A holistic ship model for variable speed generation system on a RoRo vessel

Guohong Tian[1*], *Aitor Juando*[2], *Jonathan Heslop* [1], *Manuel Solla*[2], *Tony Roskilly*[1],
Adrián Sarasquete[2], *Javier Rodríguez*[2]

[1] Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle, UK

[2] VICUS DESARROLLOS TECNOLOGICOS S.L., C/ Jacinto Benavente Nº 37 3º, 36202 Vigo, Spain

* *corresponding author*

Abstract

This paper presents an approach of a combined model for a variable speed generation system on a RoRo vessel in order to study engine operation and efficiency as part of the European FP7 funded project, TEFLES. Two numerical models were separately developed to reflect the performances of a 4-stroke medium speed diesel engine and a RoRo ship with Controllable Pitch Propeller (CPP) respectively. The two models were calibrated and validated against data provided by the engine manufacturer and sea trail data provided by a RoRo ship owner. The engine model was used as a platform to provide data to the global RoRo ship model over varies operational conditions. Validation of the combined holistic model showed a good agreement with test data for both fuel economy and emissions. The holistic model was then used to study different ship's operation scenarios including at sea, manoeuvring and in port. The results will be issued to assess various energy recovery and emission abatement technologies being studied as part of the TEFLES project, with emphases on their impact on fuel consumption and emissions.

Keywords: engine model, ship model, variable speed generation

1. Introduction

Shipping is the most important means of transportation today and very likely in the near future. About 90% of all global cargo is transported by sea in vessels powered by diesel engines run on marine diesel oils (MDO) and residual fuel oils (RFO) (Jürgens 2009). The world's shipping fleet current consists of over 100,000 vessels larger than 100 gross tonnes, which consume up to 289 million tonnes of residual fuel every year, with an estimated growth of 2-6% per year (Corbett 2003; Endresen 2003; Eyring 2005; Eyring 2005).

Oceangoing ships with slow/medium-speed diesel engines usually burn low-quality residual fuels which contain a higher percentage of sulphur and heavy metals (Lack 2009). International commercial shipping vessels operate across international waters with little or inconsistent regulation of fuel quality or pollution emissions. Apart from CO_2, the expected emissions with environmental impact from shipping include nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO) and particulate matters (PM). CO_2 is the most ubiquitous greenhouse gas and generally regarded as one of the main sources that cause global climate change. Shipping vessels are responsible for approximately 3.3% of the global anthropogenic CO2 emissions (Eyring 2005), 15-30% of fossil fuel sourced NOx emissions (Corbett 2007), 5-8% of anthropogenic SO2 emission and as much primary PM emission as road traffic (Eyring 2005).

The world's marine governing bodies have introduced a number of legislative regulations to reduce airborne emissions from ships. The International Marine Organisation (IMO) introduced legislation to prevent pollution under the MARPOL 73/78 regulations "The International Convention for the Prevention of Pollution from Ships", specifically deals with air emissions, which was amended by

MARPOL 93/97. The aims were offset future global limits for NOx, SOx and PM emissions from shipping through the implementation of technology and best practises.

Alongside with the emissions control requirement, there is a huge demand for fuel consumption reduction. In 2007, app. 369 million tonnes of fuel were burned by shipping , of which approximately 286 million tonnes were Heavy Fuel Oils (HFO) representing about half of the world's HFO production (Lauer 2009). Depending on the type of the vessel, the fuel costs can account for more than 50% of the operating cost, therefore changes in fuel price affect the relative cost structure significantly.

In 2010 a consortium including both industrial and academic partners was built to focus on the technologies to reduce emissions and fuel consumptions under varies of scenarios, mainly at sea, manoeuvring and in port. Under the framework of this project "Technologies and Scenarios for Low Emissions Shipping, (TEFLES)", a detailed engine model was built to provide basic fuel consumption and emissions data under different working conditions. This data was fed into another holistic ship model to study the different scenarios. The results presented in this paper will be used as a baseline to assess the impact of technologies in later work.

2. Models Description

Two numerical models were developed based on data and information from an engine run on-broad a real RoRo vessel. An acoustic engine model was built in an engine modelling software package, WAVE, with detailed geometry information. The engine model was then calibrated and validated against data from the engine manufacturer and ship sea trial measurements. Consequently, the model was run under different operational conditions and provided data of the engine performance profile and emissions. This data was then used in the holistic ship model, which was developed in a Simulink environment. The ship model considered the ship's hydrodynamics, engine performance and weather conditions. The model was calibrated using sea trail measurements from the RoRo vessel use in the project.

2.1. Engine acoustic model

The RoRo vessel is equipped with two 16-cylinder medium speed diesel engines. The engine specifications are shown in table 1. Engine geometric details, such as intake and exhaust pipes and junctions, were obtained from the ship's owner and the engine's manufacturer. Turbo-charger information was provided by other project partner. As fuel properties have a great impact on engine performance, the information was gathered from marine fuel different sources.

Table 1: Engine specifications

Cylinder number	16
Cylinder configuration	V-form
Cylinder bore	460 mm
Stroke	580 mm
Piston displacement	96.1 l/cyl
Number of valve	2 in, 2 exh
Rated speed	500, 514 rpm
Direction of rotation	Clockwise
Firing order	A1-B1-A3-B3-A2-B2-A5-B5-A8-B8-A6-B6-A7-B7-A4-B4

WAVE is a professional software package for IC engine simulation. In WAVE the flow-in-flow networks are calculated as a quasi-one dimensional compressible flow governed by mass, energy and momentum conservation equations, as shown below.

$$mass = \frac{dm}{dt} = \sum \dot{m} \tag{1}$$

$$energy = \frac{de_T}{dt} = \sum mh + sources \tag{2}$$

$$momentum = \frac{dmu}{dt} = -A\frac{dp}{dx}dx + \sum \dot{m}u - sources \tag{3}$$

A 2-zone combustion thermodynamics process is used to calculate the potential NOx emissions. The NOx model accounts for the formation for the “prompt” or “flame-formed” NO. During the prompt formation phase and the Zeldovich mechanism, all the NOx emissions are assumed to NO.

$$N + NO_2 \rightarrow N_2 + O \tag{4}$$

$$N + O_2 \rightarrow NO + O \tag{5}$$

$$N + OH \rightarrow NO + H \tag{6}$$

The overall burned zone is treated as an open, stratified system in which further NOx formation takes place depending on the temperature, pressure, and equivalence ratio of the burned packet. For the three reactions, the rate constants used to solve the concentration of NO versus timing are given by:

$$R_1 = A * ARC1 * e^{(T_a * AERC1/T)} \tag{7}$$

$$R_{2/3} = A * e^{(T_a/T)} \tag{8}$$

Where: A = pre-exponential constant; $ARC1$ = user-entered pre-exponent multiplier; T_a = activation temperature for the reaction; $AERC1$ = user entered exponent multiplier; T = burned-zone temperature.

A number of assumptions were made due to the lack of information, including valve actuation, fuel injections profiles and exhaust pipe conductivity, etc. Therefore, validation was carried out to bring confidence of the model before it is used.

2.2. Ship model

The holistic ship model considered the major affecting factors. It consists of following modules:

•*Hydrodynamics*. It takes into account ship resistance for different speeds and drafts. Weather and appendage added resistance is also computed.

•*Propulsion*. Module calculates propeller performance for different conditions. For given advance ratios (J) and resistance requirements, thrust and torque, are calculated from KT -10*KQ plots.

•*Engine*. Based on the WAVE model results this module is able to give engine operating parameters (BSFC, emissions, exhaust temperatures, etc) for every instant in the ship operating profile.

•*Auxiliary plant*. Depending on if she is using Shaft generator or auxiliary gensets, to provide auxiliary load demand, the model calculates fuel consumption from Main engine or auxiliary engines module.

•*Heat recovery*. This module takes into account wasted heat from engine and calculates its recovery for heating or other purposes. Efficiency of the process is also considered depending on the ship’s equipment characteristics.

•*Emissions*. NOx, CO2, SOx and PM emissions are calculated in this model. NOx and CO2, obtained directly from the WAVE engine model, SOx and PM were estimated using literature formulations (LRS 1995; EPA Oct, 2002).

The schematic of the ship model is shown in Figure 1.

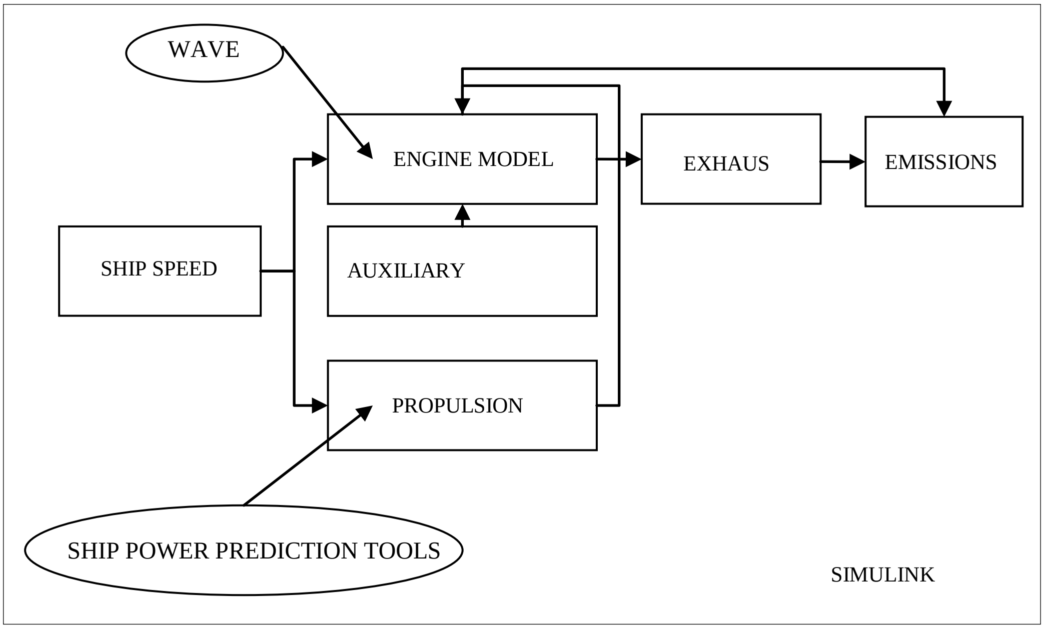

Figure 1 Schematic of ship model

3. Results and Discussion

The model was firstly validated using the engine manufacturer's data and sea-trial measurement data from the subject RoRo Vessel. Engine performance, including power, peak in-cylinder pressure and exhaust temperature before turbine, was chosen as the parameters to compare and validate the model across nine different engine loads and speeds. The first two chosen parameters represent engine performance and combustion characteristics while the last parameter directly affects the after-treatment system and economiser, which will be studied later in the TEFLES project. The input for the fuel delivery rate for the engine model was calculated and set in the model from information provided by the engine manufacturer. The results of model validation are shown in Figure 2. It is clear that the model can provide a fairly accurate simulate the real engine's operational performance. The average error in predicted brake power is -5.8% and standard deviation is 0.01, as shown in Figure 3. In all cases for the different engine operation conditions, the simulation results were always slightly lower than the test data results, however, only with marginal uncertainties. This was found to be true for in-cylinder peak pressure as well. For these two factors, the differences between modelled and measured results are around 5%, which is reasonable in this type of modelling and simulation work.

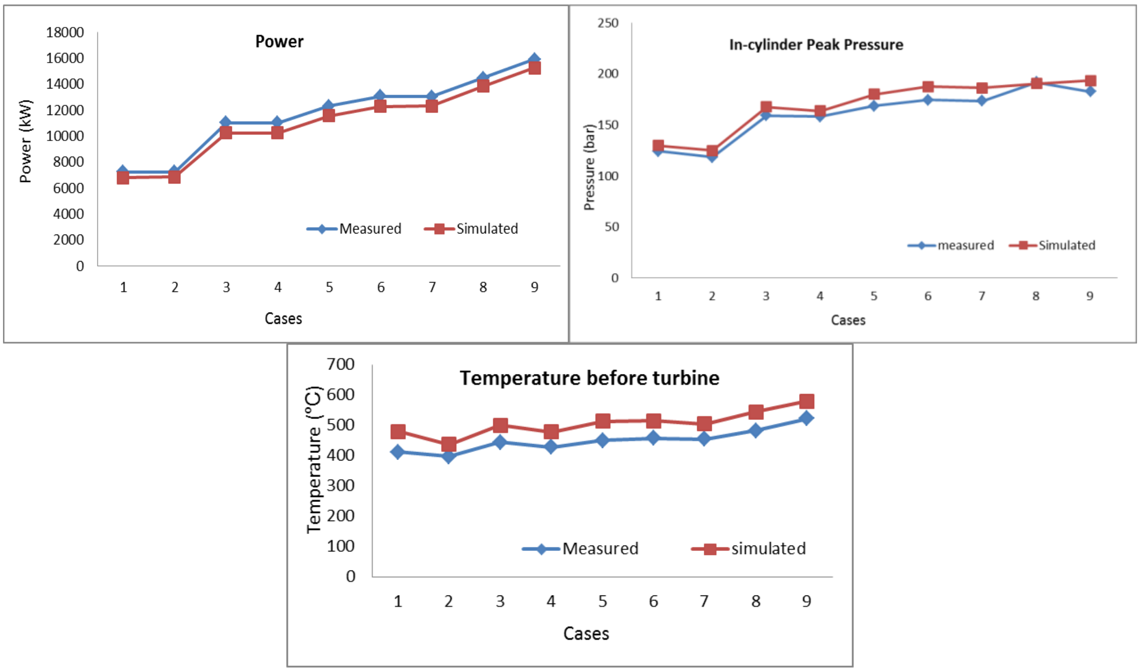

Figure 2: Model validation by power, in-cylinder peak pressure and exhaust gas before turbine

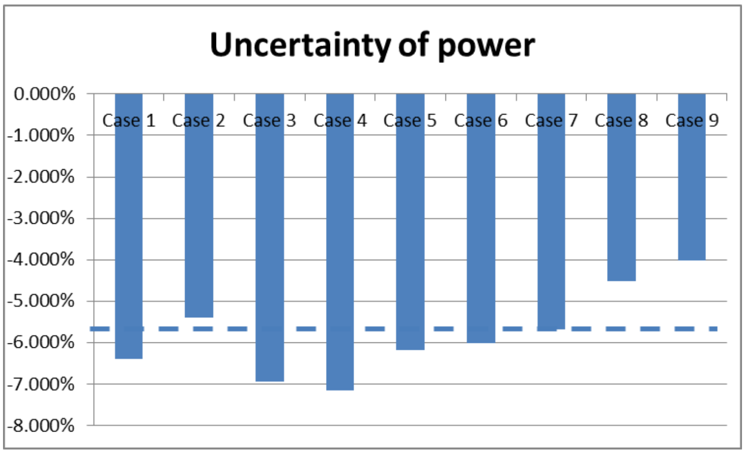

Figure 3: Power uncertainties of the model

Having been validated, the engine model was used to provide data to feed into the holistic ship model. An engine operation map was created based on the current engine situation and potential de-rating requirements, as shown in Figure 4. The simulation was performed over an engine speed range of 350 rpm to 500 rpm, in 25 rpm intervals, and over a power range of 10% to 110% load in 5% intervals. This created a total of 175 simulation data points for each engine speeds and loads. The final data was provided to the holistic ship model as a lookup table to be integrated.

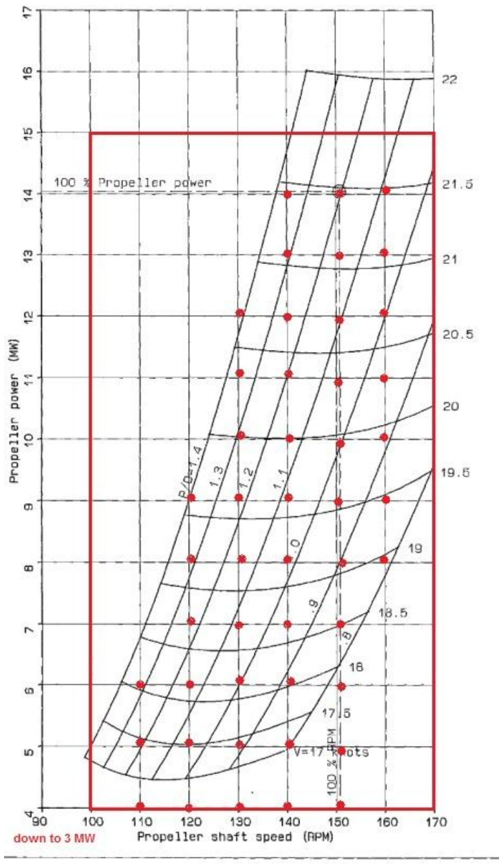

Figure 4: Ship propeller power map to determine engine simulation map

Other engine operation maps, such as fuel consumption or efficiency, were also be created from the model data, as shown in Figure 5. The orange curve shows the load limit, under which the engine can operate. Under a wide range of loads (~30% of full load) at all engine speeds, the engine runs with reasonably high efficiency (<220 g/kWh specific fuel consumption). However, fuel consumption increases significantly when the load is reduced further, heavily deteriorating the efficiency, which needs to be considered very carefully when engine de-rating is implemented.

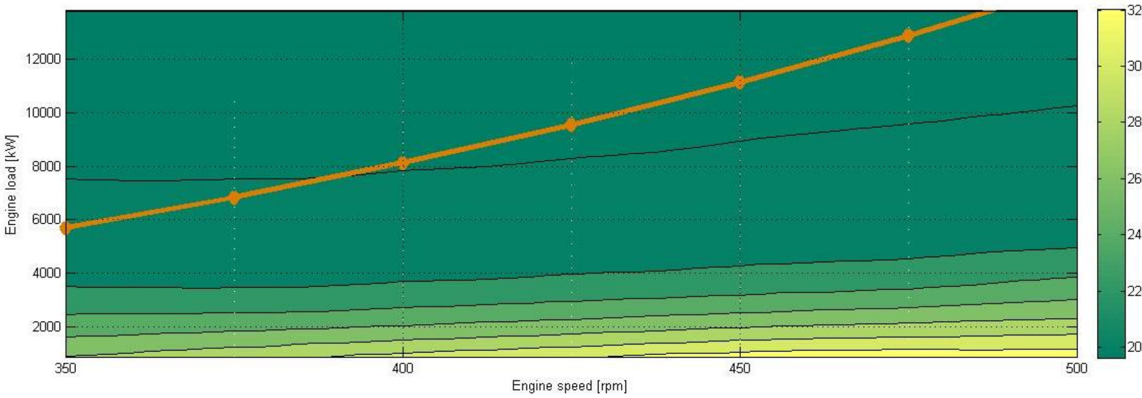

Figure 5: Engine's specific fuel consumption (g/kWh) map from model results

The model map simulation results provided data for other areas of research, including exhaust temperature for waste heat recovery and refrigeration system modelling, exhaust gases composition for evaluating emission abatement technologies, etc. Figure 6 shows the engine map for the production of NOx emissions, which again was produced to be fed into further emission reduction model.

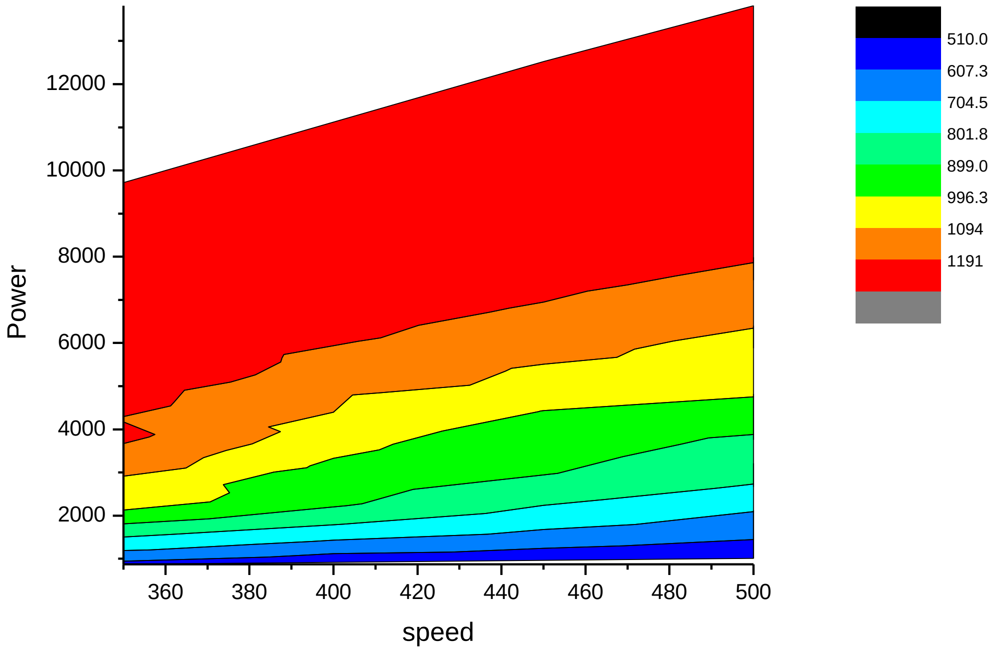

Figure 6: NOx emissions (g/kWh) MAP from model results

The holistic ship model, fed by the engine model outcomes, was validated based on sea trial measurement data. The parameters that were monitored are ship speed, main engine fuel consumption, shaft power, rpm, propeller pitch in %, and draft. This validation was performed for a whole ship cycle during a week of testing. The car carrier ship studied operates between two ports (Vigo in Spain and St Nazaire in France), in the so called North Atlantic motorway of the sea (MoS). The vessel completes a cycle performed 44 times a year. It is composed of the following trips (legs) in a single week as shown in table 2. The ship operating profile for a week's trip is shown in Figure 7. According to measurements in sea trials, propeller and engine demand for given speeds, were calculated, taking into account environmental conditions.

Table 2: RoRo trip in a single week

Trip	time	Draft	Speed
[1] Vigo- St Nazaire	40.8	6.7 m	15 kn
[2] Vigo-St Nazaire	26.8	6.7 m	17.9/18 kn
[3] St Nazaire-Vigo	29.8	6 m	16.3 kn
[4] Vigo- St Nazaire	33.8	6 m	15.5 kn

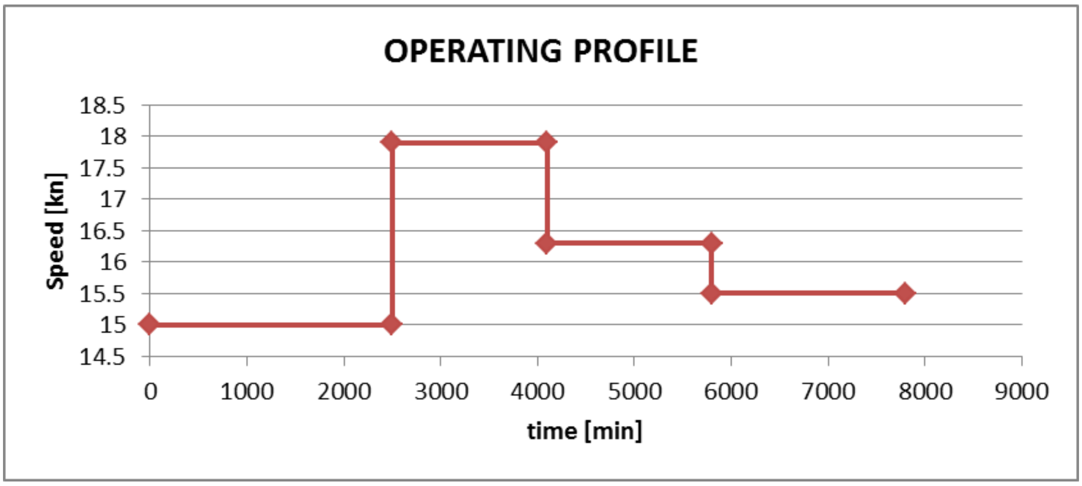

Figure 7: Ship operating profile for a week cycle (port excluded)

The power output from the model was aligned with the sea trial data, which is illustrated in Figure 8. These curves are obtained from NAVCAD (Ship power prediction tool). Some margins (weather) are added to match power measured to software results.

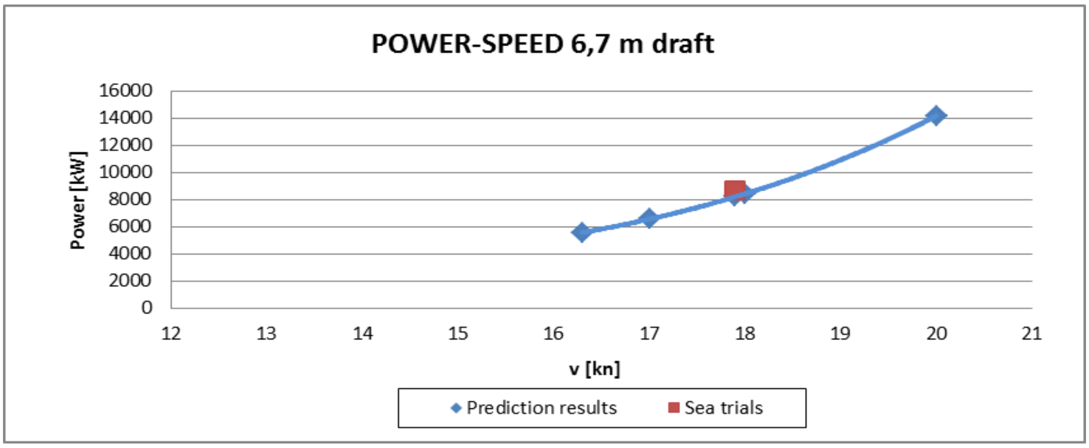

Figure 8: Power curve at reference draft

Auxiliary load measurements were imported to the ship model. Since the study RoRo vessel has very simple electric networks and clear consumers, it is unnecessary to identify every single consumer. Four engine modes were selected to represent the trip. The parameters in these four legs drawn from the engine model results are listed in table 3.

Table 3: Engine parameters for the normal operation of the vessel in the four legs

Condition	[1]	[2]	[3]	[4]
Engine eff.	0.42	0.44	0.43	0.43
Backpressure [Bar]	1.011	1.015	1.012	1.012
Temperature After TC [ºC]	285	306	300	297
Exhaust gas flow [kg/s]	15.5	20.5	18	17
Engine fuel consumption [kg/h]	1170	1770	1440	1361
Max. obtainable heat in Economizer [kW]	1165	1740	1486	1408
CO2 emissions [g/kWh]	667	630	646	652
NOx emissions [g/kWh]	16	15	16	16

The simulation has been performed with steps of 1s. A later correlation of simulation time basis and ship time basis is done with a scaling factor. The error considered for the validation is the relative error that is calculated according to

$$\varepsilon = \frac{x_{measured} - x_{simulated}}{x_{measured}} \qquad (9)$$

The comparison of model results and measurements was carried out for trip 3 (table 2). The results and errors are listed in table 4.

Table 4: Validation results

	Measured value	Simulated value	ε
Fuel consumption (T)	47.5	46	3%
Specific CO2 emission (g/kWh)	628	646	2.5%
Specific NOx emissions (g/kWh)	16	15.9	0.3%
Specific SOx emissions (g/kWh)	8	10	20%
T after TC (ºC)	329.5	300	8%

The validation shows a reasonable accuracy of the ship model. SOx emissions and temperature after turbocharger however are of slightly high discrepancy. The temperature difference is due most probably to engine uncertainties when collecting data of the actual engine on-board. SOx emissions are calculated with the formula 20xS(%) (LRS 1995). Real sulphur content in HFO380 used on-board is highly uncertain. Further chemical analysis is required if more accurate results are needed.

4. Conclusions

Two numerical models, including a detail 1-D engine acoustic model and a holistic ship model were developed to investigate the potential of fuel consumption and emissions reduction under three scenarios, including at sea, manoeuvring and in port. From the validation results of both models, it is certain that the two models are reasonably accurate and can provide valuable information. It has been demonstrated that this tool (together with ship sea trials) allows fast analysis of the current ship performance and facilitates the decision making when assisting ship owners in implementing new technologies on-board for less fuel consumption and emission reductions according to more and more stringent legislations.

5. Acknowledgements

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References

Corbett, J. J., and H. W. Koehler (2003). "Updated emissions from ocean shipping." J. Geophys. Res. **108**(D20): 4650.

Corbett, J. J., C. Wang, J. J. Winebrake, and E. H. Green (2007). Allocation and forecasting of global ship emissions. Clean Air Task Force. Boston.

Endresen, O., E. Sorgard, J. K. Sundet, S. B. Dalsoren, I. S. A. Isaksen, T.F. Berglen, and G. Gravir (2003). "Emissions from international sea transportation and environmental impact." J. Geophys. Res. **108**(D17): 4560.

EPA (Oct, 2002). A ComprehensiveAnalysis of Biodiesel Impacts on Exhaust Emissions. **EPA 420-P-02-001**.

Eyring, V., H. W. Kohler, A. Lauer, and B. Lemper (2005). "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050." J. Geophys. Res. **110**(D17): 306.

Eyring, V., H. W. Kohler, J. van Aardenne, and A. Lauer (2005). "Emissions from international shipping: 1. The last 50 years." J. Geophys. Res. **110**(D17): 305.

Jürgens, R., Thum D. (2009). The DryEGCS Process – Dry Exhaust Gas Cleaning for the Reduction of Sulphur and Particles. SOWOS 3, Marine Environmental Protection.

Lack, D. A., et al (2009). "Particualte emissions from commercial shipping: Chemical, physical, and optical properties." J. Geophys. Res. **114**: D00F00.

Lauer, P. (2009). Ship emissions in ports, 2009.

LRS (1995). Marine Exhaust Emissions Research Programme, Lloyds Registry of Shipping.