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E³ Tug Development: Economically viable, Environmentally friendly, Efficient in operation

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SYNOPSIS

Smit International is currently involved in an R&D project to develop a 'greener' tug for harbour and terminal use in cooperation with Damen Shipyards and Alewijnse. The project is referred to as E³, where the Es stand for Environmentally friendly, Efficient in operation and Economically viable.

The project is divided into three stages. In the first stage, the environmental footprint of a Damen ASD 2810 tug will be determined for various operational conditions. The information obtained will be used for input and as a benchmark for the following stages.

The second stage comprises designing, and ultimately building, a 'greener' tug with the best, currently available technology. At this stage, a propulsion configuration will be determined which best matches all conditions and constraints of the E³ project. In determining the best configuration, various options such as diesel electric, hybrid drive, shore power and LNG fuels will be envisaged. Upon completion of the tug's construction, again measurements will be performed to establish the new environmental footprint and to verify if the E³ objectives have been met.

In the third and final stage a preliminary design will be made based on emerging technologies, such as RIM drive thrusters, latest generation fuel cells, solar cell decks, etc. The environmental footprint of this design will be determined through computer modelling.

Another, equally important, objective of this project is to determine proper environmental performance indicators for tugs. Applying the conventional criterion of a maximum amount of emissions per gramme per tonne per mile for tugs is, in fact, not correct. The new performance indicators will provide the tug industry with a means of comparing different designs on their environmental impact.

INTRODUCTION

The Port of Rotterdam recently announced its ambition to reduce the amount of air pollution by 10 per cent by the year 2020. All operators within the port are encouraged to start looking at ways to help the Port of Rotterdam to achieve this ambitious goal. As a consequence this project was initiated.

Smit International, being one of the main tugboat operators in the Port of Rotterdam, is taking up this challenge together with its main supplier, Damen Shipyards Gorinchem.

They have come together in what is called the E³ Tug Project, a collaboration between Smit, Damen Shipyards Gorinchem, Alewijnse Marine Technology, the Port of Rotterdam, TU Delft, MARIN and IMARES. The goal is not only to develop a more environmentally friendly tug, but also to develop a methodology to make a realistic analysis of the environmental impact a tug has on its direct environment. While many projects place the system boundary directly around the tug, this project will try to look beyond that and make a proper environmental assessment.

THE PROJECT

A fundamental approach to the project was chosen to ensure a solid base from which we will be able to not only deliver new designs suited for the Port of Rotterdam, but also for different ports around the world. To this end the E³ Tug project is divided into three stages. The first stage is intended to determine the environmental impact of the current state-of-the-art tugs operating in the port of Rotterdam. This is achieved by measuring the operational profile and related emissions of the ***Smit Elbe,*** a Damen ASD Tug 2810. The resulting operational profile will serve as input for the second and third stages, whereas the corresponding emission profile will serve as the benchmark for the next stages.

The second stage comprises designing a new propulsion installation for the Damen ASD Tug 2810 and building it with the best technology currently available which meets the requirements of the operational profile as closely as possible, and also complies with the aforementioned three Es.

The third and final stage is to design a propulsion installation for the Damen ASD Tug 2810 with emerging technology, in other words the E^3 tug we hope to build in five to 10 years.

The primary objective of this project is to reduce the emissions of harbour tugs, but when trying to reduce certain emissions, other emissions can go up (trade-off effects). Therefore, this project will consider the overall impact of the emissions on the local environment and will strive to minimise this impact.

To be able to determine the impact on the local environment of the benchmark and the future E^3 Tug designs, IMARES is developing a methodology[1] to come to a single integral indicator, based on a principle that is already successfully applied in the oil and gas industry. Through the development of this Environmental Impact Factor (EIF) the industry will be able to identify the emissions which make the greatest contribution to the overall impact on the local environment and design an alternative propulsion configuration accordingly.

The EIF method is expected to allow the industry to make objective comparisons between different designs, based on actual benefit to the environment instead of a presumed benefit by the reduction of emitted loads only. To be able to this, the EIF will be made relative to the effective use of installed power. Traditional indicators, such as emissions in gramme per tonne cargo per mile, simply don't make sense for a harbour tug. In addition to this, a realistic EIF will enable a more accurate estimate to be made of the environmental impact of the entire tugboat fleet in a port, instead of omitting it or assuming this impact to be a certain percentage of the emissions of large, commercial vessels visiting the port. It will hopefully also aid policy makers to draw up realistic emission regulations for their respective regions.

The first stage – measuring the operational and emission profile

As explained, the first stage is to try and quantify absolute emissions to air and identify when these emissions are occurring. The purpose is to identify what part of the tugboat operation needs the most attention if the goal is to minimise emissions. To determine these specific emissions, it is necessary to know the operational profile of the tug. Specific emissions means which emissions and how much of them are occurring at a certain engine load. Operational profile means how the tug is used and which parameters, such as engine load or emissions, are attached to that use.

Every tug operator can roughly describe the operational profile of the tug; however a rough description is not sufficient to determine the overall emission footprint. Therefore, as a first stage of the E^3 Tug project, measurements to determine the overall operational profile and emissions are performed.

The Smit harbour tug, ***Smit Elbe,*** a Damen ASD Tug 2810, working in the port of Rotterdam has been chosen as the benchmark.

*Figure 1: The **Smit Elbe**.*

To accurately measure an operational profile it is important to know what to do with the profile and which parameters are of influence. In the E^3 case the goal is to discover the tug's emissions to its direct environment.

The parameters which are directly of influence are:

- Fuel consumption;
- Engine power;
- Vessel speed;
- Emissions.

These parameters were therefore logged over an extended period of time. The extended period was necessary to make sure that all types of tug jobs were represented sufficiently in the measurements.

These parameters (along with most of the engine management data, 80 parameters in total) were measured continuously at a one second interval (1Hz) over a four-week period. In total about 8Gb of plain text data was gathered.

Unfortunately, it is impossible to measure emissions over an extended period of time during normal harbour duties because the measurement equipment is too big and cumbersome and simply gets in the way. To deal with this problem the measurements were separated into two stages:

- Long-term operational measurements;
- Short-term emission measurements.

The long-term measurements are intended to determine the operational profile of the tug. The short-term measurements will aim specifically at emissions during predetermined operational modes. These modes were carefully chosen based on the long-term measurements.

An operational profile can be defined as a histogram, with the engine loads on one axis and the amount of time on the other. There is a danger, however, that by looking at the operational profile in this way useful information could be lost, and as a result the so-called operational modes have been divided up.

Five operational modes have been defined, apart from the mode where the main engines are shut down completely:

- Transit (sailing from and towards a job);
- Assist (connected to a ship on a job);
- Standby coupled (clutch engaged, propeller turning at minimal rev/min);
- Standby uncoupled (clutch disengaged, propeller free to turn);
- Cool down (main engines running in cool down mode).

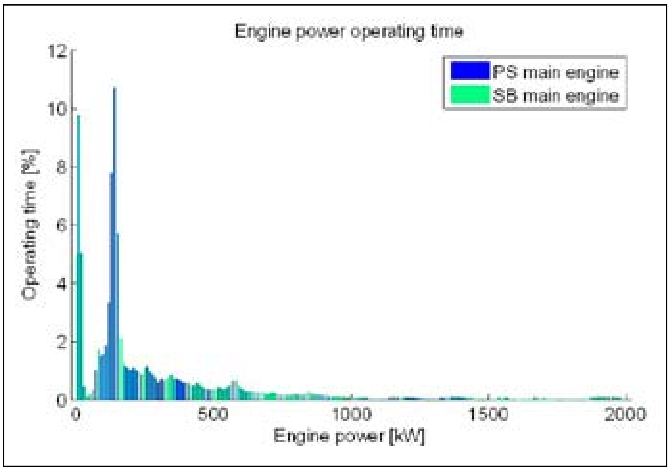

Figure 2: The traditional histogram of operating time over engine power.

An interesting observation is that the maximum engine power (bollard pull) is used less than 1-2 per cent of the operating time. Another interesting fact is that most of the time the engines operate at, or close to, idle. When the total operating time at each operating mode is summarised the following numbers can be deduced:

Operation Mode	Time
Transit	30%
Cool down	3%
Standby uncoupled	14%
Standby coupled	24%
Assist	29%
	100%

Another way of presenting the same data is by plotting the measured powers and engine speeds in a chart of the main engine power and propeller demand curves (*see Figure 3*).

The lower band of measurements corresponds with the free sailing propeller demand curve. The upper band corresponds with the bollard pull propeller demand curve. The small band at 600 rev/min corresponds with the cool down mode of the engines. What is interesting to note is that, apparently, this tug exerts very little force while at speed, otherwise there would be more measurements to be seen between the two propeller demand curves.

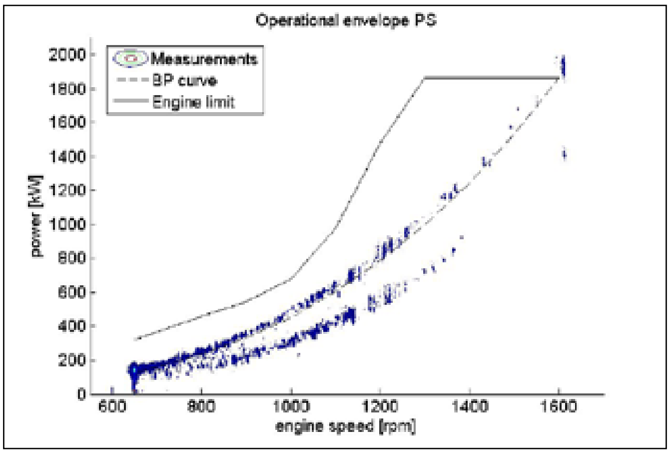

Figure 3: Power curves.

With the operational profile data available, it is possible to make an estimate of the expected emissions without actually measuring them by calculation and with information that is readily available from the engine manufacturers. Fuel-related emissions can be determined by mathematical/chemical breakdown of the fuel consumption. Combustion-related emissions can be obtained from the engine manufacturer based on test bed conditions.

However there is a problem here. Standard protocols for measuring emissions exist and engine manufacturers have to comply with these protocols. The IMO prescribes the so called E3 (not to be confused with E^3) protocol in their regulations to which marine engines must comply. This protocol is, among others, valid for NOx[2] and requires NOx measurements at four points on the propeller-demand curve of a vessel. *(See Table 2 at end of paper).*

The IMO attaches a weighting factor to each of the four points to indicate the significance of the operating area. The biggest weight factor (0.5) is attributed to a 75 per cent engine load. This is based, of course, on typical vessels designed for speed and not bollard pull. Comparing the E3 test cycle with the measured profile, one can conclude that the E3 cycle is quite far off the operational profile of a tug. From the operational profile, it can be determined that this test cycle is insufficient, since the engines spend over 40 per cent of the time at less than 10 per cent load. The choice was therefore made to design a custom-made emission measurement program that includes not only the E3 cycle but also covers the whole operational range.

The following emissions have been taken into consideration:

1. CO_2 (Carbon dioxide)
2. SO_2 (Sulphur dioxide)
3. NOx (Nitrogen oxides)
4. CO (Carbon oxide)
5. PM (Particulate matter)
6. HC (Hydrocarbons)

Carbon dioxide, sulphur dioxide and nitrogen oxides (partly) are **fuel-related emissions** which means that they are mainly dependent on the amount and type of fuel that is burned. NOx, CO and HC are **combustion-related**, meaning that they are dependent on the combustion process and normally most of them do not occur during complete combustion. PM is partly combustion-related, but mostly dependent on the sulphur and ash content of the fuel.

As it was not possible to continuously measure the above-mentioned emissions during normal harbour duties, the following measurement protocol was drawn up, which focuses on the low load conditions that are encountered in addition to the IMO E3 test cycle. *(See Table 3 at end of paper).*

At the time of writing this paper, the results of the emission measurements are being analysed and will be used to determine the absolute emissions to the air of the long-term measurement data/operational profile.

The next step is to determine the EIF of the ***Smit Elbe***, which will then be used as the benchmark for the following stages.

The second stage – designing the E^3 tug with the best technology available

For the second stage, multiple possible configurations will be evaluated. For these configurations, all options relating to emission reduction and fuel saving will be considered. To compare the alternative configurations a computer simulation model has been prepared in which the different components and their contributions have been modelled.

The computer simulation model is modular in design, allowing the user to choose different components for the propulsion train and freely sizing and connecting them. The model is dynamic; however the individual components are modelled to be steady state. The model was set up in cooperation with the Technological University of Delft; it provided components (the diesel engine) and assisted in the creation of others (electric machines, hybrid control unit and batteries). The measured operational profile will be used as the input to calculate fuel consumption and emissions. This is done by, literally, using the measured throttle settings and thruster angles over time as the input, whereby the model calculates the absorbed powers and consequently the fuel consumption and emissions. *(See Figure 4 at end of table).*

This tool will in future allow us to choose, and size, the specific components according to the requirements of any operational profile, making sure that each propulsion installation gains the most benefit out of its proposed operational profile.

The third stage – designing the E^3 tug of the future

In the final stage of this project a concept design of a propulsion installation with emerging technology will be made. Emerging technology is defined as technology that has a high potential for being effective in reducing emissions, but which is not currently available or practical in operation at this point. LNG, for instance, is a difficult technology to classify. The technology is currently available, but the infrastructure to get the LNG on board the tug is not yet economically viable. A preliminary inventory of emerging technology has been made, but no work has as yet been started on the conceptual design.

CONCLUSION

The main goal of this project is to develop an alternative propulsion configuration which will have the lowest EIF, while at the same time complying with the three Es, but by taking a fundamental approach to the project, several other equally important goals will also be reached. With the proper analysis of the operational profile we will gain an insight into the tugboat's emissions and the tug operator will gain more insight into his operations.

With the computer simulation tool, the tug builder will be able to design the propulsion train best suited for the operational profile of each of its customers.

With the development of the Environmental Impact Factor for tugs, we hope to deliver a useful instrument to the tugboat industry and, in particular, legislative organisations.

The first stage is being completed at the time of writing this paper. The results of the other stages will be published as soon as they come to their respective conclusions.

[1] Dr CC Karman, IMARES, SWZ Maritime, Jaargang 18th May 2008.
[2] Annex VI - *Regulations for the Prevention of Air Pollution from Ships*, Regulation 13, Appendix II, IMO, MARPOL.

Table 2.

Test cycle type E3	Speed [rev/min]	100%	91%	80%	63%
	Power [bkW]	100%	75%	50%	25%
	Weighting factor	0.2	0.5	0.15	0.15

Table 3.

ID	Bollard Pull Condition [per cent of nom. bkW]	ID	Free Sailing Condition [per cent of nom. rev/min]	ID	Other Conditions
1	Idle Clutched In	**12**	Idle Clutched in	**17**	Idle Decoupled
2	13	**13**	50		
3	19	**14**	60		
4	25*	**15**	75		
5	30	**16**	100		
6	37.5				
7	46				
8	50*				
9	62				
10	75*				

* These points are part of the IMO E3 measurement protocol.

Figure 4: Model layout.