The influence of ship operational profile in the sustainability of ship energy systems

N.L. Trivyza, A. Rentizelas, G. Theotokatos
The University of Strathclyde, Glasgow, U.K

ABSTRACT: In recent years, the environmental and economic sustainability of the shipping sector has gained great attention due to the imposed environmental legislation and the uncertainty on fuel prices. The extant literature review acknowledges the importance of the operational profile in the improvement of ship systems energy efficiency. However, there has not been a complete study to identify and measure the impact of the operational profile on the environmental and economic performance of ship energy systems. In this paper, the influence of the ship operational profile on the sustainability performance of the main ship energy systems is investigated. Different operational profiles are implemented and the resulting economic and environmental impact of the main engine, the thermal boilers and the auxiliary engines of an Aframax tanker ship are analysed over the ship's operational life cycle. Varying the speed distribution affects both the transportation time for a specific voyage as well as the number of voyages per year. Considering these parameters a complete estimation of the emissions emitted, the fuel consumption, the operational costs and the profits from the cargo transportation are estimated for each profile. The results show that even with small shifts in the speed distribution the differences on the sustainability indicators are significant. Therefore, the operational profile needs to be considered in the early design phases when the synthesis of the energy systems takes place, in order to achieve significant improvement on the systems environmental and economic sustainability performance.

KEYWORDS: Ship energy systems; economic performance; operating profile; environmental impact

1. INTRODUCTION

1.1 *Motivation*

Seaborne operations have a major role in today's economy, with 90% of the world trade carried by the international shipping sector (Sherbaz et al., 2015). However, the shipping sector has recently been facing challenges due to environmental legislations and bunker's prices fluctuations. Thus, environmental and economic sustainability in shipping operations has gained great interest (Mansouri et al., 2015).

1.2 *Literature Review*

In recent years, the environmental regulations imposed in the shipping industry by the International Maritime Organisation (IMO) have significantly increased, due to society's efforts to reduce global anthropogenic emissions, because of their adverse effect on health and ecosystems. Regulations have been imposed, which set limits on the emissions of NOx, SOx and particulate matter PM from ships' exhausts and prohibits deliberate emissions of ozone depleting substances (IMO, 2011). Two areas are acknowledged, the global areas and the Emission Control Areas (ECA). In the latter, more stringent limits are imposed to SOx and NOx emissions from ships (IMO, 2011).

In addition, the shipping industry is responsible for a great proportion of the global climate change problem and it is estimated that the CO_2 emissions from marine bunkers in 2013 were 64% higher than 1990 (IEA, 2015). However, the IMO has not yet taken actions for establishing limits for the CO_2 exhaust emissions, but the EU is discussing whether shipping should enter the EU emission trading scheme (EU ETS) (Eyring et al., 2010).

Although limits have not yet been set for the CO_2 emissions, on the 1st of January 2013 IMO introduced the first maritime energy efficiency regulation, because energy efficiency is a prerequisite for the reduction of the greenhouse gas emissions (Lu et al., 2015). According to the regulation all new built vessels have to comply with the Energy Efficiency Design Index (EEDI) (IMO, 2014) and all new and existing ships need to have a specific Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2012). Even though these measures will bring improvements, it is not feasible with only these two measures to reach the global objectives (Bazari and Longva, 2011). As a result, the EU adopted a monitoring, reporting and verification system (MRV) for carbon dioxide emissions on April 2015, which will enter into action on January of 2018 (EU, 2014).

In light of the environmental legislation, uncertainties on fuel prices and the fact that bunker fuel prices can account more than 50-60% of the vessel's operating costs (Wang and Teo, 2013) there has been extended literature investigating solutions. Scholars focused on the operational phase, in order to minimise the fuel consumption of merchant ships and therefore reduce fuel-related costs and emissions (Armstrong, 2013; Diakaki et al., 2015; Lu et al., 2015; Psaraftis and Kontovas, 2014).

Hence, there have been studies focusing on slow steaming, which has as consequences reduction in fuel consumption and emissions. However, the ship speed is related to the load conditions, sea states, current and wind, as well as, any existing constraints on estimated time of arrival (ETA) (Diakaki et al., 2015). Thus, shipping companies that adopt slow steaming have the disadvantage that their vessels complete fewer roundtrips for a given route, which has therefore lower revenues per vessel for the shipping company. On the other hand, adding vessels to a route leads to an increase in operating and capital costs (Wang & Teo, 2013). Other researches, emphasise on voyage optimisation, where an optimal route is chosen according to weather forecast, vessel's performance characteristics, energy consumption and finally environment (Lu et al., 2013), in order to achieve energy and cost efficiency.

Both techniques consider the operational profile of the ship in providing solutions to achieve energy efficiency with the given vessel's system design. Few researchers have focused on including the operational profile of the ship in the early design phases before irreversible decisions are made and the system becomes operational, so that the opportunities for optimal environmental and cost efficiency are maximised.

Besides the early design phase is a critical time in order to achieve better environmental performance (Winnes & Ulfvarson 2006). In this phase, the environmental, economic and technical requirements need to be defined, along with other important parameters concerning constraints from international regulations, design codes, mission of the vessel and layout. Thus, all these requirements and expectations can be equally evaluated and trade-offs between them can be assessed in order to achieve the most sustainable and efficient solution.

Furthermore, the operational profile of the vessel should be included in the early design phases with the aim of improving the energy efficiency of the ship. Depuis & Neilson (1997) have stressed how significant it is to consider the complete operational profile of the ship, even though it can be complex since it is affected by many parameters. Motley et al. (2012) suggested later that in order to improve the energy efficiency of the vessel for its life cycle operation it is important to include a real operational profile of the vessel and not just a single design point. Baldi (2013) in his thesis with subject the improvement of ship's energy efficiency included the complete operational cycle of the ship and concluded that for a 4-stroke engine there is a small improvement when the operational cycle is considered.

In addition, Sciberras and Norman (2012) identified the importance of the operational profile and included it in sizing the system with respect to the reduction of fuel consumption and installation's weight. In that respect, Baldi et al., (2013) in their research used the engine's load occurrence to optimise the carbon footprint of the system. As a result, they proved that the use of the whole operational profile for the evaluation of the propulsion arrangement has impact on multi-engine arrangements, like in 4-stroke engines. Also, Baldi (2016) concluded that the operational profile needs to be taken into consideration during the optimisation of ship energy systems, with respect to improving the ship energy efficiency.

From the literature, the importance of the ship operational profile in the improvement of the ship energy efficiency is highlighted as well as the consequential carbon footprint. However, there has not been any research including the operational profile of the ship while evaluating the life-cycle sustainability performance of the ship critical energy systems.

Thus, the purpose of this paper is to investigate the influence of the real operational profile of the ship on its life-cycle environmental and economic performance.

2. METHODOLOGY

2.1 Introduction to the method

The influence of the vessel's operational profile in the operational life cycle sustainability of the ship systems is going to be investigated through a case study in this paper. A specific type of ship is chosen and real data of its main energy systems performance (main engine, oil-fired boiler, auxiliary generators) are provided by the engine's manufacturer and sea trials performed after the construction of the vessel. The operation of each energy system according to the operational mode and profile of the ship is defined. The environmental impact and fuel consumption of each system are also identified. Thus, by implementing different case scenarios of operational profiles (speed, % of time), the environmental and economic performance of the main ship energy systems can be estimated.

2.2 Ship propulsion power requirements

According to data that are provided from the sea trials of the vessel the propulsion power requirements as a function of the speed are available both for ballast and laden conditions for specific loads. Using these measured results and the Equation 1 provided from Man Diesel & Turbo (2011), the propulsion power requirements are calculated:

$$P = c \times V^{a} \quad (1)$$

where P is the propulsion power requirement in kW, c is a constant, V is the speed in knots and a is a constant that depends on the ship type.

In the estimations of the power requirements, a sea margin of 15% is added to simulate the environmental conditions.

2.3 Sustainability indicators

The environmental indicators used in this paper to evaluate the influence of the operational profile in the systems sustainability performance are SOx, NOx, CO_2 and Particulate Matter (PM) emissions. These emissions are according to the literature the most significant in shipping and they are strictly regulated. Other indicators used in the study are VOC emissions, according to Annex VI, about regulations for prevention of air pollution from ships. VOC are to be regulated from tanker ships at loading and unloading. Another indicator, used in the study is the amount of fuel, which is highly important in order to estimate the fuel costs of the ship. These indicators are indicative and in future studies, more indicators can be introduced for the assessment of the environmental and economic impact of the ship systems.

In Table 1 the Emissions Factors (EF) that are used to calculate the environmental indicators for the main systems are shown. The CO_2 EF follow the latest IMO GHG Study and depend on the fuel used. For the SOx emissions indicator the assumption is that when the ship sails in ECA area the Sulphur contentis 0.1% and when it sails in non-ECA the sulphur content is 3.5%, according to IMO regulations (IMO, 2011). The oil fired boiler VOC, NOx and PM emissions are calculated according to the EF estimated by the U.S. Environmental Protection Agency (1999). The other EF in Table 1 are estimated by Entec UK and can be found in Trozzi et al. (2006).

Table 1 Emissions Factors for critical energy systems.

	Emissions Factors			
	CO_2	NOx	PM	VOC
Main Engine	3.021 tn/tn fuel	14 g/kWh	0.6 g/kWh	1.7 g/kWh
Oil Fired Boiler	3.021 tn/tn fuel	5.63 kg/m^3	4.24* kg/m^3	0.12 kg/m^3
Auxiliary Engines	3.082 tn/tn fuel	13.5 g/kWh	0.3 g/kWh	0.4 g/kWh

*When ship is sailing inside ECA areas PM EF for boilers is 0.5 kg/m^3, because it depends on the Sulphur content.

For the main engine, the NOx emissions are estimated according to the EF given from the EIAPP certificate of the engine for various loads. When the ship sails in the ECA areas the NOx are considered 3.4g/kWh to comply with the Tier III regulations.

As a result, for each operational profile given, the emissions and fuel consumption per unit of cargo can be calculated. Adopting this methodology, an integrated evaluation of the environmental impact of the ship systems can be performed for each operational profile.

Another important aspect of the sustainability performance of the ship systems is the economic dimension. The first indicator that is used for the economic evaluation of the systems performance is the amount of fuel consumed during the operation and consequently the cost of fuel.

This is a comparative study, thus for the evaluation of the economic sustainability the costs that are going to be considered are those that change due to the different operational profiles. As a result, the fuel costs, the harbor dues and the operational costs for crew wages and maintenance are included in the assessment, since they are related with the number of voyages and the duration the ship sails. Installation costs of the engine and machinery and depreciation of the ship and systems, as well as, the insurance and the building cost are not included since they are independent of the changes on the operational profile and a full life cycle costing of the vessel is out of the scope of this paper.

In addition, the freight rate for the cargo transportation is considered and a time chartering is assumed for costing calculation purposes, were the charterer pays only a freight rate per day of the voyage (laden conditions). In this paper the same assumption as in Psaraftis and Kontovas (2014) is adopted, where it is stated that the freight rate is independent of the charter duration within a narrow range. As a result, the freight rate of the transportation of the cargo from port A to port B is going to be estimated for the average duration of the voyage and not for its specific operational profile, as it is assumed independent of the duration and as a predetermined value.

2.4 Main energy systems performance

The critical systems included in this paper, are the main engine, the auxiliary engines and the oil fired boilers and were chosen because they are the main energy producers and have the highest fuel consumption among the energy systems (Baldi et al., 2015). For the purpose of this study, it is important to estimate their performance.

The shop trials of the energy systems provide the specific fuel consumption for various loads of the systems. These data are elaborated in order to estimate the fuel consumption for all loads. Thus, with the particular percentage of time spent in each load, which is given as an input from the operational profile of the ship, the fuel consumption is calculated.

Another important step is to relate the energy systems' performance with the operational mode of the ship. In the specific case, the following modes are identified:

- ballast
- laden
- port loading
- port unloading

From the ship and sea trials, the thermal and electricity power needs for each of those modes are estimated. However, even if those data are not available it is possible to make some initial estimations on the electrical and thermal power demand (SNAME, 1990). Thus, by changing the operational profile the time that the ship spends in every operational mode changes, as well as the systems' parameters, like the fuel consumption and the emissions. For the main engine as it was previously stated, the power requirements arise directly from the ship's operational profile according to Equation 1.

3. CASE STUDY

3.1 Ship specifics

The ship investigated in this paper is a crude oil Aframax tanker, which main characteristics are presented in Table 2 and 3.

Table 2 Tanker main characteristics.

Characteristics	Value
Size	115000 DWT
Displacement	134356 MT
Length	249 m
Beam	44 m
Draft	15 m
Propulsion	Fixed Pitch Propeller

Table 3 Tanker main systems.

Systems	Sets	Capacity	Fuel
Main Engine	1	14400 kW	HFO, ULSFO
Auxiliary Gen Sets	3	800 kW	MDO
Oil Fired Boiler	2	3000 kg/h	HFO, ULSFO

For the specific case study, it is assumed that the tanker is sailing from King Abdul Aziz Port Dammam at the Persian Gulf to Port of Atlantic City in North America. The distance of the one-way voyage is 9129nm. The area of the Port of Atlantic is regulated as an ECA area. It is thus assumed that, when the ship is approaching or leaving the Port of Atlantic, it spends 10% of the distance in an ECA area, as well as when it is unloading the cargo.

The ship is considered to operate only 80% of the calendar year due to maintenance issues (Livanos et al., 2014), so it is assumed that the tanker operates 292 days of the year. The life span of the vessel is considered to be 20 years. In addition, it is assumed that the ship tanker spends 4 days on average at each port for loading and unloading.

3.2 Operational Modes

For the different operational modes previously mentioned, the thermal and electrical power needs were provided from the ship trials and the average values are shown in Table 4.

Table 4 Thermal & Electrical Needs.

Operational Modes	Thermal Needs	Electrical Needs
laden	7020 kg/h	800 kW
ballast	500 kg/h	800 kW
unloading	23400 kg/h	800 kW x 2
loading	1050 kg/h	800 kW

These needs are considered constant at every operational profile, however the amount of time on each operational mode changes due to the change of the speed distribution of the ship, thus the actual fuel consumption and emissions are different.

3.3 Operational Profiles

The scope of the paper is to investigate the influence of the operational profile in the environmental and economic impact of the vessel. Thus, different case scenarios of speed distributions are introduced and the aforementioned economic and environmental indicators are calculated for the main energy systems.

The data for the operational profiles in ballast and laden conditions are taken for an Aframax tanker from Banks et al. (2013). The data refer to the year of operation 2011 and the speed distribution for the first case scenario are according to Figure 1 and 2.

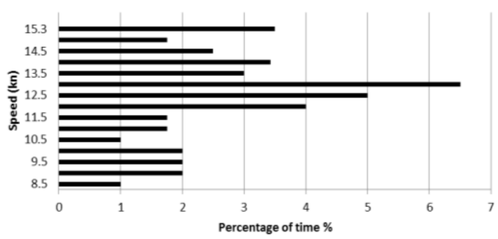

Figure 1. Speed distribution on ballast conditions, Aframax 2011 data (Banks et al., 2013).

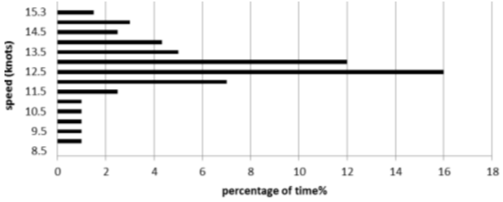

Figure 2. Speed distribution on laden conditions, Aframax 2011 data (Banks et al., 2013).

In this paper, the speed distribution of the ship on ballast conditions is considered the same in every case scenario, as a simplification. In future studies a different distribution of the speed can be introduced on ballast conditions, even though according to Banks et al. (2013) the speeds are evenly distributed to lower speeds the last years. In addition, ballast conditions do not offer economic value since the ship has no cargo to transport and the emissions as well as the fuel consumption are lower since the ship sails at the ballast draft.

However, a sensitivity analysis was performed on the operational profile on laden conditions. Three profiles were investigated: a) Base Case (Banks et al., 2013), b) Lower speeds and c) Higher speeds. The shift in the distribution of speeds was derived from the data provided by Banks et al. (2013) for the operation of Aframax tankers on 2011 according to the following process. On the second case scenario the speed distribution profile was calculated with 1kn shift to lower speeds and on the third case scenario the profile was calculated with 1kn shift to higher speeds. Figure 3 shows the operational profiles that are used for the sustainability assessment of the ship energy systems.

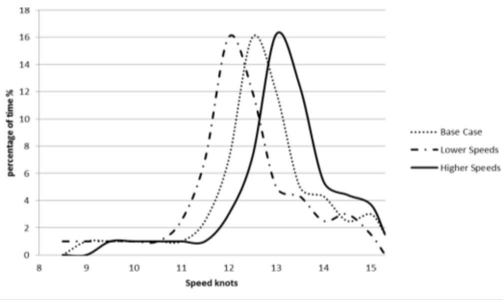

Figure 3. Operational profiles.

3.4 Economic data

In order to evaluate the influence of the operational profile of the tanker to the economic sustainability of the ship systems, the data shown in Table 5 were used.

Table 5 Data for economic investigation.

Economic data	Values
MDO	450 $/mt
IFO380 (S% =3.5%)	258.3 $/mt
ULSFO (S%<0.1%)	400.4 $/mt
Harbor Dues	12000 $/visit
Operating costs*	5605 $/day of operation
Freight Rate	15000 $/day of operation

*Includes crew costs, ship's stores costs, repairs and maintenance, administration costs.

The fuel prices are an average price of bunker prices online on the period September 2016 (http://shipandbunker.com/prices). The operating costs are according to Počuča (2006) for an Aframax tanker. The freight rate price is according to Psaraftis and Kontovas (2014) and finally the harbour dues are an average price according to ship markets (Konovessis, 2011).

4. RESULTS

The aim of this paper is to investigate the influence of the operational profile of the ship on the sustainability performance of ship systems. The different case scenarios of operational profiles shown in Figure 3 were used to calculate the duration the ship needs to sail in each case (a, b, c) for the specific voyage Table 6.

Table 6 Duration of voyage for the different profiles.

Operational Profile	Duration of Voyage (hours)*	Percentage
a	1443	-
b	1481	+2.68%
c	1424	-1.31%

*In the duration of the voyage the laden, ballast time as well as the time spend in the port are included.

The results are divided in three parts. First, the outcomes of the emissions, fuel consumption and cost per tonne of cargo transported are presented, secondly the operational lifetime estimations of the indicators are shown and finally the differences in the profits and emissions per year due to the different case scenarios are depicted. During the calculations, it was noticeable that the major impact on the emissions and the fuel consumption comes from the main engine. The only exception are the PM emissions, were the major contributor is the oil fired boiler, since according to Table 1 the EF is 35.4gal/h outside ECA areas.

4.1 Indicators per tonne of cargo transported

In Tables 7, 8 and 9 the estimated environmental and economic indicators per tonne of cargo transported for the three case scenarios are displayed.

It is evident from the results of the environmental indicators (Table 7, 8) that the energy systems emit fewer emissions per tonne of cargo transported on the profile with lower speeds. PM emissions per tonne of cargo are higher on lower speed. This is because the biggest contribution for PM emissions comes from the oil fired boilers (almost 60% of PM emissions) instead of the main engine. The calculation of the PM emissions from the oil fired boilers is dependent from the hours of operation of the boiler, because the emissions depend on the steam flow (kg/h) produced. Thus, since the second scenario operates for more hours (38 hours more than the base case) due to the lower speed, the result of the PM emissions is justified. Accordingly, it is expected that the PM emissions on the third scenarios, which operates for fewer hours (19 hours less than the base case), are going to be less. However, the PM emissions on the base case and the higher speed scenario are almost equal, due to minor difference of the voyage hours between the base case and the third scenario and the fact that the PM emissions from the main engine are higher on the third scenario.

Table 7 Tonnes of emissions per tonne of cargo transported.

Profiles	NOx ($x10^{-3}$)	SOx ($x10^{-3}$)	CO_2 ($x10^{-2}$)	PM ($x10^{-4}$)	VOC ($x10^{-5}$)
a	1.73	1.40	7.78	3.82	7.27
b	1.71	1.37	7.69	3.86	7.10
c	1.81	1.43	7.91	3.83	7.45

Table 8 Percentage of difference of emissions per tonne of cargo transported.

Profiles	NOx	SOx	CO_2	PM	VOC
a	-	-	-	-	-
b	-1.05%	-1.66%	-1.21%	+1.05%	-2.33%
c	+4.54%	+2.11%	+1.71%	+0.28%	+2.61%

The following Table 9 depicts the economic impact per tonne of cargo of the different operational profiles. The results show that when the speed is lower the fuel consumption and consequently the fuel cost are lower.

Table 9 Tonnes of fuel and $ of fuel costs per tonne of cargo transported.

Profiles	Tonnes of fuel	Percentage	Fuel costs ($)	Percentage
A	$2.57x10^{-2}$	-	7.13	-
B	$2.54x10^{-2}$	-1.22%	7.05	-1.06%
C	$2.62x10^{-2}$	+1.72%	7.24	+1.57%

From the results of the economic indicators like in the environmental indicators it is noticeable that the shift to lower speeds reduces the fuel consumption as well as the fuel costs per tonne of cargo. The percentage of reduction on the tonnes of fuel and cost of fuel is not the same due to the mix of fuels, since it is assumed that the ship while sailing on ECA areas consumes ULSFO.

4.2 Indicators per operational life time

In the following section the operational life time economic and environmental sustainability of the energy systems is investigated (Figures 4, 5, 6, 7, 8). Since the ship has a 20 years life span of operation, it is important to study the environmental and economic impact it has on the human and ecosystems. Another important aspect in these results is that the number of voyages per lifetime, which is consequence of the voyage duration of each profile, is incorporated.

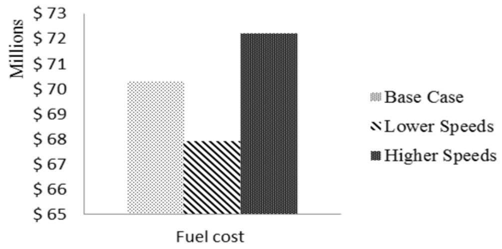

Figure 4. Operational Life time Fuel expenses.

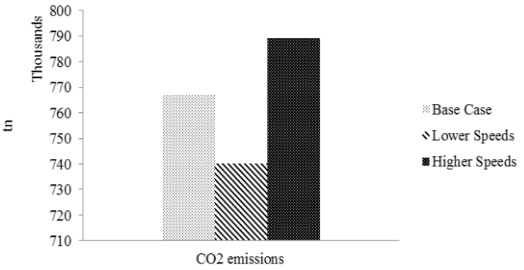

Figure 5. Operational Life time CO_2 emissions.

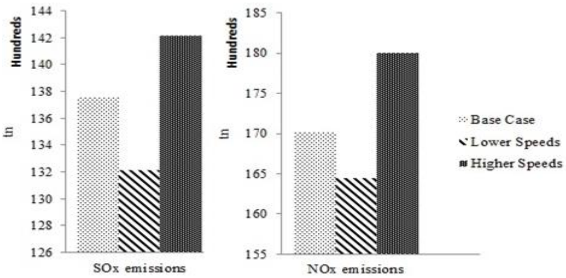

Figure 6. Operational Life time SOx & NOx emissions.

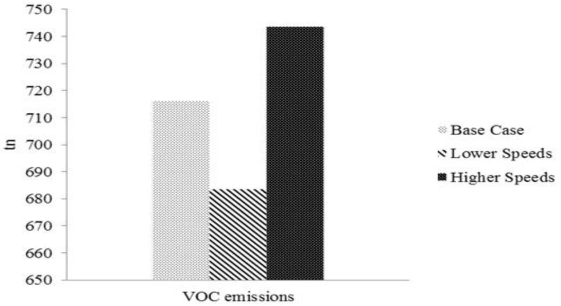

Figure 7. Operational Life time VOC emissions.

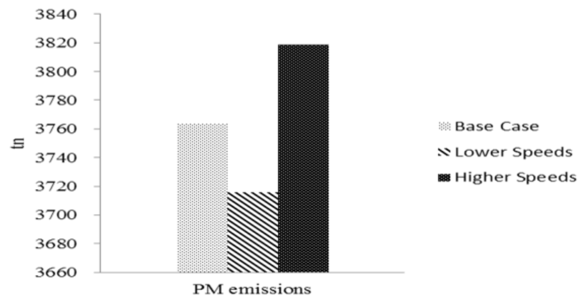

Figure 8. Operational Life time PM emissions.

The previous figures contain the absolute numbers of the tonnes of emissions and fuels from the operational life time of the ship energy systems. The results show that the more environmental profile is more cost efficient too. In addition, PM emissions for the ship lifetime are lower when sailing at lower speed, even though in reality the PM emissions per tonne of cargo transported are higher (Table 7). Due to the fact that PM emissions are highly dependent on the hours of operation and in the last case the ship sails for more voyages than the other cases.

4.3 Indicators per year of operation

In the following Tables 10, 11 and 12 the economic and environmental indicators per year of operation were calculated. In the scenario with the lowest speed, the vessel completes fewer journeys than in the other cases so the income from the cargo transportation is lower. However, it is noticeable that the profits per year are exceeding the other cases due to the lower operational costs. In addition, the amount of emissions are much lower, so the second scenario is the most economic and environmentally sustainable option among the three cases.

Table 10 Percentage of difference of emissions per year of operation.

Profiles	NOx	SOx	CO_2	PM	VOC
a	-	-	-	-	-
b	-3.34%	-3.93%	-3.49%	-1.29%	-4.59%
c	+5.76%	+3.31%	+2.90%	+1.45%	+3.81%

Table 11 Percentage of difference of fuel tonnes and fuel costs per year of operation.

Profiles	Tonnes of fuel	Fuel costs ($)
a	-	-
b	-3.50%	-3.34%
c	+2.90%	+2.76%

Table 12 Percentage of difference profits, income and operating costs per year.

Profiles	Operating Costs*	Income	Profit
a	-	-	-
b	-2.28%	-2.31%	+2.26%
c	+1.89%	+1.17%	-2.34%

*Includes crew wages, maintenance, fuel costs and harbor dues.

The analysis has as a result that the operational profile influences both the economic and the environmental sustainability of the ship energy systems. Lowering the speed leads to emissions as well as operational costs decrease, however the profits are increased.

In addition, it is worth to note that the shift of the speed distribution to 1kn less has a bigger impact in percentage absolute values on the decrease of emissions and costs than the operational profile with the shift of the distribution to 1kn more has. According to the simulation carried out, it results that the emissions and costs decrease more than proportionally when the speed of the vessel is decreased.

5. CONCLUSION

This paper aimed to investigate the impact of the ship operational profile on the environmental and economic sustainability of its energy systems. A specific case ship was investigated for the transportation of crude oil from the Persian Gulf to North America. Three scenarios of speed distributions were compared with focus on the aspects that are affected by different operational profiles.

The sustainability analysis of the scenarios showed that changes in the operational profiles affect the emissions as well as the fuel consumption and costs. Generally, the emissions and fuel costs per tonne of cargo are reduced when sailing with lower speed, except the PM emissions. However, when measuring the emissions per year or per lifetime it is noticeable that all emissions are reduced when the ship sails on lower speeds. In addition, from the calculations of emissions per year of operation, it is evident that the shift to lower speeds has a higher absolute percentage on the decrease of emissions and costs than the shift to higher speed has on the increase. Furthermore, it is evident that a win-win situation exists: the lower speeds scenario is the most environmental and economic efficient, even though the voyages of the vessel per life cycle are less.

In conclusion, the broad range of the vessel's operation and not only the design conditions should be considered on the synthesis of the ship energy systems, in order to assess and to improve their sustainability, since the operational profile influences the systems sustainability.

6. REFERENCES

Armstrong, V.N. (2013), "Vessel optimisation for low carbon shipping", *Ocean Engineering*, Vol. 73, pp. 195–207.

Baldi, F. (2013), *Improving Ship Energy Efficiency through a Systems Perspective*, Chalmers University of Technology.

Baldi, F. (2016), *Modelling , Analysis and Optimisation of Ship Energy Systems PhD Thesis*, Chalmers University of Technology.

Baldi, F., Bengtsson, S. and Andersson, K. (2013), "The influence of propulsion system design on the carbon footprint of different marine fuels", *Low Carbon Shipping Conference*, pp. 1–12.

Baldi, F., Johnson, H., Gabrielii, C. and Andersson, K. (2015), "Energy and exergy analysis of ship energy systems – the case study of a chemical tanker", *International Journal of Thermodynamics*, Vol. 18, available at:http://doi.org/10.5541/ijot.5000070299.

Banks, C., Turan, O., Incecik, A., Theotokatos, G., Izkan, S., Shewell, C. and Tian, X. (2013), "Understanding Ship Operating Profiles with an Aim to Improve Energy Efficient Ship Operations", *Low Carbon Shipping Conference*, pp. 1–11.

Bazari, Z. and Longva, T. (2011), *Assessment of IMO Mandated Energy Efficiency Measures for International Shipping: Estimated CO2 Emissions Reduction from Introduction of Mandatory*, *IMO*, available at:http://doi.org/MEPC 63/INF.2.

Depuis, R. and Neilson, J.J. (1997), "Dynamic Analysis : Sail the Ship Before it's Built", *Naval Engineers*.

Diakaki, C., Panagiotidou, N., Pouliezos, A., Kontes, G.D., Stavrakakis, G.S., Belibassakis, K., Gerostathis, T.P., et al. (2015), "A decision support system for the development of voyage and maintenance plans for ships", *International Journal of Decision Support Systems,* Vol. 1, pp. 42–71.

EU. (2014), *Proposal for a Regulation of the European Parliament and of the Council on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions From Maritime Transport and Amending Regulation (EU) No. 525/2013 – Political Agreement*.

Eyring, V., Isaksen, I., S., A., Berntsen, T., Collins, W., J., Corbett, J., J., Endresen, O., Grainger, R., G., et al. (2010), "Transport impacts on atmosphere and climate: Shipping", *Atmospheric Environment*, Vol. 44, available at:http://doi.org/10.1016/j.atmosenv.2009.04.059.

IEA. (2015), "CO2 Emissions from fuel combustion", *IEA Statistics*, pp. 1–139.

IMO. (2011), *Annex 19-Resolution MEPC.203(62), Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto*.

IMO. (2012), *Annex 9, Resolution MEPC.213(63), 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP)*.

IMO. (2014), *Annex 5, Resolution MEPC.245(66), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships*.

Konovessis, D. (2011), "Shipping Markets", Lecture Notes, University of Strathclyde, Glasgow.

Livanos, G.A., Theotokatos, G. and Pagonis, D.-N. (2014), "Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships", *Energy Conversion and Management*, Vol. 79, pp. 640–651.

Lu, R., Turan, O. and Boulougouris, E. (2013), "Voyage optimization, prediction of ship specific fuel consumption for energy efficient shipping", *Low Carbon Shipping Conference (LCS),* London, pp. 1–11.

Lu, R., Turan, O., Boulougouris, E., Banks, C. and Incecik, A. (2015), "A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping", *Ocean Engineering*, Vol. 110, available at:http://doi.org/10.1016/j.oceaneng.2015.07.042.

Man Diesel & Turbo. (2011), *Basic Principles of Ship Propulsion*, *Man Diesel & Turbo*, available at: http://www.mandieselturbo.com/files/news/filesof5405/5510_004_02 low.pdf.

Mansouri, S.A., Lee, H. and Aluko, O. (2015), "Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions", *Transportation Research Part E: Logistics and Transportation Review* , Vol. 78, pp. 3–18.

Motley, M.R., Nelson, M. and Young, Y.L. (2012), "Integrated probabilistic design of marine propulsors to minimize lifetime fuel consumption", *Ocean Engineering,* Vol. 45, available at:http://doi.org/10.1016/j.oceaneng.2012.01.032.

Počuča, M. (2006), "Methodology of day-to-day ship costs assessment", *Promet - Traffic - Traffico*, Vol. 18, pp. 337–345.

Psaraftis, H.N. and Kontovas, C.A. (2014), "Ship speed optimization: Concepts, models and combined speed-routing scenarios", *Transportation Research Part C: Emerging Technologies*, Vol. 44, available at:http://doi.org/10.1016/j.trc.2014.03.001.

Sciberras, E. a. and Norman, R. a. (2012), "Multi-objective design of a hybrid propulsion system for marine vessels", *IET Electrical Systems in Transportation*, Vol. 2, p. 148.

Sherbaz, S., Maqsood, A. and Khan, J. (2015), "Machinery Options for Green Ship", *Journal of Engineering Science and Technology Review*, Vol. 8, pp. 157–173.

SNAME. (1990), *Marine Diesel Power Plant Practises, T&R Bulletin 3-49*.

Trozzi, C., Consulting, T., Gregorio, V., Curbastro, R. and Roma, I. (2006), *Emission Estimate Methodology for Maritime Navigation*.

U.S. Environmental Protection Agency. (1999), *Emissions Factors, External Combustion Sources*, Vol. I, available at: https://www3.epa.gov/ttn/chief/ap42/ch01/index.html.

Wang, X. and Teo, C.-C. (2013), "Integrated hedging and network planning for container shipping's bunker fuel management", *Maritime Economics & Logistics*, Vol. 15, available at:http://doi.org/10.1057/mel.2013.5.

Winnes, H. and Ulfvarson, A. (2006), "Environmental Improvements in Ship Design by the Use of Scoring Functions", *Journal of Engineering for the Maritime Environment*, Vol. 220, pp. 29–39.