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A New Method for Calculating Fuel Consumption by Using Speed Loss Function

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Alderton (1981) published a formula on the fuel consumption of a ship. In this formula, the weight of the ship was neglected. Then Ronen (1982) and Chrzanowski (1989) used this formula in their work. Barras (2004) published a formula for fuel consumption, which does not neglect the weight of the ship. Notteboom and Carlou (2013) investigated the effects of slow speed applications. They also analyzed fuel consumption and BAF paid by carriers. Khor, Dohlie, Konovessis and Xiao (2013) found an optimal speed of 19.5 knots by installing a model to optimize the speed of ultra-container ships. Doudnikoff and Lacoste (2014) presented differences in speed and cost effectiveness between the total transit time and CO2 emissions in and outside the SECA. Bayırhan et al.(2019) published an article about modelling of ship originated exhaust gas emissions in the strait of Istanbul (Bosphorus) and Mersin et al. (2019) made reviewing of CO2 emission and reducing methods in maritime transportation

Rotation according to weather conditions

Weather condition affects the energy which is used for the ship's propulsion. For this reason, it is necessary to take the weather conditions into account when calculating the route. The longer the ship's route, the more flexibility can be achieved in the rotation of the weather conditions. In this context, rotation according to weather conditions in transcontinental ocean crossings can be taken as an operational measure (Eide and Endersen, 2010).

However, weather conditions have a high potential for efficiency in route determination. If used correctly, it provides fuel saving and improving the performance of the ship, but vice versa.

A strong wind taken from the bow will increase ship resistance by an average of 10%, and the importance of the issue becomes apparent when determining the route according to the weather can contribute 0.1 to 4% to energy saving (Talay et al., 2013).

In cases where the wind is blowing, the main body of the ship, the part above the water and the resistance of the superstructures vary depending on the direction and speed of the wind. Therefore, the weather resistance of a ship in windy weather conditions includes both calm weather resistance and wind resistance. In addition, wind-induced waves create additional resistance. Wind force acting on the surface of the ship; it changes the speed of the ship, causing the ship to incline or slightly trim. The wind force in question is not actually continuous, it is usually intermittent and its intensity fluctuates (Erat, 2014).

The preliminary calculation of the wind strength can be done by modelling the ship structure, provided that the regions where the ship will operate will be determined in advance. Wind tunnel tests are a very good option for detecting wind impact, but these tests are not applicable to all ships because of the high costs involved. Therefore, many numerical methods have been developed for the estimation of wind strength (Haddara, 1999). One of these methods is the Beaufort Wind Scale. Wave height and wind speed were classified by giving values between 0-12.

After determining the wind type from the Beaufort Wind Scale, the second step is determining the wind direction effect. It is important to know the wind density as well as the determination of the wind direction. Wind direction determination is a must in determining air entrainment. Ships are equipped with anemometers to determine wind power and direction. There are many different methods for calculating wind resistance (Molland et al. 2011).

In cases where the wind intensity is greater than 7 Beaufort, speed losses may occur due to the possibility that the propeller may rise above the water. So, calculations cannot yield correctly where the wind intensity is greater than 6 Beaufort (Kwon, 2008).

For the Beaufort scale, two types of Aertssen Numbers were found as m and n. These values help to calculate the speed at which the wind loses relative to the Beaufort value. Aertssen Numbers corresponding to 5,6,7,8 values are given in the table 2.

Beaufort Number	Head Sea	Bow Sea	Beam Sea	Following Sea
5	*m*= 900; *n*=2	*m*= 700; *n*=2	*m*= 350; *n*=1	*m*= 100; *n*=0
6	*m*= 1300; *n*=6	*m*= 1000; *n*=5	*m*= 500; *n*=3	*m*= 200; *n*=1
7	*m*= 2100; *n*=11	*m*= 1400; *n*=8	*m*= 700; *n*=5	*m*= 400; *n*=2
8	*m*= 3600; *n*=18	*m*= 2300; *n*=12	*m*= 1000; *n*=7	*m*= 700; *n*=3

Speed losses can be calculated as a percentage with the following formula by using Aertssen numbers:

$\frac{\Delta V}{V} \times 100\% = (\frac{m}{L_{pp}} + n)$ (Molland et. al, 2011) Where Lpp is length between perpendiculars and $\frac{\Delta V}{V}$ is speed loss. For example, speed loss of a vessel with 150 meter Lpp and in 5 Beaufort air condition is $\frac{900}{150} + 2 = 8\%$.

According to above table, we can define a function μ_i between set of Beaufort numbers (B) and set of Aertssen Numbers $(M \times N)$. Where μ_1 *for head sea,* $\mu_{2,}$ *for bow sea,* μ_3 *for beam sea and* μ_4 for following sea.

$$\mu_i : B \rightarrow M \times N$$
$$\mu_i(b) = (m, n)$$

Speed Loss Function

Speed loss percentage can be defined with a function by using μ_i function. That is

$$\alpha : \mathbb{R} \times \mathbb{R} \times B \to \mathbb{R}$$

$$\alpha(\mathrm{v}, \mathrm{L_{pp}}, \mu_i(\mathrm{b})) = \mathrm{v} \times (\frac{(100 - \mathrm{n}) \times \mathrm{L_{pp}} - \mathrm{m}}{100 \times \mathrm{L_{pp}}})$$

where v is the speed of the ship.

Effect of the Speed Loss Function to the Fuel Consumption

Displacement, time, speed and wind resistant are the important parameters which effect the fuel consumption of the ship. So, the formula which is built for fuel consumption has to contain these parameters.

We know that fuel consumption is an increasing function by weight of the ship. We can define it as $\mathrm{C}(\nabla) = \lambda . \mathrm{v}^3 . \nabla^{\frac{2}{3}}$ (Barras 2004). Nevertheless, this function is decreasing function by time. Because the weight of the ship decreases by time. So this function has to be

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

Let d be the distance between the ports. For a ship which sails with speed v, sailing time is $t_{sailing} = \frac{d}{v}$. So, fuel consumption formula can be modified by changing variable.

In addition, sailing time depends on net speed that is $v_{net} = v_{ship} - v_{wind}$. This speed can be calculated by the speed loss function.

$$v_{net} = \alpha\left(\mathrm{v}, \mathrm{L_{pp}}, \mu_i(\mathrm{b})\right) = \mathrm{v} \times \left(\frac{(100 - \mathrm{n}) \times \mathrm{L_{pp}} - \mathrm{m}}{100 \times \mathrm{L_{pp}}}\right) \Rightarrow$$

$$t_{sailing} = \frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}$$

So, the fuel consumption at time $t_{sailing}$ is

$$C\left(t_{sailing}\right) = C\left(\frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}\right) = \lambda . v^3 . (\nabla(\frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}))^{\frac{2}{3}}$$

If this formula is integrated from 0 to $t_{sailing}$; it yields total consumption. That means,

$$C_{total}\left(\frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}\right) = \lambda . v^3 . \int_0^{\frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}} (\nabla(\tau))^{\frac{2}{3}} d\tau$$

Nevertheless, displacement of a ship at time t is $\nabla(\mathrm{t}) = [\sqrt[3]{\nabla(0)} - \frac{\lambda v^3 t}{3}]^3$ (Mersin et al. 2017). So, the result of the integral above is

$$C_{total}(\mathrm{t}) = \nabla(0) - \nabla\left(\frac{d}{v} \times \frac{100 \times \mathrm{L_{pp}}}{(100 - n) \times \mathrm{L_{pp}} - m}\right)$$

Example

A vessel with a capacity of 4000 TEU and 52,600 DWT has a λ coefficient of 0.00372 is sailing from Port of Istanbul to Port of Valencia. The economic speed of the container ship is 15 kt. Length between perpendiculars of the ship is 281 meter and the wind intensity is 6 Beaufort. A calculation of total fuel consumption is above.

We will calculate fuel consumption with 2 methods and will compare them.

1.Method: Air condition is neglected in this method. That means, calculations do not contain wind speed as a parameter. Distance between ports is 1802 miles. So, the sailing time at calm weather is 120.13 hours = 5 days.

$C_{total} = 52{,}600 - [37.47 - \frac{0.00372 \times 3{,}375 \times 5}{3}]^3 =$ 48,071.021 ton.

2. Method: In this method, air condition is not neglected. So, we will find the sailing time by using the speed loss function.

$$\alpha(15{,}281) = 5 \times \left(\frac{100 \times 281}{(100 - 6) \times 281 - 1300}\right) = 5.59$$

that is $t_{sailing}$ at 6 Beaufort. So, total consumption is

$C_{total}(5.6) = \nabla(0) - \nabla(5.6) = 52{,}600 - [37.47 - \frac{0.00372 \times 3{,}375 \times 5.6}{3}]^3 =$ 52,585.966 tons

Total fuel consumption for each Aertssen number is given in table 3.

Fuel consumption according to 2. Method (ton) **1.Method (ton)**

Beaufort Number	Head Sea	Bow Sea	Beam Sea	Neglected Wind Speed
5	49,659.22	48,846.78	48,438.64	48,071.02
6	49,811.15	49,501.87	48,877.02	48,071.02
7	50,950.29	50,190.52	52,585.12	48,071.02
8	51,246.12	52,588.72	52,585.92	48,071.02

It is clearly seen that results are close to each other for 5 and 6 Beaufort but the differences are greater for 7 and 8 Beaufort. This is normal because in cases where the wind intensity is greater than 7 Beaufort, speed losses may occur due to the possibility that the propeller may rise above the water. Nevertheless, method 2 is gives the closest result to the total consumption.

Results

Displacement, time, speed and wind resistant are the important parameters which effect the fuel consumption of the ship. There are many methods to calculate the fuel consumption. Wang and Meng built up a formula in 2012 which neglects the weight of cargo and Barras creates a formula in 2004 which includes weight of cargo. Those two formulas are most common formulas for calculating formulas. But these formulas do not include wind speed as a variable.

In this study, we built up a new model for ship which has a constant speed in 5,6,7,8 Beaufort value. These wind values are the most effective values for ships. Nevertheless, ships do not leave the ports in 7 or 8 Beaufort values. In cases where the wind intensity is greater than 7 Beaufort, speed losses may occur due to the possibility that the propeller may rise above the water. So, calculations cannot yield correctly where the wind intensity is greater than 6 Beaufort. But we assumed that propeller is always in the water.

Shipping companies define an eco-speed for their ships and the ship stays this speed along the voyage. However, the speed of the ship cannot be fixed due to various reasons (weather opposition etc). So, if a ship has a speed which changes by time, the new method can calculate the fuel consumption for any given time despite Barras' formula that we call classical method, will be failed calculating the consumption.

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