediction compared to a manoeuvres without any assistant tool. The power consumption is reduced to around 65% if the candidate has carried out its manoeuvres with pre-planning and on-line prediction. Additionally, the usage of the thruster drops around to half of the previous numbers. In Fig. 8 the average usage of rudder commands in these scenarios can be seen. The small rudder changes drop down to 60% in average.

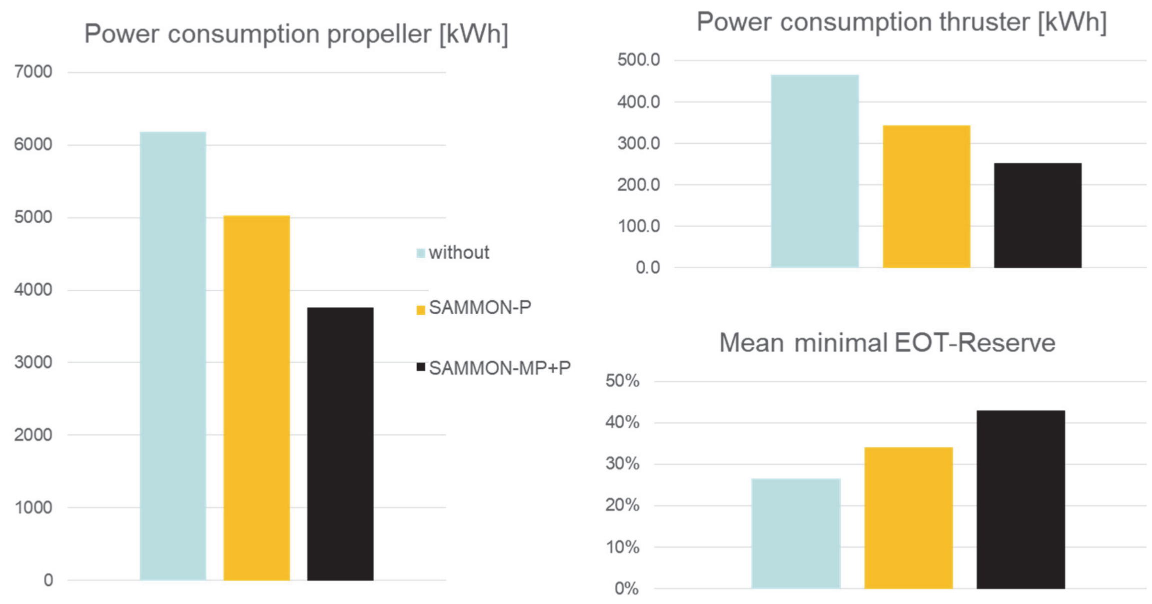


Fig. 7 SAMMON Advantage: Savings in Test runs with & without pre-planning and online-prediction

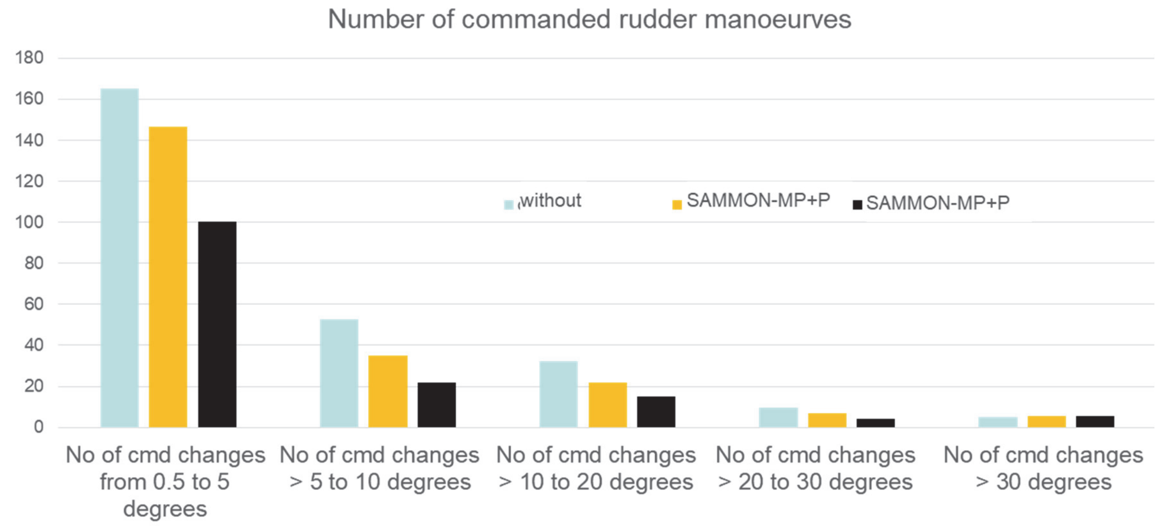


Fig. 8 SAMMON Advantage: Efficiency in Test runs with and & without pre-planning and online-prediction

For emphasizing the impact of planning and prediction in Fig. 9 the differences of rudder commands can be seen. On the left side are the rudder angles in one scenario without any prediction and assistant tools. On the right are the rudder angles displayed with planning and prediction. As a conclusion the amount and amplitude of rudder changes decrease clearly.

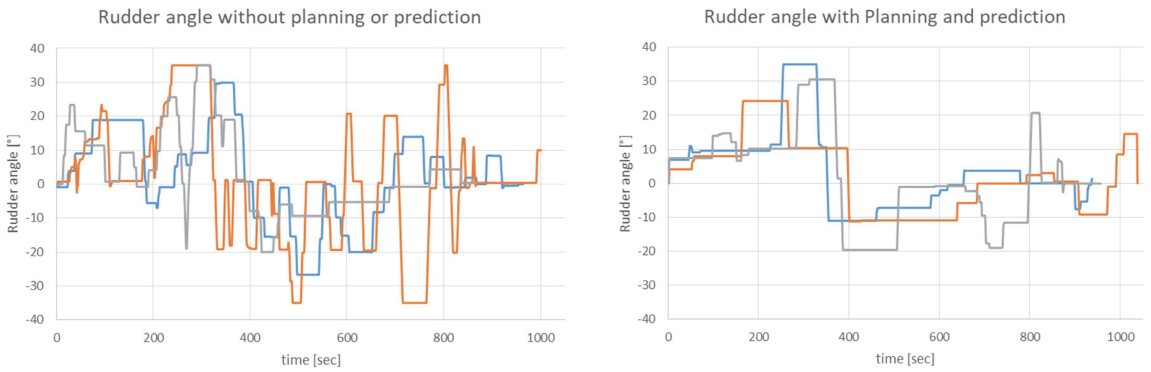
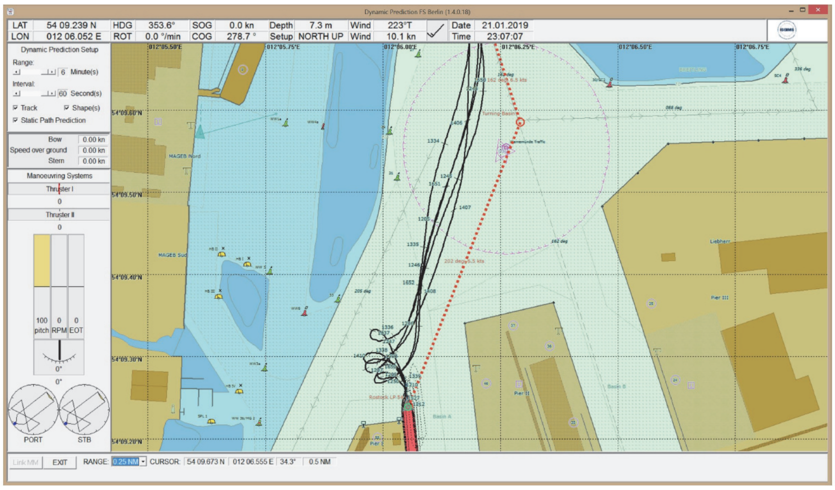


Fig. 9 Comparison of rudder angles during manoeuvring without (left) and with (right) pre-planning and online-prediction

2.2 Discussing Manoeuvres recorded for a Ro-Ro Ferry Arrival

In this chapter manoeuvres of a Ro-Ro ferry are shown which were recorded from arrival manoeuvres of the vessel at the Port of Rostock / Germany. An analysis will be made to find potentials for improvements of the manoeuvring performance. In Fig. Fig. 10 the tracks are displayed from 5 manoeuvres together with the last part of the route plan represented by the red dotted lines. It is obvious that normal route plans which are regularly only straight lines or circular segments are not suitable for the voyage planning regulation according to IMO which was already discussed and proposals were made to use the manoeuvring planning methods applying the RAPIT technology in the SAMMON planning tool to generate manoeuvring plans with Manoeuvring Points. In Fig. 11 one manoeuvre is further analysed which was the closest to the route plan. The time history of the commands to control the vessel manually and the ship responses reveals that there were many actions necessary to steer the vessel, some of them are alternating back and forth, left and right which is known to not be very efficient. As an alternative Fig. 11 b) the same manoeuvre under similar conditions was planned by means of the Planning tool – it is obvious that the controls needed not to be used so frequently and with smaller magnitudes. The responses e.g. the rate of turn is smaller and smoother. Additionally, the planned manoeuvre is about two minutes shorter than the real ship trial. The expectation is, that those manoeuvres with smaller control intensity are also smaller in fuel consumption and emissions.


Dynamic Prediction FS Berlin (1.4.0.18)

LAT	54 09.239 N	HDG	353.6°	SOG	0.0 kn	Depth	7.3 m	Wind	223°T	Date	21.01.2019
LON	012 06.052 E	ROT	0.0 °/min	COG	278.7 °	Setup	NORTH UP	Wind	10.1 kn	Time	23:07:07

Dynamic Prediction Setup
Range: 6 Minute(s)
Interval: 60 Second(s)
☑ Track ☑ Shape(s)
☑ Static Path Prediction

Speed over ground
Bow 0.00 kn
Stern 0.00 kn

Manoeuvring Systems
Thruster I 0
Thruster II 0
100 pitch 0 RPM 0 EOT
0°
0°

RANGE: 0.25 NM CURSOR: 54 09.673 N 012 06.555 E 34.3° 0.5 NM

Fig. 10 Recordings of Five different manual controlled ships tracks (black) when berthing of a ferry in port of

Rostock compared with the route plan (red dotted lines)

Table 1 – Comparison of power consumption during manoeuvring and berthing

Power consumption of each measurement		
Measurement	***Consumption (kWh)***	***Percentage***
0131	487.76	115%
0758	468.67	110%
1633	423.75	100%
2030	502.81	119%

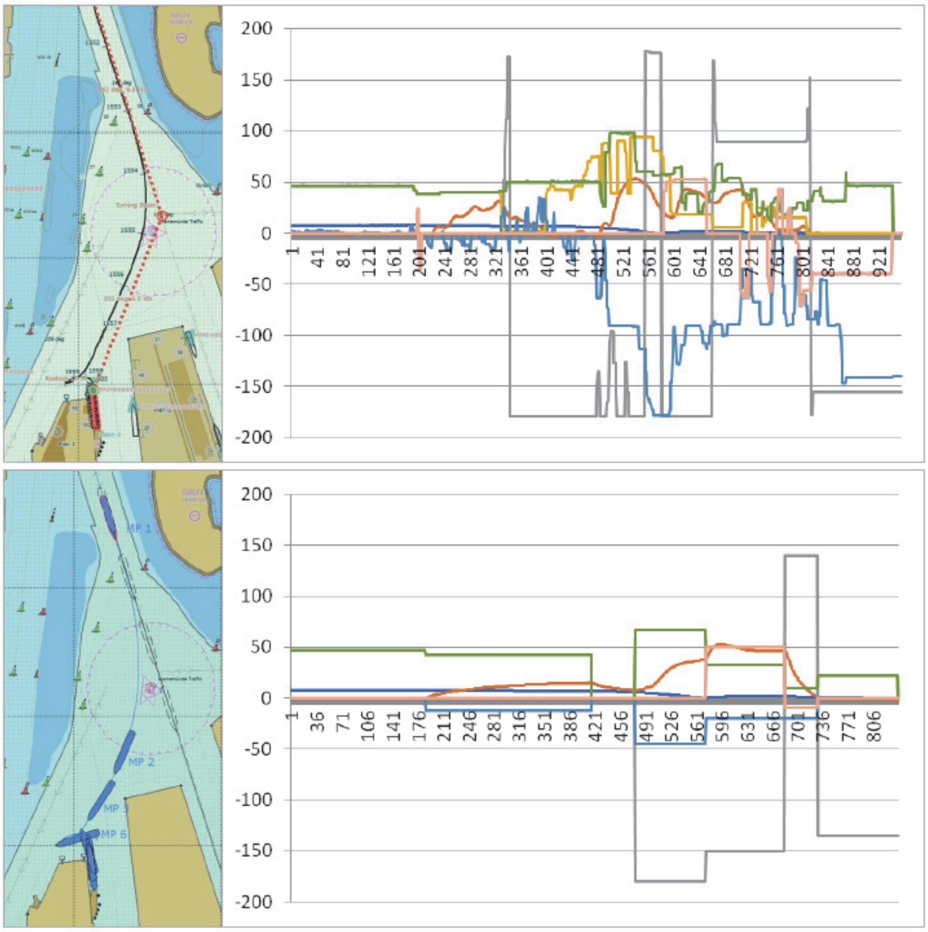


Fig. 11 Comparison of ships track (left) and time history of commands and ship responses (right) for a berthing manoeuvre of a ferry (POD power - yellow and green, POD angles - grey and blue, bow thrusters, power - salmon pink and light blue, speed over ground - dark blue, and the rate of turn - orange)

a) recorded data from real ship manoeuvre

b) Manoeuvring plan from SAMMON Planning tool with Manoeuvring Points to change commands at positions represented by the blue contours

To compare real ship manoeuvres it is necessary to gather data from the power output, caused by different manoeuvring approaches. Table 1 shows the differences in power consumption from the mole to the port carried out by different crew members under the same conditions i.e. low wind from the same direction, no current and no obstructive traffic. The measurements have been carried out over a time of 8 months and are leading in the way of differences in each measurement.

3. CONCEPT FOR FUTURE METHODS FOR CALCULATING FUEL CONSUMPTIONS AND EMISSION

3.1 Introduction into the Concept

In order to extend the software by modules to predict the fuel consumption and emissions the following two different approaches are followed as shown in Fig. 12. The first one as shown in chapter 3.1 is based on thermodynamic equations in order to calculate the NO_x and soot formation on a physical proven base. The second approach uses an artificial neural network (ANN) that could be trained by a variety of data bases e.g. a thermodynamic model like in chapter 3.1 or a set of measurements. Fig. 12 displays the concept of integration into the existing SAMMON model. It consists of the calculation of the existing ship's model including a simplified engine model in order to generate an engine torque for prediction. The engine model itself will be separated from an engine model and will consist of an PI –Governor for the calculation of the fuel consumption and of a detailed engine model or an ANN depending on the calculation speed, where the ANN can be trained using the data of the detailed engine model.

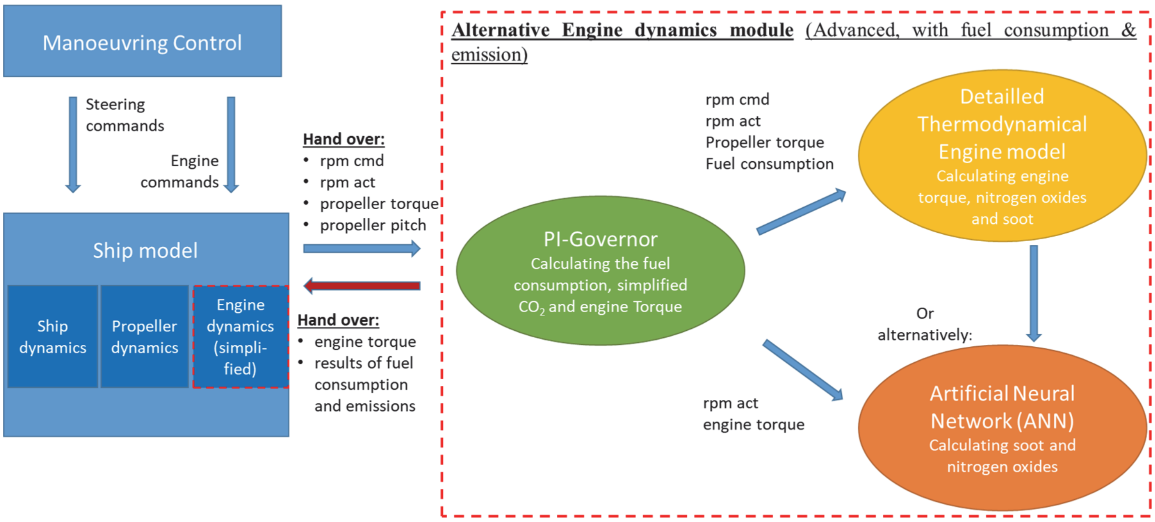


Fig. 12 Existing simulation model in the SAMMON system and intended expansion of advanced engine model

3.2 Thermodynamic simulation model for calculation of soot and Nitrogen Oxides.

The formation of soot and nitrogen oxides is strongly depending on the combustion process inside the engine. The NO_x – formation is determined mainly by the temperature inside the combustion chamber. The soot formation is additionally depending on the air to fuel ratio. The calculations of emissions are more or less an output of the fuel delivered by the governor. In order to achieve more realistic engine simulation it is necessary to model the governor and the automation system more precisely. In contrast to the existing simplified engine model (which is based on look-up table controlled processes) the signal of the Engine Order Telegraph will regulate the fuel flow to the engine and to the cylinder simulating the combustion process. The air intake into the combustion chamber is depending of the geometrical shape of the inlet valve, the opening and closing times and the charge air pressure before the combustion chamber. Also the turbocharger that is driven by exhaust gas has a substantial impact, its mass inertia is the main source for soot during manoeuvring. The main base for a calculation of the average temperature inside the cylinder is the basic energy balance (1).

$$\frac{dU}{dt} = -p\frac{dV}{dt} + \dot{Q}_B + \dot{Q}_W + \dot{H}_{BB} + \dot{H}_{in} - \dot{H}_{out} \qquad (1)$$

The inner energy u in formula (2) can be ascertained by a function of temperature and air-fuel ratio λ according to [15] . The pressure volume work pdV expresses the work carried out by the piston in the up and down movement during the compression or expansion phase. $\dot{Q}_B$ is the heat released during fuel combustion. The time, duration and form of heat release can be described using approach in [16] . $\dot{Q}_W$ is heat flow through the liner wall. The heat transfer coefficient can be calculated using the approach in [17] $\dot{H}_{in}$ and $\dot{H}_{out}$ stands for the enthalpy flow through inlet and outlet valve.

$$u(T,\lambda) = 0{,}1445\left[1356, + \left(489{,}6 + \frac{46{,}4}{\lambda^{0{,}93}}\right) * (T - T_{Bez})10^{-2}\right.$$

$$\left. + \left(7{,}768 + \frac{3{,}36}{\lambda^{0{,}8}}\right)(T - T_{Bez})^2 10^{-4} - \left(0{,}0975 + \frac{0{,}0485}{\lambda^{0{,}75}}\right)(T - T_{Bez})^3 10^{-6}\right] \quad (2)$$

With the thermodynamic average temperature it is possible to calculate the temperature of the flame front T_2 and the temperature of the unburned zone T_1 according to [18] and to estimate the formation of NO_x in (3), using the mechanism described in [19] . The Arrhenius–factor $k_{1,r}$ has the highest activation energy delivered by the temperature T_2 (detailed description can be found in [14]).

$$\frac{d[NO]}{dt} = k_{1,r}[O][N_2] + k_{2,r}[N][O_2] + k_{3,r}[N][OH] - k_{1,l}[NO][N] - k_{2,l}[NO][O] - k_{3,l}[NO][H] \quad (3)$$

Fig 13 is presenting the approach of the detailed engine model [14] , that will be used to replace the simplified one in the ship's model.

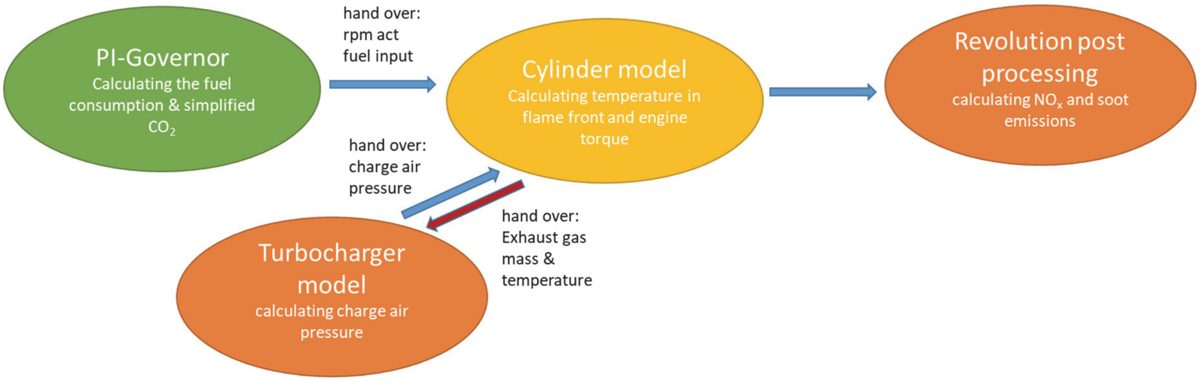


Fig. 13 Process overview of detailed engine model

3.3 Using an Artificial Neural Network (ANN) to be trained by Experiments for calculation of soot and Nitrogen Oxides

Purely data-based models do not need any information about the physical, chemical or other laws and relationships that determine the processes to be modelled. Attention is to be payed to numerous data of high quality covering as many input/output combinations as possible. Data can come from theoretical models or from test bed measurements. For the present studies the data is coming from the MAN 6L23/30 test bed engine. With respect to a restricted availability of input data from the ship model in the SAMMON software, only two input data will be defined: The engine revolutions and the fuel consumption. For clarity, the following examples will only focus on the data-based modelling of particulate matters (PM) which consist mainly of soot. The process of soot formation is not yet fully understood and described and even less the formation of PM during transient engine operation. For this reason, it is of special interest to find a reliable data-based method to create an instrument in order to simulate the formation of PM. Furthermore, the following examples refer to the test bed engine running in generator mode. Generator mode means that the commanded engine revolutions are constant. The PI-governor is responsible to hold the revolutions as far as possible by adapting the fuel rack position.

Fig. 14 presents the particulate matters depending on the engine torque. Close to the zero-PM line, a couple of clusters can been seen. These are the measurements during stationary engine operation. The measurements used for the training and the validation of the data-based model are shown in Fig. 15. These figures make it evident, that during stationary operation in generator mode almost no soot is emitted. But as soon as increasing the engine torque the formation of PM rises to the hundredfold of the stationary values. In propeller mode, when engine torque and speed increase in parallel, the amount of emitted PM during transient operation differs even more from the values of stationary engine operation.

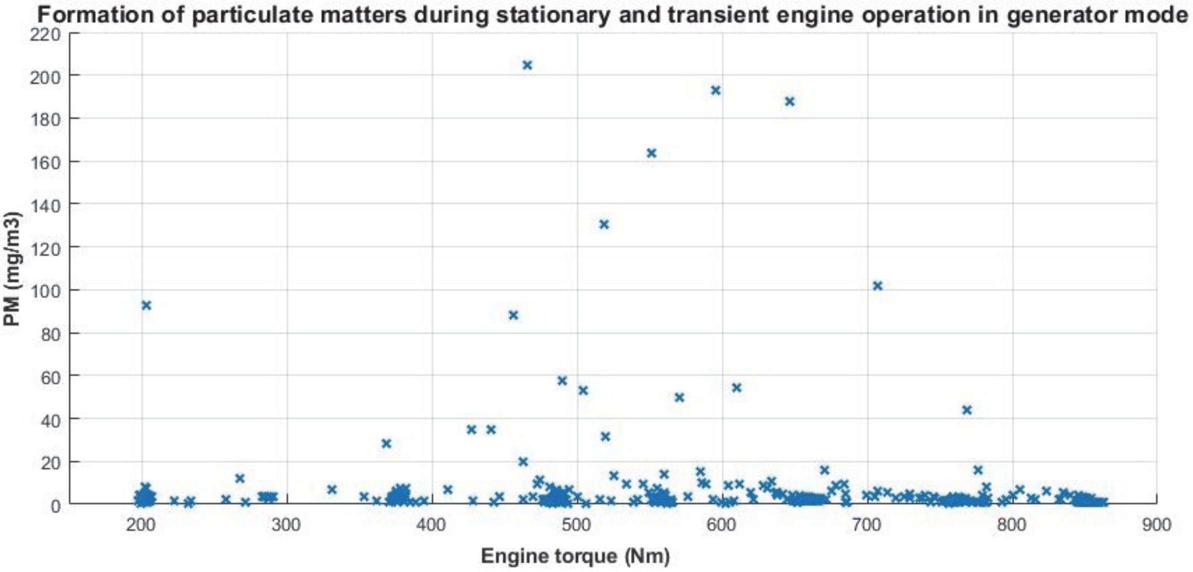


Fig. 14 PM emissions at different engine torques measured from the MAN 6L23/30 test bed engine

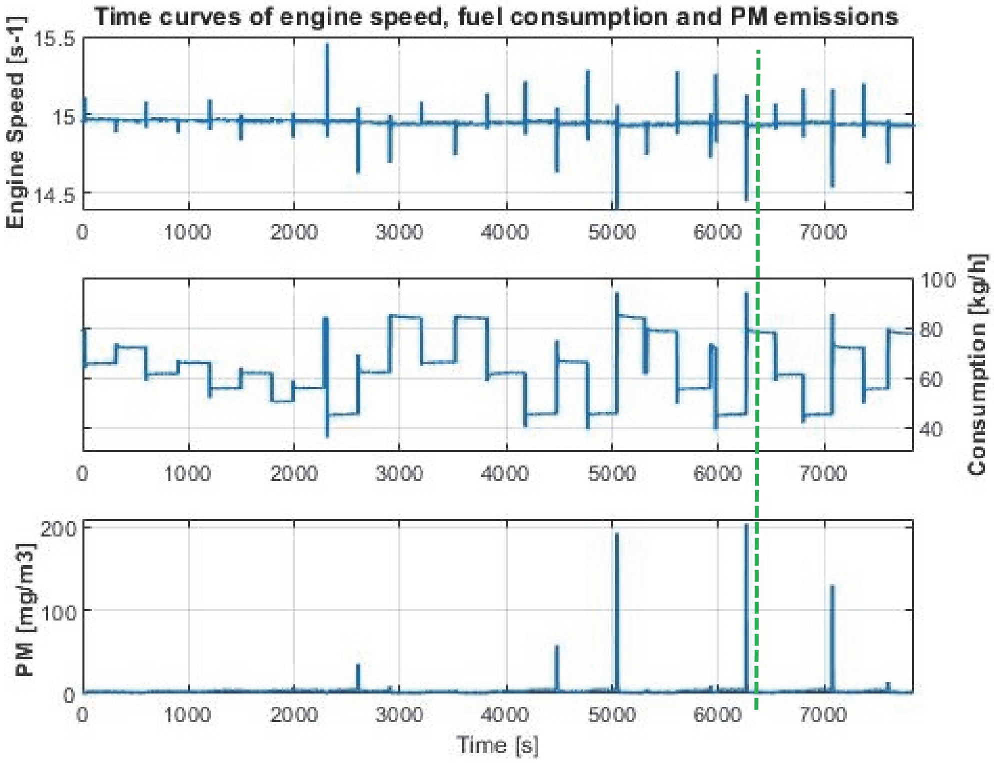


Fig. 15 Time curves of input and output data. Green dotted line shows the cut between training (75%) and validation (25%) data.

Among a big variety of data-based model architectures an Artificial Neural Network (ANN) architecture has been selected for a first attempt. Due to their flexibility regarding input dimensions and their relatively good interpolation characteristics they seemed to be adequate for the present study.

The observations presented above lead to the conclusion that PM formation during transient operation differs completely from stationary results at same load levels. Therefore, not only the inputs of the current time t_0 have to be considered in a data-based dynamic model but also their preceding values. Such a time delay neural network (TDNN), a so-called lumped dynamics recurrent network, leads to a multi-dimensional input vector exceeding the two input variables by multiples.

The Multilayer Perceptron (MLP), being a widely known ANN architecture was selected for a first approach. It consists of an input vector (u), one or more hidden layers with neuron vectors (h) and one output vector (y) as schematically shown in Fig. 16.

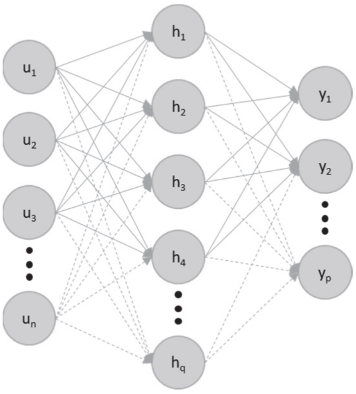


Fig. 16 MPL network architecture (inputs u, hidden neurons h, output y)

The neurons of the hidden layer are called perceptrons. All input data are multiplied by parameters (synaptical weights) in order to intensify or attenuate the input effect on the following neuron. All input signals are added up and the sum enters a nonlinear activation function that transforms the result which is then forwarded to the next layer. For the present study, a multiple-input single-output (MISO) network with one hidden layer is designed. In contrast to networks with internal dynamics the herein presented approach describes an external dynamic (lumped dynamics) network. For training purposes, the input vector contains measurement data of the input variables u and their time histories. The output value at t_0 is needed to determine the difference between the desired and the current network output. The difference is propagated back through the network in order to adapt the parameters (synapse weights). Due to the fact that the model is nonlinear in its parameters no direct optimization strategy is applicable. The Levenberg-Marquardt algorithm, a more robust extension of the Gauss-Newton algorithm, has been chosen for training with backpropagation.

First practical experiments with data from the 6L23/30 test bed engine have been performed by taking a data set of 15 load increases in generator mode (Fig. 15). 75% of the data served for training whereas 25% were retained for validation. The number of hidden neurons was set to 20 and the delay to 70 seconds, taking only one sample in ten cycles.

Fig. 17 shows the curves of the training data in green colour. The data points are almost totally covered by the blue curve displaying the simulation of the same data with the already trained network. This means that the network suits well with the dynamics of the training data except for the very high PM peaks.

For validation the last 25% of the measurement data set was taken. As already observed in the pre-validation making use of the training data (blue curve in Fig. 17) the network does not yet calculate the real height of the PM emission peaks. Zooming into the stationary simulation within Fig. 18 it can be stated that in the average the simulation suits quite well with the validation data, but there are a lot of small oscillations in the simulation.

This first attempt to simulate the dynamics of the PM emissions during transient engine operation by means of an ANN is a promising approach. Nevertheless, there is still work to be done in order to reproduce the emission peaks with more reliability and to get a smoother simulation. More training data will be provided soon, but in addition, a division of the ANN in part models as well as internal dynamics will be taken into account for further investigations.

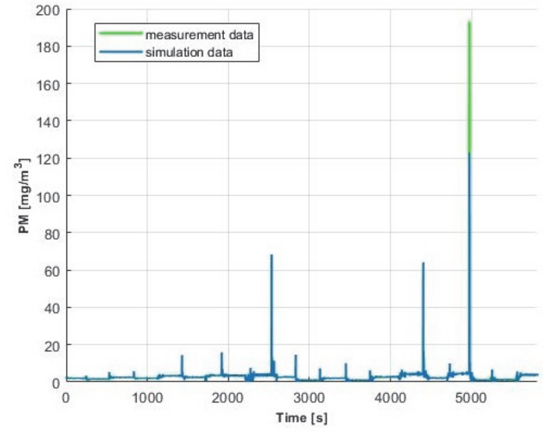


Fig. 17 Training data (green) and pre-validation by simulating with the same input data as used for training (blue).

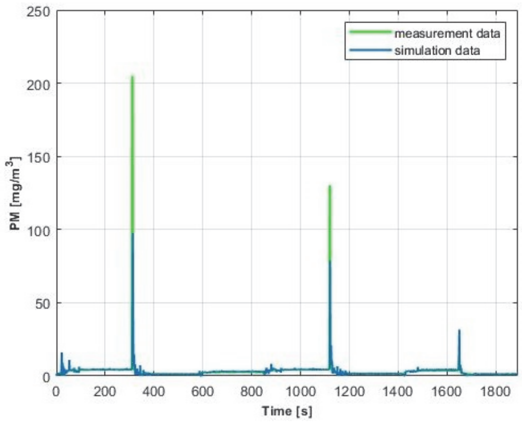


Fig. 18 Validation of network by using the validation data set.

Recently, this trained ANN has been transferred to an interface for data exchange with the FTS ship model in order to simulate the fuel consumption and soot emissions during manoeuvres (Fig. 19). A model was generated for a fictive ship which size was adjusted to the size of the testbed engine. During the first few seconds, the ANN needs to collect data from its two inputs fuel consumption and actual propeller revolutions in order to calculate the output which is soot from the start at the green line.

Unfortunately, there is no possibility for validation, but for a qualitative verification of the method, which is working quite well. In future, measurements from a real vessel, e.g. the above mentioned Ro-Ro ferry, could be taken in order to train the ANN by data coming from a real ship.

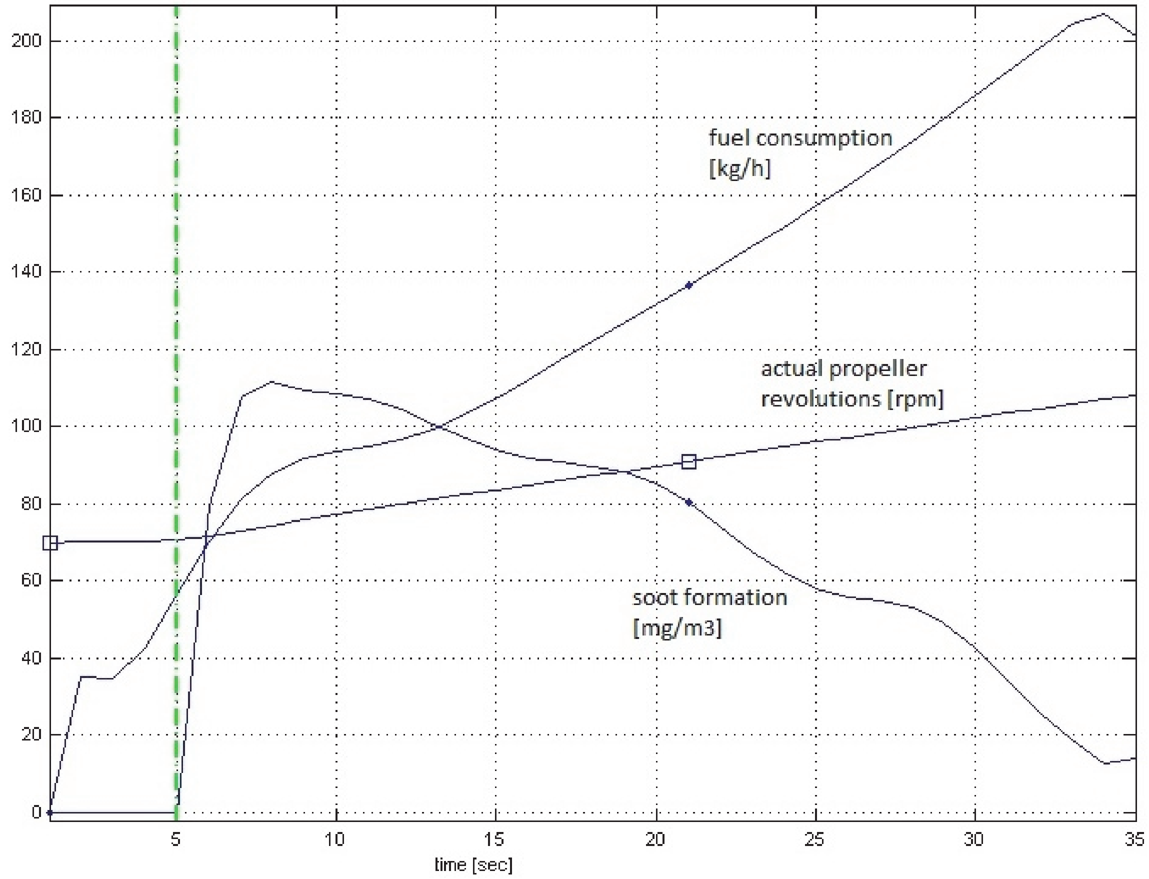


Fig. 19 Verification of network by using the trained ANN for a fictive ship model with FPP for acceleration from 20 to 90% EOT

4. CONCLUSIONS / OUTLOOK

Fast Time Manoeuvring simulation and specifically the new technology “Rapid Advanced Prediction & Interface Technology” (RAPIT) as core element of the unique SAMMON method for Simulation-Augmented Manoeuvring Design, Monitoring & Conning has proven its benefits for both lecturing and training for improving ship handling knowledge and skills. It can be used as an individual training tool but unfolds its potential interfaced to a full mission simulator which is successful implemented with the Rheinmetall Electronics ANS 6000 Ship

Handling Simulator, manufactured and distributed by MarineSoft / benntec. It increases the effectiveness of simulation training which can be seen in the fact that the success rate of the trainees is increasing: An analysis has shown that navigators are able to successfully manage demanding ship handling exercises after preparation & briefing using the SAMMON planning tool and even more to perform the manoeuvres with less power consumption.

This shows there is a high potential for optimisation to reduce manoeuvring time and power consumption due to less and better adjusted control action during the manoeuvres. A first approach was shown how to introduce modules for estimating fuel consumptions & emissions during the manoeuvring process based on thermodynamic simulation models and Artificial Neural Networks. For the time being the ANN model was trained only for a small diesel engine from our Ship Engine Lab, but in future also measurements with real ship engines will be used to achieve higher realism.

ACKNOWLEDGEMENTS

The presented results were partly achieved in several research projects:

- MultiSimMan and MultiSimMan-GREEN ("Multi Media for Improvement of MET"), funded by the German Federal Ministry of Education and Research (BMBF) surveyed by DLR-Project Management Agency.
- GALILEOnautic 2 project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) surveyed by the Project Management Agency DLR (registration number FKZ 50NA1811 and 50NA1809)
- Membran project (03SX423E), funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and surveyed by the Project Management Agency PTJ
- ProGreenShipOperation - Simulation-based training module to promote green energy-efficient ship operation – funded by the International Association of Maritime Universities IAMU.

The professional version of the SAMMON software has been further developed by the start-up company Innovative Ship Simulation and Maritime Systems GmbH (ISSIMS GmbH) [3] .

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