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Research Article

A New Formula for Calculation of Optimum Displacement and Its Effects

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Abstract

In maritime transport, fuel consumption is one of the biggest costs. So, various methods are used to reduce fuel consumption. The most common of these methods is to reduce the cruise speed of the ship. However, decreasing the voyage speed causes an increase in ship time. Nevertheless, the cruise speed is not only parameter which effects the fuel consumption. Weather condition, weight of the ship and even hull cleansing can affect the consumption. In this study, the effect of speed reduction and the effect of weight reduction were analyzed, and weight optimization was made for a ferry. In addition, cost of this reductions and amount of CO_2 emissions were compared. Finally, the advantages of weight optimization were revealed.

Keywords: Fuel Consumption, CO_2 Emission, Maritime Transport

Introduction

In maritime transport, all of the fuel and lube oil costs are referred to as bunker costs and this cost varies depending on the ship type and size. The main factors that technically affect this cost are the type, age, power in kilowatts of the ship's main engine, the type of fuel burned in the machine (HFO Heavy Fuel Oil, Marine Diesel Oil, etc.)] (Beşik, Şıhmantepe,2020). Considering that the fuel consumed on the ship accounts for more than 60-70 percent of the total cruising cost on average (Alexadridis et al., 2018). So, fuel consumption is the biggest expense item for ships. In addition, reducing fuel consumption can reduce CO2 emission of a ship (Kiliç and Deniz, 2009).

Various methods are used to reduce fuel consumption. The most common of these methods is to reduce the cruise speed of the ship. However, decreasing the voyage speed causes an increase in ship time. Nevertheless, the cruise speed is not only parameter which effects the fuel consumption. Weather condition, weight of the ship and even hull cleansing can effect the consumption.

In this study, two conditions are analyzed. The effect of speed reduction and the effect of weight reduction. Of course, cargo weight can not be reduced because of cargo amount depends on the demand. So, weight of the bunker can only be reduced.

Literature Review

Alderton published a formula for consumption of a ship (Alderton, 1981). In this formula, weight of the ship was neglected. According to this formula, the fuel consumption was directly proportional to the cube of the speed. Then Ronen and Chrzanowski used this formula in their studies (Ronen,1982; Chrzanowski, 1989). Barras published a formula for fuel consumption which does not neglect the weight of the ship (Barras,2004). In this formula, displacement of the ship was added to Alderton's formula. So, the formula was modified to

$$C(v) = \lambda v^{\Omega} \nabla^{\frac{2}{3}}.$$

Where ∇ is displacement tonnage of a ship. If the service speed is 20 kt or greater, it is more accurate when making comparisons, to change the power of velocity from being three to being four. Kim, Chang, Kim, and Kim determined amount of fuel and optimum vessel speed for a specific vessel route (Kim et al., 2012). The study was solved the problem by using epsilon-optimal algorithm. Considering more recent studies, Mersin et al built up a new formula which does not neglect instant weight changing and showed that displacement tonnage at any time t is(Mersin et al,2017);

$$\nabla(t) = \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}\right)^3 \text{ and}$$

fuel consumption for t day is

$$C(t) = \nabla(0) - \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}\right)^3$$

Bayırhan et al. analyzed the exhaust emissions generated by the ships of the local companies transporting in Strait of Istanbul (Bayırhan et al.,2019). Tokuşlu analyzed energy efficiency of a passenger ship in Turkey (Tokuşlu, 2020). The Energy Efficiency Design Index (EEDI) of the ship was calculated. EEDI formula equations based on the study of passenger ships. Ülker et al. made a comparison between emissions of ro-ro and ferry lines (RFLs) in the Sea of Marmara and emissions of road transport (Ülker et al., 2020). Energy efficiency in terms of EEDI performance of sea buses which were operating in Istanbul Strait was analyzed. In terms of number sea buses, analysis showed over two thirds of the sea buses were not energy efficient. The analysis showed that speed reduction caused decrease in CO_2 emission and increase in energy efficiency (Tokuşlu, 2021-2022).

Methodology

In this study, the Trozzi & Vaccaro method is used for calculating CO_2 emission. According to the method, 3 different situations should be examined while making calculations. They are cruise mod, manoeuvre mod and port mod. Despite the estimated emission factors created by the machine types according to the cruise modes of the ships (cruise, maneuver, hotelling), CO_2 emission is 3.20 for each mode and for each machine type. In the light of all these data, the formula for the total CO_2 emission of a ship is given below;

$$E(t_{total}) = \sum_{i=1}^{3} C \times f \times t \times p_i \quad \text{(eq.1)}$$

Where,

$E(t_{total})$: The total amount of CO_2 emissions per passenger at t-day sailing.
C:Fuel consumption (tonne)
$f = 3200$ kg/tonne(CO_2 emission factor)
t: time (day)
p_1: Sailing mode multiplier (0,8)
p_2: Maneuver, mode multiplier (0,4)
p_3: Hotelling mode multiplier (0,2)

Scenario Analysis

In this part of the study, two scenarios were analyzed for M/V Spokane ferry. This jumbo class ferry sails between Edmonds and Kingston and properties of the ferry is given at Figure 1.

M/V Spokane

Features / ADA Information

Car Deck ADA Shelter: No
Car Deck ADA Restroom: No
WiFi Access: No
Main Cabin Restroom: Yes
Elevator: Yes

ADA Notes: The MV Spokane has elevator access from both auto deck levels to all of the passenger cabin areas. Restrooms are on both the auto deck and the main passenger deck, but the auto deck restroom is not ADA compliant. If you are traveling by car and want to park near the elevator, be sure to let the ticket seller know. The main passenger deck also has vending and newspaper machines and a galley. This vessel is equipped with our visual paging system.

Vessel Information

Class: Jumbo	**Type:** Auto/Passenger Ferry
Length: 440'	**Engines:** 4
Beam: 87'	**Horsepower:** 11,500
Draft: 18'	**Speed in Knots:** 18
Max Passengers: 2000	**Propulsion:** DIESEL-ELECTRIC (DC)
Max Vehicles: 188	**Displacement (weight in long tons):** 4859
Tall Deck Space: 60	**City Built:** Seattle, WA
Auto Deck Clearance: 15' 8"	**Year Built / Re-built:** 1972 / 2004

Meaning of Spokane: Eastern Washington Native American tribe: "children of the sun or sun people." A city, county and river are also named after the tribe.

Fig. 1. Properties of M/V Spokane (www.wsdot.wa.gov, Retrieved 02.01.2021)

In the first scenario, "ship speed" was reduced and reduction of total emission of the ship was calculated. In the second scenario, the ship had fuel enough to complete the voyage and the emission of the ship was compared with "full tank" emission of the ship. Although, number of carried passenger is assumed 2000 and all passengers are adults (age 19-64).

Scenario 1.

In this scenario, the amount of fuel in the tank is assumed 130000 gallons=419,328 tonne (it means fuel tank) (www.wsdot.wa.gov, 02.01.2021). The distance between Edmonds and Kingston is 5.67 nm. (www.distance-cities.com, 02.01.2021). Nevertheless, the ferry can take this route in 24 minutes. So, speed of the vessel is 5.67/0.4≅14 kt. Fuel consumption can be calculated with the formula which is given below:

$$C(t) = \nabla(0) - \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}\right)^3 \quad (1)$$

Where C(t) is t-day fuel consumption, ∇(0) is the displacement of the ship at t=0, v is speed of the ship and =1/120,000 . This formula can be modified for calculating hourly fuel consumption as

$$C(t) = \nabla(0) - \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{72}\right)^3.$$

So, the fuel consumption of the ship is 0.1135 tonne for 14.175 kt ship speed. If this speed reduced to 14 kt, the fuel consumption will be 0.1107 tonne. It is obvious that reducing speed can effect fuel consumption positively. This effect is given at Table 1.

Table 1. Effects of fuel consumption with variable speed per voyage.

Speed (kt)	Time (h)	Consumption (tonne)	CO_2 Emission (tonne)	Cost (USD)	Reducing Rate
14	0.40	0.109331747	0.279889271	54.66587328	0%
12.6	0.44	0.088558841	0.226710633	44.27942046	10%
11.2	0.50	0.699725070	0.179129618	34.98625337	20%
9.8	0.57	0.535727610	0.137146267	26.78638037	30%
8.4	0.67	0.039359618	0.100760622	19.67980885	40%
7	0.80	0.027333090	0.069972711	13.66654520	50%
2.8	2	0.004373301	0.011195651	2.18665068	80%

Bunker price is assumed \$500 per tonne and emission factor is assumed 3200 kg/tonne while calculating the CO2 emission values at the table. That means 1 tonne of fuel emits 3200 kg CO2. Nevertheless, reducing ship speed causes a decreasing in the number of voyage. For example, when the ship sails at 14kt speed, it can make 23 voyages a day. But, if the ship speed is reduced by 80%, it can only make 4 voyages. If it is assumed that 2000 passengers are carried per voyage, Table 2 shows the effects of reducing ship speed on daily income.

Table 2 Effects of reducing ship speed on daily income.

Speed (kt)	Carried passenger	CO_2 Emission (tonne)	Consumption (tonne)	Income (USD)	Cost (USD)	Profit (USD)
14	46000	8.046816547	6.437453238	\$416300	\$1257.315085	\$415042.6849
12.6	40000	5.667765819	4.534212655	\$362000	\$885.5884092	\$361114.4116
11.2	36000	4.030416388	3.22433311	\$325800	\$629.7525606	\$325170.2474
9.8	32000	2.742925350	2.19434028	\$289600	\$428.5820860	\$289171.4179
8.4	26000	1.637360096	1.309888077	\$235300	\$255.8375151	\$235044.1625
7	22000	0.962124782	0.769699826	\$199100	\$150.3319972	\$198949.668
2.8	8000	0.055978257	0.044782606	\$72400	\$8.74660272	\$72391.2534

Scenario 2.

In this scenario, the ship starts its voyage with less than full tank. Nevertheless, the ferry can still take this route in 24 minutes. So, speed of the vessel can still be taken 14 kt. It is obvious that reducing fuel amount effects fuel consumption positively because of reducing displacement of the ship. Table 3 shows the effects of fuel consumption with variable fuel amounts.

Table 3. Effects of fuel consumption with variable fuel amounts.

Fuel Amount (tonne)	Displacement (tonne)	Consumption (tonne)	CO_2 Emission (tonne)	Cost (USD)	Reducing Rate
419.328	4859	0.109331747	0.279889271	54.66587328	0%
377.3952	4817.0672	0.108701820	0.278276658	54.35090978	10%
335.4624	4775.1344	0.108070062	0.276659358	54.03503102	20%
293.5296	4733.2016	0.107436453	0.275037318	53.71822625	30%
251.5968	4691.2688	0.106800969	0.273410481	53.40048455	40%
209.664	4649.3360	0.106163589	0.271778789	53.08179471	50%

According to the Table 3, reducing the amount of fuel in the tank reduces fuel consumption. But, this reducing has to be stopped at an optimum fuel amount. Because the ship must have fuel enough to complete the voyage. The question is "what is the optimum amount of fuel to complete the voyage?"

Theorem: Let W be the total weight of the cargo and light ship weight and F(0) be the weight of the fuel that the vessel has at time t=0. The optimum amount of bunker that vessel should have is

$$F(0) = \left(\sqrt[3]{W} + \frac{\lambda v^3 t}{3}\right)^3 - W$$

Proof:
It could be calculated that the displacement of a ship at any time t is $\nabla(t) = \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}\right)^3$ where ∇(0) is the displacement of the ship at time t=0. So, fuel consumption of the ship for t- day is C(t)=∇(0)-∇(t). In this part of the proof, W+F will represent the displacement of the ship where W= the weight of the cargo + weight of the light ship and F is the weight of the fuel that vessel has. So,

$$C(t) = \nabla(0) - \nabla(t) = \nabla(0) - \left(\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}\right)^3 = (\mathrm{W}+\mathrm{F})(0) - \left(\sqrt[3]{(\mathrm{W}+\mathrm{F})(0)} - \frac{\lambda v^3 t}{3}\right)^3$$

It is obvious that W is constant and F is variable during the voyage. So, the above formula can be rewritten as

$$C(t) = \mathrm{W} + \mathrm{F}(0) - \left(\sqrt[3]{(\mathrm{W}+\mathrm{F}(0)} - \frac{\lambda v^3 t}{3}\right)^3$$

Where F(0) is the amount of fuel at time t=0. The fuel consumption and the ship's weight are directly proportional. That means fuel consumption decreases as the weight of the ship W decreases and it will be best if there is no fuel left in the tank at the end of the voyage. If this formula equals zero, the desired result is obtained.

$$W + F(0) - \left(\sqrt[3]{W+F(0)} - \frac{\lambda v^3 t}{3}\right)^3 = F(0)$$

$$W - \left(\sqrt[3]{W+F(0)} - \frac{\lambda v^3 t}{3}\right)^3 = 0$$

$$W = \left(\sqrt[3]{W+F(0)} - \frac{\lambda v^3 t}{3}\right)^3$$

$$F(0) = \left(\sqrt[3]{W} + \frac{\lambda v^3 t}{3}\right)^3 - W$$

According to this formula, if the ship starts a voyage with F(0) tons of fuel, fuel consumption can be minimized. If this formula is used for M/V Spokane, optimum displacement will be,

$$F(0) = \left(\sqrt[3]{4859} + \frac{14^3 0.4}{8640000}\right)^3 - 4859$$ =0.109 tonne.

Table 4 shows the effect of optimum fuel amount.

Table 4. Effect of optimum fuel amount.

Fuel Amount (tonne)	Displacement (tonne)	Consumption (tonne)	CO_2 Emission (tonne)	Cost (USD)	Reducing Rate
419.328	4859	0.109331747	0.279889271	54.66587328	0%
377.3952	4817.0672	0.108701820	0.278276658	54.35090978	10%
335.4624	4775.1344	0.108070062	0.276659358	54.03503102	20%
293.5296	4733.2016	0.107436453	0.275037318	53.71822625	30%
251.5968	4691.2688	0.106800969	0.273410481	53.40048455	40%
209.664	4649.3360	0.106163589	0.271778789	53.08179471	50%
0.109	**4439.781**	**0.102949115**	**0.263549735**	**51.47455771**	**99%**

Table 5 Effects of reducing fuel amount on daily income

Fuel Amount (tonne)	Carried passenger	CO_2 Emission (tonne)	Consumption (tonne)	Income (USD)	Cost (USD)	Profit (USD)
419.328	46000	8.046816547	2.514630171	$416300	$1257.315085	$415042.6849
377.3952	46000	8.000453919	2.500141850	$416300	$1250.070925	$415049.9291
335.4624	46000	7.953956565	2.485611427	$416300	$1242.805713	$415057.1943
293.5296	46000	7.907322904	2.471038408	$416300	$1235.519204	$415064.4808
251.5968	46000	7.860551325	2.456422289	$416300	$1228.211145	$415071.7889
209.664	46000	7.813640181	2.441762557	$416300	$1220.881278	$415079.1187
0.109	**46000**	**7.577054895**	**2.367829655**	**$416300**	**$1183.914827**	**$415116.0852**

In this scenario, carried passenger and income do not depend on reducing rate. So, this method can be more profitable than reducing speed method. Table 5 shows the effects of reducing fuel amount on daily income

Discussion and Conclusion

In this study, two different scenarios' performances had been illustrated in which environmental and financial impacts were taken into consideration. Performances of these scenarios were evaluated through amount of CO_2 emission release, profit and fuel cost in this paper. Independent variables of the scenarios were speed and initial tank fuel amount. While one of the independent variables was kept as constant in each scenario, a set of values was assigned to the other independent variable. Analysis carried out on the values of amount of CO_2 emission release amount, profit and fuel cost. Both single voyage and daily based values were subject to analyze. It was seen that amount of CO_2 emission release and fuel cost should be evaluated together. In the initial scenario, the effect of ship speed was analyzed. It had been observed that the percentage change in speed, CO_2 emission release amount and fuel cost were moving in the same direction. In addition, the percentage change in CO_2 emission amount and fuel cost were equal due to the formula in which they are being calculated. For any given speed value, voyage based percentage change values for CO_2 emission amount and fuel cost were higher than daily figures. It was stand out as a result of the increase in operation times. For CO_2 emission amount and fuel cost, exact parallelism between daily and voyage based values could not be observed on percentage change values. It was due to slight difference in engine operation times. The decrease in speed resulted a negative impact on the profit. In the relevant scenario, it had been seen that the profit values move parallel to the speed value. It was a natural result of decrease in the number of trips made at decreased speed. As a result of decrease in number of trips on daily basis yielded significant drop on sales figures. Decrease in the number of trips caused the decrease in fuel cost which had a positive impact on profit. It had been observed that the percentage drop value in profit was greater than percentage drop value in speed. The most important point to mention in this issue was the CO_2 emission tax. CO_2 emissions could be taxed at certain countries. The tax rate in Finland, British Columbia and BAAQMD, California were \$30, \$0.045 and \$9.50 per metric ton CO_2 or CO_2 equivalent respectively in 2008(Sumner et al.,2009). Decrease in CO_2 emission would result in decrease in related tax which would result in profit increase. In the second scenario, while speed was taken as constant initial tank fuel amount was taken as

Independent variable. As a result of keeping the speed constant, the number of trips and sales value during the day was constant for all alternatives. Daily and voyage based percentage change values for CO_2 emission amount and fuel cost were same for all initial fuel amount alternatives. This was another result of keeping speed and number of daily trips constant. Reducing the initial fuel quantity to the minimum did not make any significant effect in profit. Operating with minimum fuel quantity bring operational load. The result of the effort yielded %6 drop on CO_2 emission and fuel cost. Even though the figure was relatively low compared to available drop in previous scenario, it should be noted that the reduction is obtained without any profit sacrifice. Any reduction on possible CO_2 tax payable could have a positive in impact on profit amount. The study had shown that among the two scenarios, speed reduction yields significant drop in CO_2 emission amount. The minimum fuel tank scenario would be more desirable option when not only CO_2 emission and fuel cost reduction aimed but also profit increase was desired

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