Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan
(Kapal: Journal of Marine Science and Technology)
journal homepage : http://ejournal.undip.ac.id/index.php/kapal
2301-9069 (e)
1829-8370 (p)

The Effect of Trim on Tanker, Container and Bulk Carrier Ship Toward the Reduction of Ship's Exhaust Gas Emission

Robin Undap[1)], Arif Fadillah[1)*)]

[1)] Department of Naval Architecture, Darma Persada University, Jakarta 13450, Indonesia
[*)] Corresponding Author : arif_fadillah@ftk.unsada.ac.id

Article Info

Keywords:
Tanker Ship;
Container Ship;
Bulk Carrier Ship;
Trim Optimization;
Exhaust Gas;

Article history:
Received: 02/11/2020
Last revised: 10/05/2021
Accepted: 19/05/2021
Available online: 19/05/2021
Published: 30/06/2021

DOI:
https://doi.org/10.14710/kapal.v18i2.33877

Abstract

Emission is one of the few environmental problems, and ships are one of the modes of transportation that produce it. This study aims to define the impact of using optimal trim during the cruising phase, so it can decrease the resistance and the fuel consumption, which will lead to less emission produced by the ship. The type and amount of ships used in this study are three tanker ships, three container ships, and two bulk carrier ships. The methodology used in this study is by using Holtrop's resistance calculation method with the help of Maxsurf software. The resistance, the power needed, and the fuel consumption is calculated on 22 trim variations and seven speed variations. This study determined that the average decrease in fuel consumption caused by trim optimization for tanker, container, and bulk carrier ships is 5.641%, 8.269%, and 15.704%. Furthermore, the average decrease of emissions produced by tanker, container, and bulk carrier is 6.494%, 11.317%, and 13.775%, respectively. These results are narrowed down to conclude that trim optimization can reduce fuel consumption by up to 9.871% and decrease the emission produced by up to 10.529% for the three types of ships used in this study.

1. Introduction

The shipping industry is responsible for 90% of the world trade currently helping and developing the global economy to date [1]. As ships being responsible for a huge part of the exchange of goods, internationally and domestically, it's only natural for ships to emit a lot of exhaust gasses. During the year 2007–2012, it is estimated that ships produce 3,1% carbon dioxide (CO2), 15% nitrogen oxides (NOX), and 13% sulfur oxides (SOX) [1]. According to the International Maritime Organization (IMO), it is forecasted that the potential carbon dioxide (CO2) emission from international shipping could grow as much as 50% to 250% by 2050 [1]. Seeing the constant increase of emission, IMO, through the Marine Environment Protection Committee (MEPC), imposes regulations and recommendations regarding the means of reducing exhaust gas emissions from ships. In the IMO strategy on reducing greenhouse gas (GHG) at MEPC72, the target of reducing CO2 emitted by ships at least reaches 40% by 2030 and pursuing 70% target by 2050 compared to 2008 [2].

To reduce emissions, ships need to consume less fuel or operate in a fuel-efficient manner– MEPC70 guides to decrease the ships' fuel consumption, starting from ship handling, voyage planning, improved fleet management, etc [3]. The ship's handling could be from utilizing ship Turnaround Time (TRT) in port to the trimming of the ship. TRT could reduce exhaust gas emission in port by up to 10% compared to the Business as Usual (BAU) scenario [4]. Specifically, about ship trimming, it could decrease the total exhaust gasses from ships by reducing the Wetted Surface Area (WSA), thus decreasing its resistance, fuel oil consumption, and in the end, decreasing the exhaust gasses emitted by the ship. A study finds the potential CO2 reduction by adjusting a ship's trim ranging from 1%-10% [5].

Research done on the S60 hull model determined the reduction of wave-making resistance and total resistance compared to the even keel condition, ranging from 9.7%–26.2% and 3.5%–7.2%, respectively [6]. Another definite evidence from several researches conducted on a container ship modelled by the Korean Research Institute of Ships and Ocean Engineering (KRISO) conclude the impact of optimized trim on reducing container ship's total resistance ranging from 2.29% to up to 5.13% [7], [8]. Moreover, a trim optimization study on 4250-Twenty Equivalent Units (TEUs) container ship with the implementation of the study on the real 4250-TEUs ship finds the trim optimization could save energy by 5%–8%, which results in saving fuel consumption around 3.2 ton/day [9]. Another study with three loading conditions at different speed ranges in a bulk carrier ship found the ship could reduce resistance by 14% with a slight trimming angle [10].

Based on the studies mentioned, it can be concluded that all the research for trim optimization was done only by using a very little data model for the case study. Contrary to all the research that has been done, this paper will mainly use 3 models for tanker and container ship and 2 models for bulk carrier ships. This paper selects these 3 types of ships (i.e. tanker, container and bulk carrier ship) because these ships are the type of ships to use the most fuel oil out of other types of ships [1]. The purpose of this study is to prove the utilization of ship trim as the easiest and quickest alternative to decrease ships' exhaust gas emissions by reducing the fuel oil consumption, regardless of the type of the ship.

2. Methods

The process of selecting the best trim was carried out on varying types of ships with various trim and speed conditions. This research uses lines plans from ships that are currently active (cruising) as a reference, which was acquired from several sources, and then all the lines plans are redrawn to be analyzed further. The principal dimensions and data used for tanker, container and bulk carrier ships are shown in Table 1, Table 2 and Table 3, respectively. Furthermore, an example of the original source of lines plan and one of the redrawn lines plan are shown in Figure 1 and Figure 2, respectively.

Table 1. Principal Dimensions and Data for Tanker Ships

Parameter	Value			Unit
	TS-1	TS-2	TS-3	
Length Between Perpendicular (L_{BP})	84.50	149.50	233.00	m
Breadth (B)	15.40	27.70	42.00	m
Height (H)	7.30	12.00	22.20	m
Draught (d)	5.00	7.00	15.45	m
Service Speed (Vs)	11.00	13.00	15.70	knot
Main Engine Type	MSD	SSD	SSD	-
Main Engine Power	1620	4440	15540	kW
Main Engine Total	1	1	1	-
Propeller Total	1	1	1	-
Fuel Type	HFO	HFO	HFO	-
Specific Fuel Oil Consumption (SFOC)	175	179	173	g/kWh

Table 2. Principal Dimensions and Data for Container Ships

Parameter	Value			Unit
	CS-1	CS-2	CS-3	
Length Between Perpendicular (L_{BP})	69.20	92.00	112.80	m
Breadth (B)	17.20	23.50	18.20	m
Height (H)	4.90	10.00	8.20	m
Draught (d)	3.50	6.50	6.20	m
Service Speed (Vs)	12.00	11.25	12.00	knot
Main Engine Type	HSD	MSD	MSD	-
Main Engine Power	1220	2206	2574	kW
Main Engine Total	2	1	1	-
Propeller Total	2	1	1	-
Fuel Type	MDO	MDO	MDO	-
Specific Fuel Oil Consumption (SFOC)	217	189	178	g/kWh

Table 3. Principal Dimensions and Data for Bulk Carrier Ships

Parameter	Value		Unit
	BCS-1	BCS-2	
Length Between Perpendicular (L_{BP})	182.00	217.00	m
Breadth (B)	32.26	32.26	m
Height (H)	17.20	19.60	m
Draught (d)	12.49	14.20	m
Service Speed (Vs)	14.70	14.50	knot
Main Engine Type	SSD	SSD	-
Main Engine Power	9480	8833	kW
Main Engine Total	1	1	-
Propeller Total	1	1	-
Fuel Type	HFO	HFO	-
Specific Fuel Oil Consumption (SFOC)	172	172	g/kWh

As shown in Table 1, Table 2, and Table 3, there are three main engine types and two fuel types used by the ships in this study. The engine types are High-Speed Diesel (HSD), Medium Speed Diesel (MSD), and Slow Speed Diesel (SSD), while the fuel that is commonly used for all the subjects of this study is Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). These two data (i.e., engine type and fuel type) will affect the emission factor that will be used to quantify the number of exhaust gasses produced by each ship.

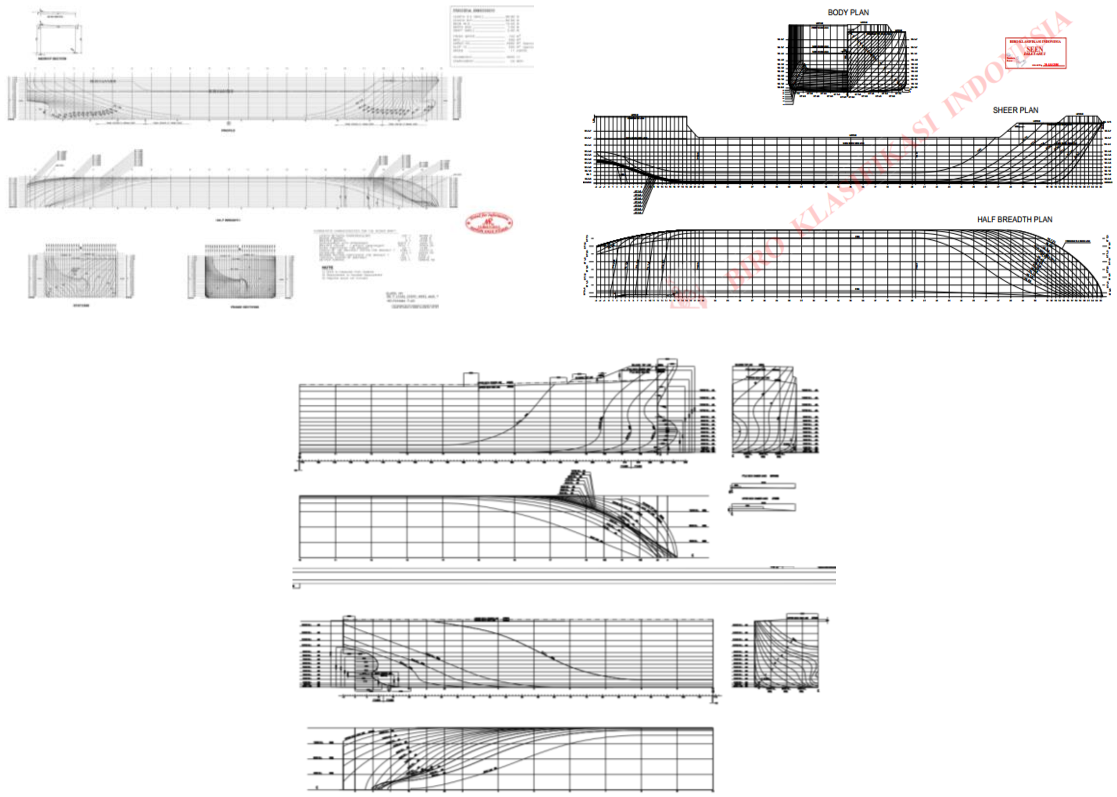

Figure 1. Lines Plan of TS-1, CS-1 and BCS-1

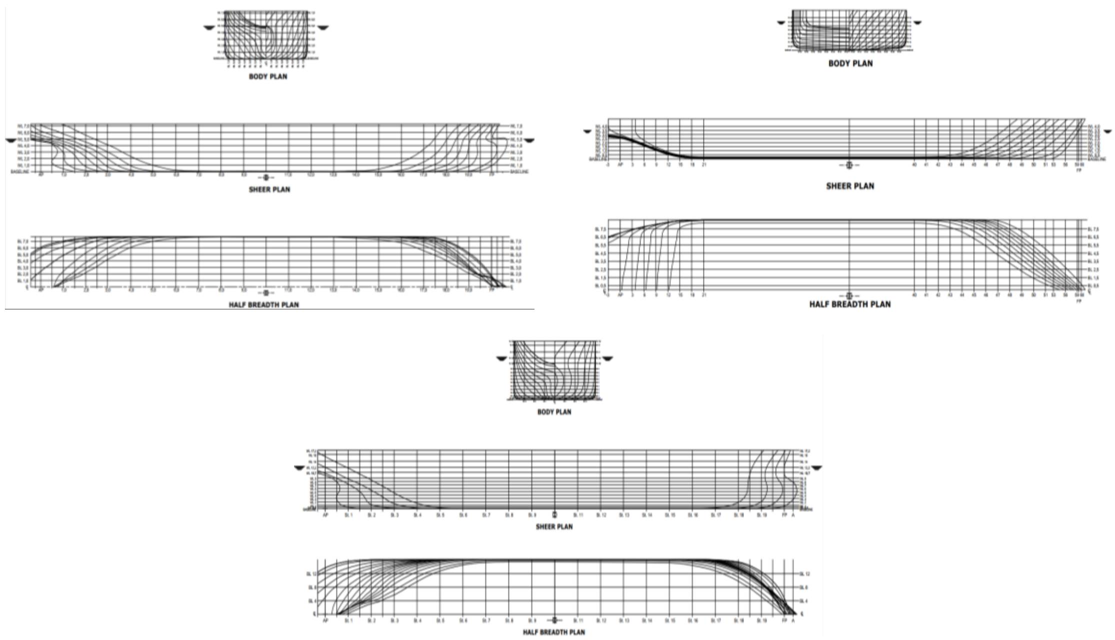

Figure 2. Redrawn Lines Plan from the Original Data of TS-1, CS-1 and BCS-1

After redrawing all the lines plans with the help of Maxsurf software, it continues to analyze each of the ship's resistance while the ships are on an even keel condition and during the trim condition. The variety used to decide which is the best trim for each ship uses 22 trim conditions (trim by bow and trim by stern) and 7 speed variations. After selecting the most optimum condition for each ship, then the fuel consumption and the total estimated exhaust gas produced by each ship can be measured.

2.1. Trim Variations and Speed Range

The trim variations are constrained by 2-meter trim by stern and trim by bow, with the addition of a trim condition that is limited by an Eq. 1 as follows [11]:

$$Trim\ Max = \frac{1\%\ L_{BP}^2}{GM_L} \tag{1}$$

The speed range is needed to determine at which speed the ship could efficiently cruise, despite the there is an addition to the resistance. The speed range is decided upon the service speed of the models that are going to be used for the research with a bit of bit addition to the speed range. It is decided that the speed range starts from 8 knots to 20 knots with the interval of 2 knots between each of the speed ranges.

2.2. Ship Resistance

The method of calculating the total resistance (RT) by Holtrop, because the hull type is U, is used in this study with the help of Maxsurf Resistance software. The data used for calculating the ship's resistance is based on the redrawn lines plans of each model so that this study can estimate the resistance as accurately as possible. The resistance calculated will vary even with the same model because the WSA and the ship's speed will impact the resistance experienced by the ship′s hull. The total resistance consists of form factor, frictional resistance (RF), wave-making resistance (Rw), appendage resistance (RAPP), correlation allowance resistance (−RA), and air resistance (RAA); the formula for total resistance can be seen in Eq. 2

$$R_T = (1+k)R_F + +R_W + R_{APP} + R_A + R_{AA} \tag{2}$$

2.3. Ship Trim

The trimming of a ship happens when the forward draught (dF) value is not the same as the after draught (dA), resulting in the ship longitudinally uneven. This condition could affect many things in a ship because it modifies one of the most important parameters, that is, the draught of the ship. Ship trimming could be achieved through the shift of weight inside the ship. Ship trim could be defined through the following convenient formula (Eq. 3):

$$Trim = d_A - d_F \tag{3}$$

If the trim value is positive (+) it indicates the ship is trimming by stern, whereas if the value is negative (-) it indicates the ship is trimming by bow.

2.4. Ship Engine Power and Fuel Consumption

The power for the prime mover has to be specified first before defining the total fuel oil consumption of the ship. Several formulas are needed to calculate the Brake Horse Power (BHP) of the ship, and the first one is the Effective Horse Power (EHP). EHP can be calculated by multiplying the RT with the ship speed (VS); the Eq. 4 is as follows:

$$EHP = R_T \times V_S \tag{4}$$

After the value of EHP has been determined, then the Shaft Horse Power (SHP) can be calculated. There are 2 types of formulas to specify the SHP– the first one is to calculate SHP for ships with a single screw propeller, and the other one is for ships with twin screw propellers. SHP for single screw and twin-screw can be seen in Eq. 5 and Eq. 6, respectively. The Propulsive Coefficient (PC) usually ranging from 50%–70%, and this study uses 70% as its PC.

$$SHP = \frac{1}{PC} \times EHP \tag{5}$$

$$SHP = \frac{1}{2} \times PC \times EHP \tag{6}$$

Lastly, the BHP of the ship can be determined by adding the SHP with a percentage of Sea Margin (SM), which ranges from 15%–20%, and then dividing the BHP with added SM with 0,85 as the engine margin is usually around 15%. The order of calculating the BHP for the ship is as follows:

$$BHP_{SM} = (SM \times SHP) + SHP \tag{7}$$

$$BHP_{MCR} = \frac{BHP_{SM}}{0.85} \tag{8}$$

As for the fuel consumption, this study uses Specific Fuel Oil Consumption (SFOC) from the existing main engine data used by each of the models. The following equation (Eq. 9) is the formula for calculating the total fuel consumption:

$$W_{FO} = P \times SFOC \times \frac{S}{Vs} \times C \times 10^{-6} \tag{9}$$

Where P is the power estimated for the main engine, S is the distance travelled by ship, and C is the constant addition of fuel value, usually ranging around 1.3–1.5, this study uses 1.5 as its C value. This study assumed the value of S by all of the ships as 1000 nautical miles; the purpose of selecting that value is so that the comparison of the fuel consumption can be on a more equal standing.

2.5. Exhaust Gas Emission

The emitted exhaust gas is only estimated during the cruising phase of the ships, that means during hoteling and maneuvering the exhaust gas is not calculated, because trim doesn't give a lot of impact during those two phases (i.e. hoteling and maneuvering). The following formula is used to estimate the total exhaust gas [12]:

$$E = 10^{-3} \times FC \times EF \tag{10}$$

Where FC is the total fuel consumption of the ship and EF is the emission factor of the pollutant. The emission factor used in this study can be seen in Table 4 and Table 5, as follow [12], [13]:

Table 4. Emission Factor with the Main Engine Type

Pollutant	Fuel Type					
	High-Speed Diesel		Medium-Speed Diesel		Slow-Speed Diesel	
	HFO	MDO	HFO	MDO	HFO	MDO
NOX	57.7	57.1	63.4	63.1	89.7	88.6
NMVOC	0.9	1	2.3	2.4	3	3.2
PM	3.8	1.5	3.8	1.5	8.7	1.6

Table 5. Emission Factor without the Main Engine Type

Pollutant	Fuel Type	
	HFO	MDO
CO	7.4	7.4
CO2	3200	3200
SOX	20 * S	20 * S

From Table 4 and Table 5, all the emission factor unit is kg/ton. It can be seen that the pollutants that are going to be estimated are Nitrous Oxide (NOX), Non-Methane Volatile Organic Compound (NMVOC), Particulate Matter (PM), Carbon Monoxide (CO), Carbon Dioxide (CO2), and Sulphur Oxide (SOX). As for SOX, in particular, the amount of SOX emitted is based on the Sulphur (S) content of the fuel. The Sulphur content for HFO is 3,5%, and 1,5% for MDO, are used in this study [14], [15].

3. Results and Discussion

The calculation for the ships' resistance, power, fuel, and exhaust gas are all correlated. Before going further into those calculations, the trim variations need to be established. The first constraint for the trim is that the variation will be limited to 2-meter trim by bow and 2-meter trim by stern, with the interval of 0.2-meter trim between each of the trim conditions. The second constraint, the limited trim, is limited based on the state of the ship (i.e., the LBP and GML), where Eq. 1 will be used. In Table 6, the LBP and GML for each ship used in this study are shown, which later can be used with the formula in Eq. 1 to get the second constraint known as the "limited trim" to get a more controlled and more narrow scope of discussion in this study.

Table 6. Limited Trim for Each Ship

Parameter	Value (m)							
	TS-1	TS-2	TS-3	CS-1	CS-2	CS-3	BCS-1	BCS-2
L_{BP}	84.50	149.50	233.00	69.20	92.00	112.80	182.00	217.00
GM_L	109.856	265.577	273.037	115.450	104.837	164.447	212.080	271.669
Limited Trim	0.650	0.842	1.988	0.415	0.807	0.774	1.562	1.733

In Table 7, Table 8 and Table 9 the total resistance of each ship for 3 types of vessel in every condition is specified with the help of Maxsurf, then the power needed for the ship to overcome the resistance to achieve the selected service speeds are calculated with Eq. 9. After that, the total fuel consumption in each condition is then measured for every model of the ship

Table 7. The Total Resistance (kN) of TS-1 with the Variations of Trim and Speed

Trim (m)	**Speed (knot)**						
	8	**10**	**12**	**14**	**16**	**18**	**20**
2,000	40,20	63,00	96,40	148,30	231,20	358,30	456,20
1,800	42,00	65,40	99,50	152,70	236,30	369,80	469,60
1,600	44,60	68,80	103,90	158,60	243,20	383,40	486,00
1,400	52,00	78,60	116,50	175,00	262,20	416,30	527,60
1,200	55,90	84,00	123,50	184,10	273,00	434,10	551,20
1,000	56,10	84,20	123,70	184,50	273,50	434,90	552,30
0,800	59,60	89,30	130,50	193,70	284,90	453,90	578,40
0,650	61,70	92,40	134,90	200,00	293,10	468,20	599,00
0,600	62,20	93,20	136,20	201,90	295,60	473,00	605,90
0,400	63,20	95,20	139,70	208,00	304,60	490,80	633,70
0,200	62,40	94,80	140,50	211,50	311,80	509,00	663,80
-0,200	58,60	90,20	136,20	209,40	314,00	523,70	684,70
-0,400	58,00	89,60	135,80	210,20	317,00	534,40	694,00
-0,600	57,50	89,10	135,80	211,90	321,60	548,90	708,50
-0,650	57,40	88,90	135,60	212,00	322,00	550,60	709,40
-0,800	56,80	88,10	134,70	211,00	321,70	551,20	705,90
-1,000	56,00	86,90	132,80	208,00	318,70	543,50	689,60
-1,200	55,20	85,60	130,80	204,60	315,00	533,20	671,20
-1,400	54,40	84,30	128,70	201,10	311,20	522,00	652,80
-1,600	53,60	83,00	126,70	197,40	307,20	509,40	634,30
-1,800	52,80	81,90	124,90	194,80	305,90	501,90	623,80
-2,000	52,00	80,70	123,50	193,00	306,70	498,40	619,80

Table 8. The Total Resistance (kN) of CS-1 with the Variations of Trim and Speed

Trim (m)	Speed (knot)						
	8	**10**	**12**	**14**	**16**	**18**	**20**
2,000	34,10	54,90	90,10	154,50	278,90	390,40	621,20
1,800	34,60	55,70	92,20	158,20	293,40	409,50	631,60
1,600	35,00	56,60	94,40	162,30	308,60	432,10	645,50
1,400	35,50	57,60	96,80	166,90	324,20	458,30	662,40
1,200	36,00	58,60	99,20	171,80	339,30	487,40	681,20
1,000	36,50	59,70	101,70	177,20	353,80	519,90	703,00
0,800	37,00	60,80	104,20	182,70	366,20	554,00	726,00
0,600	37,60	62,00	106,88	188,80	377,50	591,10	752,60
0,415	38,20	63,10	109,20	195,00	386,90	628,00	780,60
0,400	38,20	63,20	109,50	195,60	387,60	631,10	783,10
0,200	38,90	64,50	112,20	202,70	396,20	672,70	817,10
-0,200	38,70	64,40	112,40	203,90	398,10	680,90	825,60
-0,400	38,00	62,90	109,20	195,90	387,20	637,40	787,40
-0,415	37,90	62,80	109,00	195,30	386,30	634,10	784,70
-0,600	37,20	61,40	106,00	188,20	375,30	594,10	752,60
-0,800	36,30	59,70	102,40	180,20	360,30	550,00	717,70
-1,000	35,70	58,70	101,10	177,90	360,70	536,00	716,70
-1,200	35,20	57,90	99,90	176,10	359,90	521,60	717,40
-1,400	34,70	56,90	97,80	172,40	350,70	497,50	707,80
-1,600	34,10	55,80	95,60	168,60	338,60	473,00	697,70
-1,800	33,50	54,70	93,30	164,80	324,60	449,70	695,60
-2,000	33,00	53,60	90,90	161,10	309,10	427,80	691,20

Table 9. The Total Resistance (kN) of BCS-1 with the Variations of Trim and Speed

Trim (m)	**Speed (knot)**						
	8	**10**	**12**	**14**	**16**	**18**	**20**
2,000	229,00	352,70	503,70	695,40	958,20	1339,40	1897,70
1,800	226,70	349,20	499,40	691,70	958,40	1349,70	1926,40
1,600	219,60	338,00	483,90	672,60	937,00	1328,60	1907,90
1,562	214,90	330,40	473,10	657,70	915,90	1297,50	1860,60
1,400	214,10	329,10	471,50	656,80	918,20	1307,20	1883,60
1,200	210,00	322,40	462,20	645,40	905,70	1295,90	1875,50

1,000	207,10	317,70	455,70	637,40	897,40	1289,20	1872,50
0,800	205,40	314,80	451,50	632,50	892,70	1286,70	1874,10
0,600	204,40	313,20	449,40	630,70	893,30	1293,40	1891,80
0,400	204,10	312,50	448,50	629,90	893,60	1296,50	1899,30
0,200	204,20	312,60	448,70	630,50	895,50	1301,20	1908,40
-0,200	203,30	311,10	446,60	627,80	892,10	1297,40	1904,50
-0,400	201,60	308,60	442,80	622,30	883,80	1284,60	1886,60
-0,600	200,00	306,00	439,10	616,90	875,60	1271,70	1867,40
-0,800	198,30	303,50	435,50	611,50	867,50	1258,90	1848,90
-1,000	196,70	301,00	431,90	606,20	859,40	1246,10	1830,50
-1,200	195,10	298,50	428,20	600,80	851,20	1233,20	1811,80
-1,400	193,50	296,10	424,60	595,50	843,10	1220,40	1793,30
-1,562	192,30	294,20	421,90	591,50	836,90	1210,50	1778,90
-1,600	191,90	293,70	421,10	590,30	835,10	1207,70	1774,90
-1,800	190,40	291,30	417,60	585,20	827,30	1195,20	1756,60
-2,000	188,80	288,90	414,10	580,00	819,40	1182,70	1738,20

3.1. Trim Optimization based on the Fuel Consumption

The results of using trim to modify the total fuel consumption are mostly generating fuel-saving conditions. However, results denoting fuel consumption increased compared to even keel condition when using some trim conditions. This study compared the total fuel oil consumption during trim with the even keel condition on every speed variation to obtain the most fuel-efficient condition for each ship. After that, the mean value of increasing/decreasing the fuel consumption in each trim condition with every speed variation is calculated.

As seen in Table 7, Table 8 and Table 9, the resistance of the ships analyzed are in every speed and trim variations, these result of resistance in each condition of the ship is then used to proceed to calculate the fuel consumption of each ship based on the resistance that the hull of the ship experienced. The result of the mean value of the fuel consumption in every condition can be seen in Table 10, Table 11, and Table 12, and those mean values are used to establish the curves in Figure 3, Figure 4, and Figure 5

Table 10. The Percentage of Increasing/Decreasing of Fuel Consumption Compared to Even Keel Condition of TS-1

Trim				**Speed (knot)**				**Mean (%)**
(m)	**8**	**10**	**12**	**14**	**16**	**18**	**20**	
2,000	32,323	31,072	30,044	29,815	26,812	31,830	34,132	30,861
1,800	29,293	28,446	27,794	27,733	25,198	29,642	32,198	28,615
1,600	24,916	24,726	24,601	24,941	23,014	27,055	29,830	25,583
1,400	12,458	14,004	15,457	17,179	16,999	20,795	23,823	17,245
1,200	5,892	8,096	10,377	12,873	13,580	17,409	20,416	12,663
1,000	5,556	7,877	10,232	12,683	13,422	17,256	20,257	12,469
0,800	-0,337	2,298	5,298	8,329	9,813	13,642	16,489	7,933
0,650	-3,872	-1,094	2,104	5,348	7,217	10,921	13,514	4,877
0,600	-4,714	-1,969	1,161	4,449	6,426	10,008	12,518	3,983
0,400	-6,397	-4,158	-1,379	1,562	3,577	6,621	8,504	1,190
0,200	-5,051	-3,720	-1,959	-0,095	1,298	3,158	4,158	-0,316
-0,200	1,347	1,313	1,161	0,899	0,601	0,361	1,141	0,975
-0,400	2,357	1,969	1,451	0,521	-0,348	-1,674	-0,202	0,582
-0,600	3,199	2,516	1,451	-0,284	-1,804	-4,433	-2,296	-0,236
-0,650	3,367	2,735	1,597	-0,331	-1,931	-4,756	-2,426	-0,249
-0,800	4,377	3,611	2,250	0,142	-1,836	-4,871	-1,920	0,250
-1,000	5,724	4,923	3,628	1,562	-0,886	-3,406	0,433	1,711
-1,200	7,071	6,346	5,080	3,171	0,285	-1,446	3,090	3,371
-1,400	8,418	7,768	6,604	4,827	1,488	0,685	5,746	5,077
-1,600	9,764	9,190	8,055	6,578	2,754	3,082	8,418	6,835
-1,800	11,111	10,394	9,361	7,809	3,166	4,509	9,934	8,040
-2,000	12,458	11,707	10,377	8,661	2,912	5,175	10,511	8,829

Table 11. The Percentage of Increasing/Decreasing of Fuel Consumption Compared to Even Keel Condition of CS-1

Trim				**Speed (knot)**				**Mean (%)**
(m)	**8**	**10**	**12**	**14**	**16**	**18**	**20**	
2,000	30,691	29,706	29,389	28,933	29,123	42,112	22,233	30,312
1,800	29,675	28,681	27,743	27,231	25,438	39,279	20,931	28,426
1,600	28,862	27,529	26,019	25,345	21,576	35,928	19,191	26,350
1,400	27,846	26,248	24,138	23,229	17,611	32,043	17,076	24,027

1,200	26,829	24,968	22,257	20,975	13,774	27,728	14,722	21,608
1,000	25,813	23,560	20,298	18,491	10,089	22,909	11,993	19,022
0,800	24,797	22,151	18,339	15,961	6,938	17,853	9,114	16,450
0,600	23,577	20,615	16,238	13,155	4,066	12,352	5,784	13,684
0,415	22,358	19,206	14,420	10,304	1,677	6,880	2,278	11,018
0,400	22,358	19,078	14,185	10,028	1,499	6,421	1,965	10,791
0,200	20,935	17,414	12,069	6,762	-0,686	0,252	-2,291	7,779
-0,200	21,341	17,542	11,912	6,210	-1,169	-0,964	-3,355	7,360
-0,400	22,764	19,462	14,420	9,890	1,601	5,486	1,427	10,722
-0,415	22,967	19,590	14,577	10,166	1,830	5,976	1,765	10,982
-0,600	24,390	21,383	16,928	13,431	4,625	11,907	5,784	14,064
-0,800	26,220	23,560	19,749	17,111	8,437	18,446	10,153	17,668
-1,000	27,439	24,840	20,768	18,169	8,335	20,522	10,278	18,622
-1,200	28,455	25,864	21,708	18,997	8,539	22,657	10,190	19,487
-1,400	29,472	27,145	23,354	20,699	10,877	26,231	11,392	21,310
-1,600	30,691	28,553	25,078	22,447	13,952	29,864	12,656	23,320
-1,800	31,911	29,962	26,881	24,195	17,510	33,319	12,919	25,242
-2,000	32,927	31,370	28,762	25,897	21,449	36,566	13,470	27,206

Table 12. The Percentage of Increasing/Decreasing of Fuel Consumption Compared to Even Keel Condition of BCS-1

Trim (m)	**Speed (knot)**							**Mean (%)**
	8	**10**	**12**	**14**	**16**	**18**	**20**	
2,000	-1,687	-3,431	-4,199	-3,977	-2,734	-0,676	1,131	-2,225
1,800	-0,666	-2,405	-3,310	-3,424	-2,755	-1,451	-0,365	-2,054
1,600	2,487	0,880	-0,103	-0,568	-0,461	0,135	0,599	0,424
1,562	4,574	3,109	2,131	1,660	1,801	2,473	3,063	2,687
1,400	4,929	3,490	2,462	1,794	1,555	1,744	1,865	2,548
1,200	6,750	5,455	4,386	3,499	2,895	2,593	2,287	3,981
1,000	8,037	6,833	5,730	4,695	3,785	3,097	2,443	4,946
0,800	8,792	7,683	6,599	5,428	4,289	3,285	2,360	5,491
0,600	9,236	8,152	7,034	5,697	4,224	2,781	1,438	5,509
0,400	9,369	8,358	7,220	5,816	4,192	2,548	1,047	5,507
0,200	9,325	8,328	7,178	5,727	3,988	2,195	0,573	5,331
-0,200	9,725	8,768	7,613	6,130	4,353	2,480	0,776	5,692
-0,400	10,480	9,501	8,399	6,953	5,243	3,443	1,709	6,532
-0,600	11,190	10,264	9,164	7,760	6,122	4,412	2,709	7,375
-0,800	11,945	10,997	9,909	8,568	6,990	5,374	3,673	8,208
-1,000	12,655	11,730	10,654	9,360	7,859	6,336	4,632	9,032
-1,200	13,366	12,463	11,419	10,167	8,738	7,306	5,606	9,867
-1,400	14,076	13,167	12,164	10,960	9,607	8,268	6,570	10,687
-1,562	14,609	13,724	12,722	11,558	10,271	9,012	7,320	11,317
-1,600	14,787	13,871	12,888	11,737	10,464	9,223	7,528	11,500
-1,800	15,453	14,575	13,612	12,500	11,301	10,162	8,482	12,298
-2,000	16,163	15,279	14,336	13,278	12,148	11,102	9,440	13,106

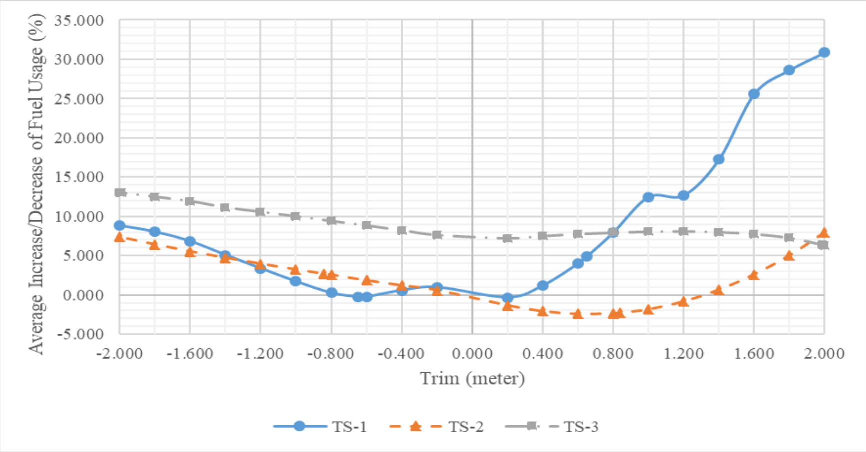

Figure 3. Effect of Trim on Fuel Consumption for Tanker Ships

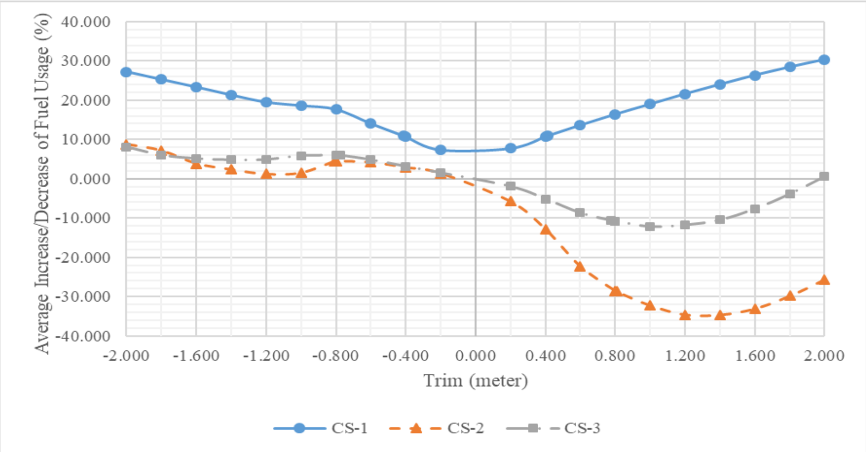

Figure 4. Effect of Trim on Fuel Consumption for Container Ships

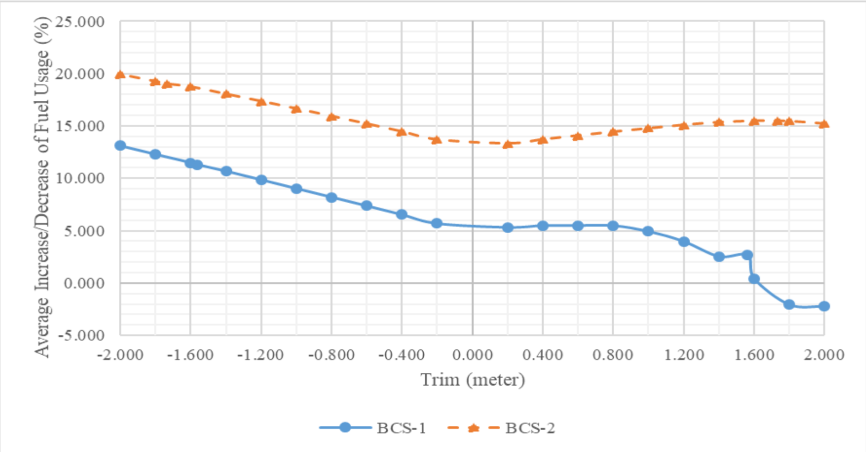

Figure 5. Effect of Trim on Fuel Consumption for Bulk Carrier Ships

However, as there is a second constraint for the trim, Table 13 shows the most optimum trim to save fuel within the trim constraint shown in Table 6, and Table 14 shows the percentage of average decrease of fuel consumption by using the limited optimal trim with the ships' service speed or the closest speed variations with the ships' service speed. Ultimately, the average reduction of the fuel consumption for tanker, container and bulk carrier ships is 5.641%, 8.269% and 15.704%, respectively. As a result, the average reduction of the fuel consumption after trim optimization for the 3 types of ships is 9.871%.

Table 13. Optimal Trim within the Established Range of Trim

Parameter	Value (m)								Unit
	TS-1	TS-2	TS-3	CS-1	CS-2	CS-3	BCS-1	BCS-2	
Limited Optimal Trim	0.650	−0.842	−1.988	0.415	−0.800	−0.774	−1.562	−1.733	m

Table 14. Decrease of Fuel Consumption in Trim Condition Compared to Even Keel Condition

Parameter	Value								Unit
	TS-1	TS-2	TS-3	CS-1	CS-2	CS-3	BCS-1	BCS-2	
Even Keel	100.751	378.785	950.385	101.127	193.854	131.630	480.602	631.365	ton
Limited Optimal Trim	98.630	368.315	835.824	86.544	185.326	123.747	425.054	506.040	ton
Average Decrease	2.104	2.764	12.054	14.420	4.399	5.989	11.558	19.850	%

3.2. Emitted Exhaust Gas on Trim Optimized Ships

The emitted exhaust gas by each ship is measured on the limited optimal trim condition, and then the results are compared to the emitted exhaust gas when the ships are in even keel condition. The percentage of the reduced exhaust gas by ships is shown in Table 15. The percentage decrease of NOX, NMVOC, PM, CO, and CO2 is the same because it depends solely on fuel consumption and emission. Although SOX isn't the same as the other pollutant because it depends on the Sulphur content in the fuel, the amount of SOX emitted differs from the others. In the end, the total reduction of exhaust gas for tanker, container, and bulk carrier ships is 6.494%, 11.317%, and 13.775%, respectively. All in all, the average reduction of the exhaust gasses after trim optimization for the 3 types of ships is 10.529%.

Table 15. Decrease of Exhaust Gas in Trim Condition Compared to Even Keel Condition

Parameter	Value (%)							
	TS-1	TS-2	TS-3	CS-1	CS-2	CS-3	BCS-1	BCS-2
NO_X NMVOC PM CO CO_2	2.104	2.764	12.054	16.238	4.399	8.983	6.599	17.517
SO_X	4.165	5.452	22.655	29.840	8.605	17.159	12.763	31.965

4. Conclusion

By using 3 types of ships (i.e., tanker, container, and bulk carrier ships), this paper can conclude that trim optimization can give a good amount of reduction to fuel consumption and emitted exhaust gasses. Seeing from the results, there is no particular "golden ratio" for the trim of each ship, and that is caused by the hull form of each ship having differences between each other. Despite there are 3 types of ships, it can be concluded that a ship will likely have a decent fuel-saving condition by using the optimized trim condition, which will later impact the exhaust gasses produced by the ship. In this study, the average reduction in fuel consumption and exhaust gas for the 3 types of ships are 9.871% and 10.529%, respectively.

As the whole research is based on only certain types of ships with a limited variation of principal dimension, and at the time being there is no absolute benchmark for the result of this study– it is advisable to wait for further study, specifically on the mean of decreasing fuel consumption and exhaust gas emission, so this study can be more reliable and well-versed as it can be more accurately verified by future works.

Acknowledgements

The first author wants to thank all the colleagues and acquaintances in Darma Persada University, specifically in Naval Architecture department for all the guidance and insight to the author during the process of finishing this research.

References

[1] T. W. P. Smith *et al.*, "Third IMO Greenhouse Gas Study 2014," in *International Maritime Organization (IMO)*, 2014.

[2] Marine Environment Protection Committee (MEPC), "Resolution MEPC.304(72) - Initial IMO Strategy on Reduction of GHG Emissions from Ships," in *International Maritime Organization (IMO) Resolutions*, 2018.

[3] Marine Environment Protection Committee (MEPC), "Resolution MEPC.282(70) - 2016 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP)," in *International Maritime Organization (IMO)* Resolutions, 2016.

[4] A. Fadillah, A. Pusaka, S. Manullang, Y. Arya Dewanto, and D. Faturachman, "Strategy for reducing pollutant emissions from ship activities at the port of Tanjung Perak, Surabaya," *WSEAS Transactions on Environment and Development*, vol. 11, pp. 155–162, 2015.

[5] E. A. Bouman, E. Lindstad, A. I. Rialland, and A. H. Strømman, "State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review," *Transportation Research Part D: Transport and Environment*, vol. 52, pp. 408–421, 2017. doi: 10.1016/j.trd.2017.03.022

[6] X. Lyu, H. Tu, D. Xie, and J. Sun, "On resistance reduction of a hull by trim optimization," *Brodogradnja*, vol. 69, no. 1, pp. 1–13, 2018. doi: 10.21278/brod69101

[7] S. Sherbaz and W. Duan, "Ship trim optimization: Assessment of influence of trim on resistance of moeri container

ship," *The Scientific World Journal*, vol. 2014, 2014. doi: 10.1155/2014/603695
[8] H. Islam and G. Soares, "Effect of trim on container ship resistance at different ship speeds and drafts," *Ocean Engineering*, vol. 183, no. March, pp. 106–115, 2019. doi: 10.1016/j.oceaneng.2019.03.058
[9] J. Sun, H. Tu, Y. Chen, D. Xie, and J. Zhou, "A study on trim optimization for a container ship based on effects due to resistance," *Journal of Ship Research*, vol. 60, no. 1, pp. 30–47, 2016. doi.org/10.5957/jsr.2016.60.1.30
[10] M. M. Moustafa, W. Yehia, and A. W. Hussein, "Energy efficient operation of bulk carriers by trim optimization," *18th International Conference on Ships and Shipping Research, NAV 2015*, pp. 484–493, 2015.
[11] R. D. Andrianto and D. Manfaat, "Penentuan Ukuran Utama Kapal Dengan Metode Basis Ship Menggunakan Sistem Komputer," *Jurnal Teknik POMITS*, vol. 2, no. 1, pp. 1–5, 2013.
[12] C. Trozzi, "Emission estimate methodology for maritime navigation," *US EPA 19th International Emission Inventory Conference*, 2010.
[13] C. Trozzi, and R. Vaccaro, "Methodologies for estimating future air pollutant emissions from ships," *2th International Scientific Symposium*, 2006.
[14] Direktorat Pemasaran dan Niaga PT. Pertamina, "Fuel Oil Material Safety Data Sheet," 2007.
[15] Direktorat Pemasaran dan Niaga PT. Pertamina, "Diesel Oil Material Safety Data Sheet," 2007.