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Research Article
Effect of Ship Speed on Ship Emissions

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Abstract

Background and Objective: The shipping industry contributes for about 2.2% of the world's total emissions. It is expected to continue rising by 50-250% by 2050, depending on future economic growth and energy development. Therefore, efforts are needed to reduce the amount of emissions issued by ships. There are many methods that can be used in order to reduce the level of ship emissions, one of which is decrease the speed of the ship. By lowering the speed of the vessel, it is expected that fuel consumption and ship emissions are also reduced. **Methodology:** This review paper focused the effect of ship speed on ship emissions, as well as highlighted the most common and effective methods recommended for reducing ship emissions. **Results:** In this study the relationship between ship speed and ship emissions were discussed. The past research was also discussed about the several methods of reducing the ship's emission levels in terms of operations and the effect of speed on ship emissions. **Conclusion:** Research on speed optimization is mostly conducted for tankers and container types. For future studies it is expected that more speed optimization research with ship objects other than tankers and containers, such as LNG vessels or other fast vessels so that more renewal can be reviewed in it.

Key words: Fuel consumption, ship emission, speed optimization, ship speed, slow steaming

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INTRODUCTION

Based on research conducted by the international maritime organization (IMO) in third IMO GHG Study 2014, the shipping world currently generates 796 million t of CO_2 emissions in 2012, accounting for no more than about 2.2% of the total volume of emissions for that year[1]. Still based on the same report, indicating that by 2050, CO_2 emissions from international shipping expected to continue rising between 50 and 250%[1]. It depends on economic growth and energy development in the future. Therefore, efforts are needed to reduce the amount of emissions issued by ships. The IMO is responsible for regulating the rules concerning the safety and security of shipping and preventing maritime pollution by ships. The regulation covers all measurements from technical to operational to broad emission types, ranging from greenhouse gases (GHG) such as carbon dioxide (CO_2), to non-GHG gases such as sulfur oxides (SO_X), nitrogen oxides (NO_X), particulate matters (PM) and others[2].

There are many methods that can be used in an effort to reduce emissions from ships. It is divided into categories: Technical, logistic-based and market-based[3]. For technical categories include, engine modifications, design and ship hull modifications, propeller modifications, cleaner fuels, alternative fuel, emissions reducing equipment such as scrubber etc, various kites and others. Several studies on technical emission reductions such as using alternative fuels have also been widely used[4-9]. While for the category of logistics-based, including speed optimization, route optimization, weather routing optimization, fleet optimization and others that impact the logistic side. The latter is a market-based category, including emission trading schemes (ETS), carbon tax and others[3]. Methods to reduce ship emissions in logistic-side are considered more attractive these days than emissions-reduction methods in technical side which spend more cost and time. Therefore, in this paper will be more focused on the method of logistics side.

In recent years, maritime environmental issues, rising ship fuel prices and depressed maritime market conditions have brought a new perspective on the speed of ships [2]. The ship speed is a key in maritime transport[10]. The non-linear relationship between speed and fuel consumption shows that lower-speed vessels will consume less fuel than high speed vessels. By lowering the speed of the vessel, it is expected that fuel consumption and ship emissions are also reduced. Much research has been done regarding ship speed optimization with the aim of reducing fuel consumption and ship emissions. Among others are Psaraftis *et al.*[11], Corbett *et al.*[12], Fagerholt *et al.*[13], Lindstad *et al.*[14], Gkonis and Psaraftis[3], Banawan *et al.*[15], Fagerholt and Psaraftis[16], Fagerholt *et al.*[17], Gusti and Semin[18] and many more. In this paper, several papers related to the effect of speed on ship emissions were reviewed.

MATERIALS AND METHODS

This study is a review of collection of papers on several methods used in efforts to reduce ship emissions. This study discovers the possibility of the effect of speed on ship emission levels that can be useful for reducing ship emission levels. This study will help researchers to find out the optimization methods that can be used in optimizing the speed and decision variables that are influential in modeling. Thus, a new theory of speed optimization against ship emission levels may be arrived at. The literature used in this review paper focused on methods of reducing ship emissions in terms of logistics. The method used as the focus is a method of reducing ship emissions with ship speed optimization. Paper used as literature is a collection of papers from 2000-2017. This study will also be presented feedback on future research.

RESULTS AND DISCUSSION

As mentioned earlier, many methods that can be used with the aim of reducing the level of ship emissions. Based on a report written by ICCT GHG 2011, there are fifteen methods that can be used to reduce ship emission levels, both technically and operationally. Table 1 shows the methods that can be used to reduce ship emissions[19]. Figure 1 shows the level of CO_2 decrease in each method with different types of vessels.

Table 1: Technologies and operations strategies to reduce GHG emissions from ships

Number	Categories	Number	Categories	Number	Categories
1	Propeller polishing	6	Hull cleaning	11	Speed reduction
2	Autopilot upgrade	7	Air lubrication	12	Main engine retrofits
3	Water flow optimization	8	Hull coating	13	Speed controlled pumps and fans
4	Weather routing	9	Wind power	14	High-efficiency lighting
5	Propeller upgrade	10	Waste heat reduction	15	Solar panels

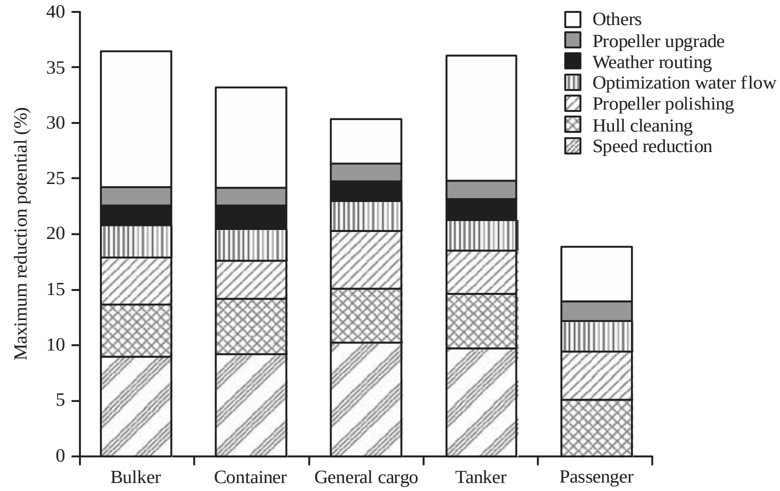

Fig. 1: CO_2 reductions of technical and operational measures by ship types

In the rule of thumb, the engine power output is a is a third power function of speed. When the ship reduces its speed by 10%, engine power will be reduced by 27%. When sailing at a lower speed, at the same distance, the sailing time will be longer and the energy required becomes reduced by 19% (quadratic function). Fuel consumption, CO_2 and SO_X emissions are reduced in line with energy consumption. The NO_X emissions are reduced in line with fuel consumption unless the engine load becomes very low. In short, slow steaming can reduce the level of all emissions on ships[20].

The equation below shows the definition of the extent to which the determinant speed relationship affects the emission level. The CO_2 emissions from ships per unit of time depend on different factors, as shown by the equation below[20]:

$$CO_2 \text{ emissions} = \text{Emission factor} \times \left[\begin{array}{l} \text{Engine power} \times \\ \int_0^T \left(\text{SFOC}_t \times \text{Engine load}_t \right) dt \end{array} \right]$$

The CO_2 emissions from a vessel are determined by factors of CO_2 emissions from fuel (constants), fuel consumption per unit time, function of engine power (constant), specific fuel oil consumption (SFOC) and engine load. At higher speeds, ships require higher engine loads, mainly to overcome the sharp increase in wave resistance[21]. SFOC will increase the engine further from its optimum design point, which is often between 65 and 80% of the maximum engine power[21]. Since the change in engine power is usually greater than the change in SFOC, the speed determines most of the ship's fuel consumption and its CO_2 emissions. The same applies to emissions of SO_X, NO_X and possibly BC.

Reducing ship emission methods: Ballou *et al*.[22] proposed an advanced method of optimizing ship operations to reduce emissions that could be detrimental to climate change. The advanced method is a computer program called voyage and vessel optimization system (VVOS). The VVOS provides features to reduce ship fuel consumption and GHG emissions without increasing transit time. This is conduct by optimizing ship operations in facing the sea conditions such as winds, waves and currents, taking into account the performance criteria of ships and safe operating limits. Then the fuel savings generated by VVOS will be verified by computer simulations and analyzed using individual vessel performance models, shipping logs and historical weather data. With the current high fuel costs, the savings offered by VVOS easily justify the cost of implementing it.

Cariou[23] conducting research on whether continuous slow steaming can reduce CO_2 emissions. In this research, container vessels serve as research objects. The CO_2 emission reduction rates measured for various container trade and bunker prices are also calculated where the strategy is sustainable over a long period of time. The calculation results show that the reduction can only be maintained at a minimum bunker price of $350-400 for the main container trade.

Kim *et al*.[24] proposed an epsilon-optimal algorithm taking into account greenhouse gas emissions for the management of bunker fuel vessels. The algorithm can determine the optimal vessel speed, bunkering port and the amount of bunker fuel for the given vessel route. The results show that ship speed and CO_2 emissions are very sensitive to the factors under consideration.

Kowalski[25] conducting research on fuel cost optimization as an important factor affecting sulfur and nitrogen oxide emissions. It is proposed as an efficient and objective method to optimize fuel costs during sailing vessels. This study uses a new method for vessels that are in operation. The data and calculations used are derived from the day-to-day practice of ship masters and ship management divisions. The results show the greatest advantage of using this method is that it does not require additional cost to determine the effectiveness of the ship's fuel.

Reducing ship emission with ship speed: Psaraftis *et al.*[11] doing research on speed reduction as an effort to reduce emissions for fast vessels. The study was conducted using mathematical modeling. Presented several models and speed reduction scenarios and their effects on rapid ship emission reductions, including container ships and ferry. The results show that speed reduction is beneficial in terms of emission reductions, but the actual effectiveness of the scheme depends on reducing the time at the port.

Corbett *et al.*[12] conducts research on the cost effectiveness of speed reductions to ship emissions. It is examined whether ship speed reductions are a solution to effective and cost-effective reduction of CO_2 emissions. This study is only for ships located in US ports. Use the profit maximizing equation by estimating the speed of a specifically efficient ship. The impact of the fuel tax policy on reducing the ship speed to CO_2 emissions is also a consideration. The profit maximization function consists of unobserved speed reduction costs in cost analysis. The results show that a fuel tax of about $ 150/t of fuel can lead to CO_2 reduction with an average speed of about 20-30%.

Faber *et al.*[26] conducting research on estimates that bulk ship emissions, tankers and container vessels can be reduced by a maximum of about 30% in the coming year by using current oversupply to reduce speed. This is relative to the situation in 2007.

Fagerholt *et al.*[13] conducting research on how to reduce fuel emissions by optimizing ship speed on shipping routes. According to the research, fuel consumption and emissions on a delivery route is a cubic function of speed. Substantial savings by optimizing the speed of each leg can be done in the presence of a delivery route consisting of several port sequences with a standard time window. Problem solved by using non-linear programming. An alternative solution methodology is proposed, where the arrival time is settled using the shortest path problem (SPP) in the directed acyclic graph. The calculation results show that the approach using SPP proved effective and potentially saving fuel on the shipping route.

Lindstad *et al.*[14] conducting research on sailing at low speeds to reduce greenhouse gas emissions and costs. The study was conducted an investigation of the effect of speed reduction on emissions and transportation costs on ships. This emission reduction is based purely on low speed. The results show that there is substantial potential to reduce CO_2 emissions. Emissions may be reduced by 19% with negative abatement costs and by 28% at zero reduction costs.

Gkonis and Psaraftis[3] conducting research by modeling the optimization of speed and emission from tankers. The modeling has two objectives, the first is to determine the optimal operating speed for tankers as a function of fuel prices, freight rates and other parameters when the vessel is in laden and ballast conditions and the second is estimation, of global fleet emissions from the ship segment certain tankers. Modeling consists of two stages. The first stage is to optimize the current speed at laden and ballast conditions in each leg for a certain tanker. The second step is to estimate the annual emissions and other operational attributes (e.g., fuel consumption) for the tanker fleet segment, based on the output of the optimization at stage one. The approach was conducted by modeling using Microsoft Excel™.

Prpic-Orsic and Faltinsen[27] conducted a study of ship speed loss estimates and CO_2 emissions while sailing by proposing a method to estimate the speeds that can be achieved in medium and heavy seas. Loss of speed is calculated taking into account the performance of the engine and propeller in the real ocean as well as mass inertia on the ship. The speed of the attainable vessel is obtained as a time series. Correction of lost speed with sea conditions allows predictors of actual marine performance. The expected CO_2 emissions for a container vessel are estimated to route north of the North Atlantic.

Qi and Song[28] conducting research on minimizing fuel emissions by optimizing ship schedule with uncertain port time. The paper considers the problem of planning an optimal ship schedule in a shipping route with the objective of minimizing total fuel consumption and ship emissions with consideration of port time and uncertain requirement level on ship schedule. The optimal scheduling problem is formulated using the simulated stochastic approximate method. Case studies are presented to illustrate the results of the study. The results show that for special cases limited to 100% service levels, it is evident that there is a possibility of convexity and continuity of objective function. The structural nature of the optimal schedule under certain conditions is obtained through managerial insights that are useful in terms of the impact of port uncertainties.

Cariou and Cheaitou[29] conducting research by investigating the policy options considered by the European Commission and comparing speed limits with bunker charges as a measure to reduce GHG. The object study of the research is trading using containers. The study stated that the measure is counterproductive for two reasons. First, because it ultimately generates more emissions and raises the cost per ton of CO_2 more than people are willing to pay. Secondly, it is suboptimal compared to the results obtained if international bunkers are implemented. This is illustrated by using two direct transatlantic services operated in 2010.

Banawan *et al.*[15] conducting research on reducing fuel consumption and emissions by decreasing speed on catamarans. Decreasing the ship speed is expected can reduce fuel consumption and CO_2 emissions from ships. The paper analyzes the methods used to determine the variations in fuel consumption that may occur and their impact on ship emissions when implementing a strategy of catamaran speed reduction. The comparable method are power-speed law, experimentation and software usage (Maxsurf). The results show that there is a significant meeting point between the published theoretical models and those obtained from the real data.

Fagerholt and Psaraftis[16] conducts research on speed optimization for ships sailing in and out of emission control areas (ECA) with strict limits on sulfur emissions. For ships sailing in and out of the ECA, the common thing every ship is subject to is the limitation of using heavy fuel oil (HFO) outside the ECA and switching to a low sulfur marine gas oil (MGO) known to be sailing within the ECA. Because the price of these two fuels is much different, the speed of the vessel is modified in this case. The purpose of this study is to maximize daily profits. In addition to mathematical formulations, samples and sensitivity analyzes are presented in this study.

Fagerholt *et al.*[17] conducting research on maritime routing and speed optimization in emissions control areas. Developed optimization models that can be used by ship operators to determine the velocity and speed of shipping that can minimize the operating costs for a ship in a single shipping route. Computational studies were conducted on a number of shipping routes to evaluate possible impacts on shipping lanes, ship speed, fuel consumption and costs due to ECA regulations. In addition, the objective is to look at the environmental impacts on communities. A case comparison indicates that the likely impact of the regulation is that the ship operator will often choose to sail further to avoid sailing within the ECA. Another effect is that they will sail at low speeds within the ECA and higher speeds beyond the ECA to keep fuel consumption from being too high. This will probably provide a substantial increase in fuel consumption and CO_2 emissions.

Gusti and Semin[18] conducting research on the effect of ship speed on fuel consumption and ship emissions. Performed calculations using simple mathematical formulas. Speed is varied to see the impact on fuel consumption and emissions. The results showed that at higher the speed, the level of fuel consumption and ship emissions increased.

CONCLUSION

From the results of previous reviews, it can be concluded that the speed of the ship is the key in the operation of a ship, therefore, it required the speed control when the ship sailed. Speed reduction is one of the methods to reduce the level of ship emissions. Many research has been conducted in this regard. Research on speed optimization is mostly conducted for tankers and container types. For future studies it is expected that more speed optimization research with ship objects other than tankers and containers, such as LNG vessels or other fast vessels so that more renewal can be reviewed in it. In addition, the development of decision variables or constraint can be more tailored to the needs of the shipping industry.

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